

Application of An Ecosystem-based Disaster Risk Reduction Design Framework for Compound Rainstorm and Heatwave Extreme risk

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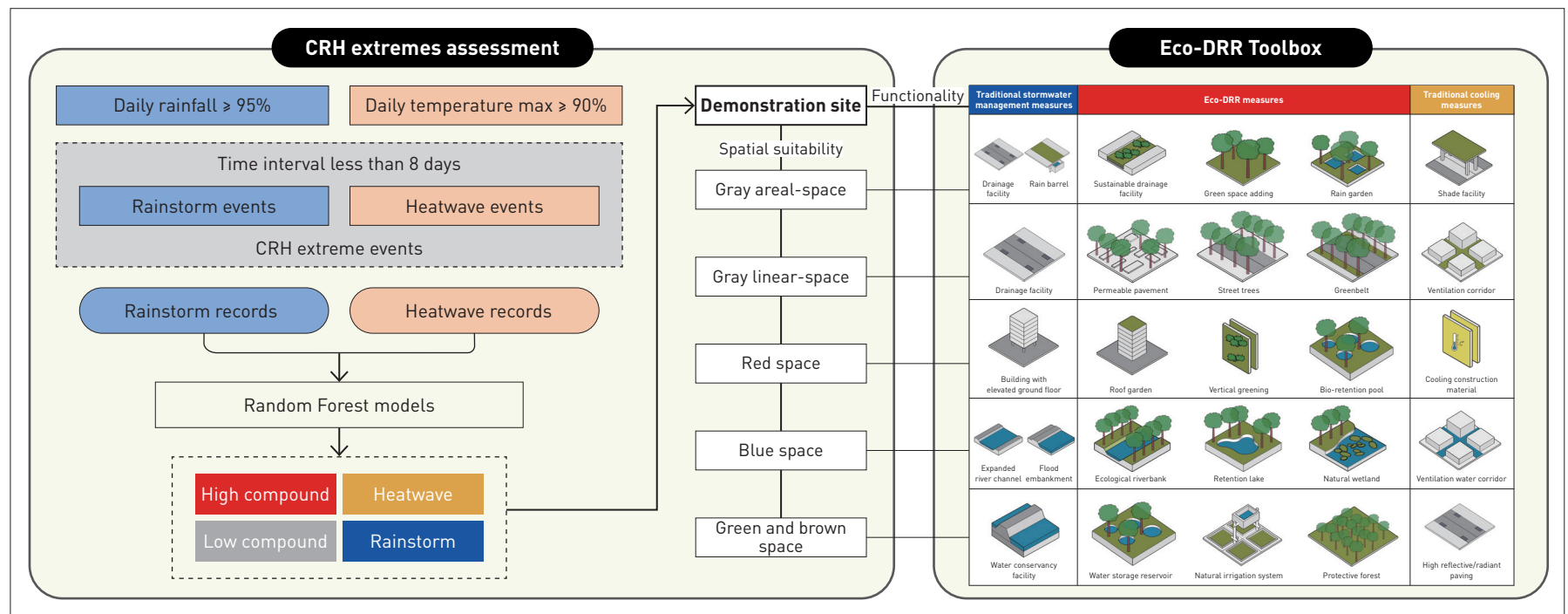
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GRAPHICAL ABSTRACT



ABSTRACT

Cities face a growing threat from compound rainstorm and heatwave (CRH) extremes. However, prevailing research and practice remain fragmented, treating the hazards in isolation and neglecting the critical need for integrated solutions. While Ecosystem-based Disaster Risk Reduction (Eco-DRR) is a theoretically promising approach, its practical application is hampered by a lack of integrated, multi-scale risk assessment and design frameworks. To address this gap, this study proposes a novel Eco-DRR design framework for CRH extreme mitigation and

adaptation. First, it identified CRH extreme events and assessed the spatial distribution of CRH extreme risk in Shanghai using Random Forest models. Results reveal that CRH extreme risk is intensively driven by urbanization, with a distinct spatiotemporal concentration in central districts during the plum rain and summer seasons. Then, we operationalized the framework through an Eco-DRR Toolbox, demonstrating its efficacy in a site on Jiangchuan Street. The demonstration site shows that the Toolbox forges site-specific, synergistic combinations of Eco-DRR and traditional measures,

guided by a structured process of selection, integration, and monitoring and evaluation (M&E). This design framework provides an actionable pathway for robust CRH risk assessment and moves beyond theory by offering a replicable Toolbox for embedding Eco-DRR into urban climate adaptation, thereby advancing urban resilience against compound climate extremes.

KEYWORDS

Ecosystem-based Disaster Risk Reduction; Compound Rainstorm and Heatwave Extreme Risk; Climate Adaptation; Stormwater Management; Heatwave Mitigation; Design Support Toolbox

HIGHLIGHTS

- The framework possesses the capability to adapt to CRH extremes across spatial scales
- The framework identifies CRH events and assesses their spatial distribution in Shanghai using Random Forest models
- The framework provides a toolbox to integrate Eco-DRR and traditional measures based on spatial suitability

RESEARCH FUND

Key Disciplines Construction Project of Shanghai Municipal (No. 22-3-YB-13)

1 Introduction

The accelerating climate change and urbanization have significantly increased the frequency, intensity, and duration of climate extremes^[1]. As an emerging climate hazard, compound climate extremes are associated with more extensive and severe impacts on human health^[2], ecosystems^[3], and infrastructure^[4], than individual extremes. This poses significant challenges to meteorological hazard management, emergency response systems, and climate adaptation strategies. Nature-based Solutions (NbS) demonstrate multiple benefits for hazard mitigation and climate adaptation,

providing effective approaches to addressing compound climate extremes^[5]. However, the practical application of ecosystem-based disaster risk reduction (Eco-DRR)—a key theory under the NbS umbrella—has been limited in addressing compound rainstorm and heatwave (CRH) extremes. Consequently, a design framework integrating Eco-DRR theory with CRH extremes is essential for effective climate mitigation and adaptation strategies.

1.1 Compound Climate Extremes

1.1.1 Definition and Characteristics

Research on weather and climate extremes has been conducted for decades, with the focus shifting to compound climate extremes in recent years. The Intergovernmental Panel on Climate Change (IPCC) formally introduced the concept of compound climate extremes in its 2012 *Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation*^[6]. Since then, the academic community has sought to refine this framework and enhance the understanding by defining compound climate extremes as the co-occurrence or sequential occurrence of multiple extreme events^[7].

Compared with traditional multi-hazard risks, compound climate extreme risk primarily focuses on drivers and hazards within the climate system^[8]. The compound climate extreme risk is categorized into four types based on the relationships among different factors—preconditioned, multivariate, temporally compounding, and spatially compounding^[9]—facilitating understanding of the mechanisms and impacts of compound climate extremes. However, the extreme risk often requires the use of more flexible definitions^[9] due to ambiguities in this classification.

1.1.2 CRH Extremes

The coincident occurrence of intense precipitation and extreme temperature has been widely examined among varieties of compound climate events^[10]. CRH extremes refer to typical extreme weather events resulting from precipitation and temperature changes^[6,11], which do not fit neatly into existing single-category classifications due to their complex nature. CRH extreme events have increased by 2.51% per decade on average across China since the 1960s^[12]. The upward trend is stronger in eastern coastal regions and has accelerated more rapidly in recent decades^[13]. Studies on CRH extremes have been conducted from multiple perspectives. Initially, research emphasized defining and identifying CRH extreme events and analyzing their spatiotemporal evolution^[11]. As research advanced, scientists shifted from examining characteristics to exploring the underlying mechanisms

driving these events, while also projecting their potential changes under a warming climate^[14]. Today, although scholars increasingly recognize the importance of societal, economic, and ecological impacts of CRH extremes, research on mitigation and adaptation strategies for CRH extremes remains limited. Addressing this gap is a pressing priority for designing climate adaptation and mitigation measures to counteract CRH extremes.

Eco-DRR has demonstrated efficacy in addressing multiple climate hazards^[15] by enhancing heat mitigation and stormwater management^[16-17]. It synergizes water-sensitive urban design and green infrastructure approaches^[18], amplifying the cooling benefits of urban vegetation. Eco-DRR strategies, particularly green and blue infrastructure, can establish a beneficial feedback cycle for urban climate adaptation. These measures not only mitigate heat by enhancing evapotranspiration and reducing the urban heat island intensity^[5], but also increase rainwater retention, thereby diminishing surface runoff^[18]. The reduction in heat, in turn, can moderate the convective processes that often intensify local rainstorms, enhancing the compounded climate resilience against compound extremes. While Eco-DRR's spatial compatibility has been leveraged to mitigate urban heat islands and stormwater pollution^[19], its integration into CRH extremes adaptation remains limited in policy frameworks, where Eco-DRR theory can offer cost-effective, energy-efficient, and environmentally sustainable approaches^[20].

1.2 Linking Eco-DRR to CRH Extremes Adaptation

Historically, urban rainstorms and heatwaves have been assessed and addressed as independent hazards^[5], with strategies developed in isolation. However, emerging research highlights their interconnection^[21], as both are linked to urbanization (e.g., building height^[22], urban development^[13]) and the urban heat island effect may amplify rainfall intensity^[23]. While Eco-DRR offers dual benefits for cooling and stormwater infiltration^[24], interventions that address multi-hazard interactions have yet to be explored.

NbS have been considered an umbrella framework for addressing multiple sustainability crises including climate change, ecological security, land degradation, and biodiversity loss. Eco-DRR and ecosystem-based adaptation are two key and closely-aligned concepts falling under the NbS umbrella^[25]. The main differences between the two approaches relate to temporal and spatial scales: ecosystem-based adaptation often addresses long-term climate change impacts and ecosystem dynamics, whereas Eco-DRR concentrates on specific hazard events within specific time periods and locations^[15]. Thus, Eco-DRR provides a robust theoretical basis

for reducing vulnerability associated with climate change while simultaneously mitigating and adapting to CRH extremes.

1.2.1 Eco-DRR Design

Eco-DRR design process commonly comprises four phases: ecosystem disaster regulation service assessment, natural disaster risk assessment, Eco-DRR planning decision-making, and Eco-DRR monitoring and post-evaluation (M&E)^[26]. At each phase, the larger landscape must be considered, as ecosystems interact with and influence their broader environment and cannot be managed in isolation^[25]. Thus, effective Eco-DRR design for CRH extremes adaptation requires integrated consideration for both regional and site scales.

1.2.2 Risk Assessment

Credible Eco-DRR design processes require assessing the risk of undesirable system changes caused by external events such as CRH extremes. This is particularly critical for the negative impacts occurring beyond the boundaries of the intervention site in Eco-DRR design. Risk assessments, alongside proactive risk management measures, determine the success or failure of Eco-DRR interventions^[25].

Risk assessments for rainstorms primarily use hydrological simulation techniques to identify flood-prone areas, locate waterlogged zones, and calculate inundation areas^[27]. Risk assessments for heatwaves often focus on thermal environment simulations at the site scale, measuring indicators such as air temperature and physiological equivalent temperature to characterize risks^[28]. However, existing research predominantly emphasizes single-hazard mitigation. The significant differences in risk indicators between the separate hazards complicate the evaluation of CRH extreme risk.

Previous studies have proposed several methods to identify CRH extreme events and assess CRH extreme risk at the macro-scale. 1) Simple superposition is a binary classification method that identifies multiple CRH extreme events occurring simultaneously or successively^[29]. However, this method fails to quantify the severity of CRH extremes. 2) Machine learning, particularly the Random Forest (RF) algorithm, has enhanced the analysis accuracy of climate extreme risk^[30] by capturing nonlinear relationships between spatial drivers and hazards^[31-32], calculating quantitative probability as an indicator^[33], and generating accurate hazard maps^[34]. 3) Joint probability treats multiple environmental factors as different random variables and detects CRH extreme risk using the combined density distribution and predefined thresholds^[35]. 4)

Spatial clustering methods, coupled with event encoding, detect CRH extreme risk through spatiotemporal connectivity and identify extreme types using an event coding system^[36]. While existing studies have provided researchers and practitioners with diverse analytical tools, CRH extreme risk assessment still lacks support for cross-scale Eco-DRR design.

By synthesizing temporal and spatial compounding, this study innovatively proposes a method for CRH extreme risk assessment to support cross-scale Eco-DRR design by quantifying the extreme probabilities via RF models and assessing the spatial distribution of CRH extreme risk through joint probability calculation. Such a method is critical for aligning preparedness with multi-scale Eco-DRR measures.

1.2.3 Eco-DRR Design Toolbox

Eco-DRR design should not be viewed as a singular solution to risk reduction^[15]. Instead, Eco-DRR measures should be part of a package that synergizes traditional measures (e.g., engineering measures) to address CRH extreme risk^[25].

Implementing Eco-DRR requires systematic methods for selecting, evaluating, and designing context-specific measures^[37]. Planners and designers need frameworks to systematize the decision-making criteria and translate the technical aspect of Eco-DRR for planners and designers^[38–39], yet existing tools are restricted in typical hazards^[40–41]. Climate adaptation tools can reduce risks associated with extreme weather events^[37]; however, the support framework for CRH extremes remains undeveloped. Moreover, spatial constraints in high-density cities^[5] and land-use conflicts limit the applicability of Eco-DRR measures. To bridge these gaps, this study proposes the Eco-DRR design toolbox (“Toolbox” hereafter). Site suitability—considering scale, ownership, characteristics, etc.—is critical, with public spaces (e.g., streets, buildings) offering viable implementation opportunities^[19]. The Toolbox aims to provide a package for Eco-DRR design through a structured process by integrating Eco-DRR measures with traditional measures and seeking synergies across diverse types of spaces.

1.2.4 M&E Plan

Eco-DRR is inherently dynamic, acknowledging the uncertainty in bio-economic systems. All interventions must be grounded in scientific evidence and incorporate an M&E plan to facilitate implementation^[42]. Ideally, the M&E plan should be institutionalized to ensure its sustained operation beyond the initial design phase, because it facilitates systematic evaluation of the Eco-DRR design

against baseline conditions and emerging evidence^[43]. Evidence-based learning supports adaptive design strategies, while iterative learning–application cycles are critical for refining Eco-DRR design schemes. Consequently, this study introduces the integration of stormwater models into a continuous iteration loop to quantify and enhance the effectiveness of Eco-DRR design, especially under future climate extremes scenarios.

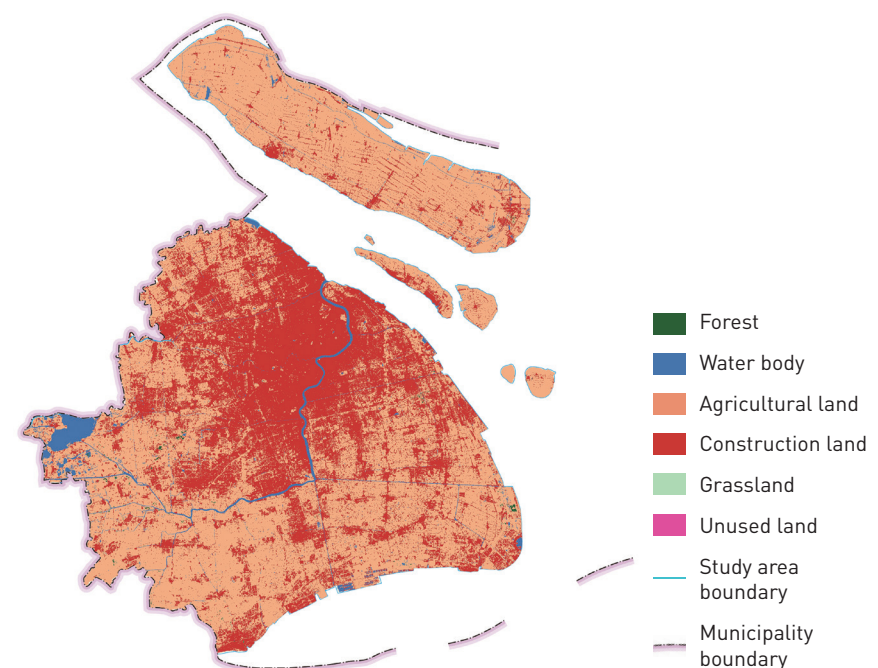
Building on prior discussions, this study proposes an Eco-DRR design framework for mitigating and adapting to CRH extremes coupled with a Toolbox. The framework assists practitioners in developing a package tailored to CRH extreme risk. The research objectives are fourfold: 1) to identify CRH extreme events and assess their spatial distributions; 2) to develop a Toolbox to select combine, and integrate various measures; 3) to demonstrate the customized application of the design framework through a case study; and 4) to examine and enhance the effectiveness of the design through an M&E plan informed by stormwater models.

2 Materials

2.1 Study Area

Shanghai, situated in eastern China, encompasses an area of 6,340.5 km² and hosts a permanent population of 24.28 million residents (Fig. 1). The city features a subtropical monsoon

Fig. 1 Study area [source: Standard Map Service of Shanghai City, map No.GS [2019] 3333].



climate characterized by mild, humid weather, with an average annual precipitation of 1,365.5 mm and summer temperatures occasionally exceeding 40°C^[44]. As a coastal metropolis, Shanghai exhibits pronounced “rain island” and urban heat island effects^[45], which exacerbate the spatiotemporal overlap of CRH extremes, posing a critical challenge for urban planners and policymakers.

2.2 Data Sources and Collection

Daily meteorological data from Shanghai observation stations (2011–2023) were collected to identify the CRH events. Historical rainstorm and heatwave records were sourced from the Data Center for Resilient City Planning. Based on prior research^[46–47], key factors influencing rainstorm and heatwave hazards—including climatic, topographic, hydrological, and landform variables—were compiled. Climatic data (i.e., typhoon tracks, temperature, precipitation) were obtained from the National Earth System Science Data Center. Topographic factors were derived from digital elevation models (DEM) acquired from the China Geospatial Data Cloud. Land cover data were originated from the European Space Agency (ESA) WorldCover 10-meter 2020 product; road data were extracted from OpenStreetMap; and building data were sourced from Baidu Maps.

3 Methods

This paper presents an Eco-DRR design framework incorporating three key aspects: generalizability, practical flexibility, and context-specific adaptation. Generalizability is achieved through assessment methods grounded in driving factor analyses, ensuring feasibility across diverse contexts. Practical flexibility is enabled by the modular structure of the design framework, allowing components to be adapted to local constraints and opportunities. Context-specific adaptation is realized by developing the site-specific Toolbox informed by case studies, ensuring the framework’s effectiveness under varied scenarios^[28,48]. The framework comprises five sequential steps: 1) identifying CRH extreme events; 2) analyzing CRH extreme events using machine learning model outputs; 3) assessing the spatial distribution of CRH extreme risk; 4) developing the Toolbox; and 5) implementing the Toolbox for the demonstration site.

3.1 Identifying CRH Extreme Events

This study employed daily precipitation and maximum temperature records to identify the CRH extreme events by detecting instances where rainstorm and heatwave days occurred

within a defined maximum time interval, using percentile thresholds. Following prior research^[49], this study selected the 95th percentile as the rainfall threshold and the 90th percentile as the heatwave threshold. Referring to the definition by the China Meteorological Administration^[50–51], all potential binary CRH extreme events were extracted. Overlapped individual events were then merged into consolidated CRH events. Finally, the temporal distribution of CRH extreme events was analyzed across months and years.

3.2 Machine Learning Model Outputs

The compound impacts of rainstorms and heatwaves should be incorporated into CRH extreme risk assessments. This study advances prior research by integrating both temporal and spatial compounding impacts of CRH extremes and leveraging machine learning to improve the accuracy of risk assessment.

3.2.1 Assessment of the Driving Factors of CRH Extremes

This study compiled spatial hotspots within the temporal windows of identified CRH extreme events. Rainstorm and heatwave extreme records (as response variables) with values exceeding the median threshold were classified as positive cases, while those below the median were designated as negative cases. All cases were processed and exported as uniformly formatted grid datasets. The driving factors of rainstorm and heatwave events (as explanatory variables) were compiled based on prior research^[44,49] (Table 1), including climate factors (i.e., average precipitation, average temperature, typhoon intensity), topographic factors (i.e., elevation, slope, aspect), hydrological factors (i.e., river density, distance from coastline), and landform factors (i.e., land cover, underlying surface, road density, building density). Following standardized acquisition and processing protocols, all driving factors were normalized to a 0 ~ 1 scale using the ArcGIS platform. Rainstorm and heatwave datasets were formed according to the spatial correspondence between explanatory and response variables.

The RF algorithm was applied to detect non-linear relationships between response and explanatory variables. The algorithm captures complex interactions without assuming linearity, quantifies feature contributions to predictive outcomes, minimizes overfitting risks, and enhances prediction reliability^[52]. Datasets were partitioned into the training set (70%) and the test set (30%). The model was implemented utilizing the scikit-learn library in the PyCharm environment. Relative importance was calculated via Mean Decrease Accuracy, reflecting each variable’s impact on predictive accuracy^[52].

Table 1: The driving factors of rainstorm and heatwave extremes

Factor classification	Variable	Unit	Calculation method
Climate factor	Average precipitation	mm	Classified into high, medium, and low tiers by Natural Breaks method
	Average temperature	°C	Divided into high, medium, and low categories by Natural Breaks method
	Typhoon intensity	mm/h	Categorized into super typhoon, strong typhoon, and typhoon by the intensity level with Natural Breaks method
Topographic factor	Elevation	m	Tiered into high, medium, and low levels by Natural Breaks method
	Slope	°	Calculated based on DEM in ArcGIS
	Aspect	—	Calculated based on DEM in ArcGIS
Hydrological factor	River density	km/km ²	Calculated using the kernel density method in ArcGIS and stratified into high, medium, and low tiers by Natural Breaks method
	Distance from coastline	km	Computed using the Euclidean distance in ArcGIS and divided into far, medium, and near categories by Natural Breaks method
Landform factor	Land cover	—	Reorganized into construction land, farmland, water bodies, forest land, and barren land categories
	Underlying surface	—	Classified into permeable surface, impermeable surface, and other types
	Road density	km/km ²	Calculated using the kernel density method in ArcGIS and stratified into high, medium, and low tiers by Natural Breaks method
	Building density	1/m ²	Executed using the kernel density method in ArcGIS and tiered into high, medium, and low levels by Natural Breaks method

3.2.2 Hazard-level Estimation of Rainstorm and Heatwave Extreme Events

To generate spatially explicit maps of CRH extreme risk, at first, driving factor rasters were extracted for the study area using ArcGIS. The trained RF model then predicted the probability for each raster, which was termed the Urban Rainstorm Index (*URI*) and the Urban Heatwave Index (*UHI*). Hazard impacts were categorized into five levels (i.e., very high, high, moderate, low, and very low) using Natural Breaks method^[53]. Final results were visualized via ArcGIS.

3.3 Assessing the Spatial Distribution of CRH Extreme Events

This study proposes the indicator Urban Rainstorm–Heatwave Extreme Index (*URHI*) to quantify the compound impacts of rainstorms (*URI*) and heatwaves (*UHI*). The construction of *URHI* follows three steps:

Step 1: Quantify the variations in *URI* and *UHI*. Probabilities of

rainstorm and heatwave extremes derived from the RF models were converted into the $URI(x,y)$ and $UHI(x,y)$. $URI(x,y)$ and $UHI(x,y)$ refer to the values of the *URHI* at the geographic location defined by coordinates (x,y) of a specific location within the study area, respectively. The Coefficient of Variation (*CV*) was applied to assess spatial variability of $URI(x,y)$ and $UHI(x,y)$. To minimize bias, datasets with higher variability $URI(x,y)$ ($CV = 1.535$) were downscaled and datasets with lower variability $UHI(x,y)$ ($CV = 0.347$) were enhanced.

Step 2: Transform the original distribution of *URI* and *UHI*. Exponential and logarithmic functions were employed to normalize $URI(x,y)$ and $UHI(x,y)$ values within the [0, 1] range. The function curves were constrained to intersect at (1, 1) to ensure a balanced and continuous transitions across the range spectrum. Specifically, $URI(x,y)$ was downscaled using exponential function, and $UHI(x,y)$ was enhanced using logarithmic function. Mathematical derivation

identified 2 as the optimal base for these functions, yielding the *URHI* equation. Based on the above transformations, the *URHI* was formulated as Eq. (1):

$$URHI(x, y) = \left(2^{URHI(x, y)} - 1\right) \times \left(\log_2(UHI(x, y) + 1)\right). \quad (1)$$

Step 3: Classify CRH extreme risk based on *URHI*. Using Natural Breaks method, the study area was divided into three hazard levels: high, medium, and low (Table 2). Areas with higher *URHI* values, which indicate higher severity of CRH impacts, should receive priority for Eco-DRR design interventions.

3.4 Developing the Toolbox

Given the current scarcity of decision-making tools for addressing compound climate extremes, this study systematically reviews and evaluates domestic and international Eco-DRR case studies addressing rainstorms and heatwaves, and develops a Toolbox to provide decision-making support for mitigating and adapting to CRH extremes. The Toolbox is designed to ensure applicability across diverse contexts.

Tailored to the context of Shanghai and the study's focus on CRH extremes, the retrieval scope of literature and case studies was restricted to "coastal cities," and the targeted disasters were defined as "rainstorms" (i.e., "stormwater," "flood," "rainfall") and "heatwaves" (i.e., "heat," "heatwave," "high temperature," "elevated temperature"). Due to limited prior use of the term "Eco-DRR measures" in scientific literature, the review also incorporated research on sustainable urban drainage systems (SUDSs), stormwater best management practices (BMPs), green infrastructure, and green spaces from the China National Knowledge Infrastructure (CNKI) and Web of Science databases^①. To address the lack of practical cases in research papers, this study compiled Nature-based Solutions case studies from two platforms:

the Natural Hazards–NbS platform^[54], focusing on European climate risk reduction, and the PHUICOS platform^[55], which aggregates global Eco-DRR applications. The relevance of the retrieved articles was assessed through a rapid manual screening of their abstracts, introductions, and results, and ultimately 97 papers and 61 practical cases were collected for the development of the Toolbox.

Consequently, this study conducted a qualitative analysis of the included Eco-DRR literature and case studies across two dimensions—functionality and spatial suitability—and responded to three questions: 1) What Eco-DRR and traditional measures can address rainstorms and heatwaves? 2) Why should Eco-DRR measures be prioritized, and how do their functions differ from the traditional measures? And 3) how to select and combine Eco-DRR and traditional measures suitable for specific sites?

3.4.1 Measures for Mitigating Rainstorms and Heatwaves

The frequency of each Eco-DRR and traditional measure in the literature and case studies was recorded and ranked, with those in the top 80% selected as commonly used measures and incorporated into the study (Table 3), which were further categorized into four groups (i.e., traditional, Eco-DRR point, Eco-DRR linear, and Eco-DRR surface) to facilitate subsequent analysis.

① Expanded search terms for Eco-DRR case studies on rainstorm and flood disasters were ("ECO-DRR" OR "Green infrastructure" OR "GI" OR "Ecological infrastructure" OR "Ecosystem services") AND ("urban" OR "city" OR "cities") AND "disaster" OR "hazard" OR "emergency" OR "response" OR "recover*" OR "resilien*" OR "risk reduction" OR "disrupt*" AND ("stormwater" OR "flood" OR "heavy rain"). Expanded search terms for Eco-DRR case studies on extreme heat disasters were ("ECO-DRR" OR "Green infrastructure" OR "GI" OR "Ecological infrastructure" OR "Ecosystem services") AND ("urban" OR "city" OR "cities") AND "disaster" OR "hazard" OR "emergency" OR "response" OR "recover*" OR "resilien*" OR "risk reduction" OR "disrupt*" AND ("heat" OR "heatwave" OR "high temperature" OR "elevated temperature").

Table 2: The classification of CRH extreme risk

Hazard level	<i>URHI</i> range	Relative severity	Description
High	$URHI_i \geq URHI_1$	—	Prioritize mitigation measures in areas severely impacted by CRH extremes
Medium	$URHI_2 < URHI_i \leq URHI_1$	$URI_i > UHI_i$	Focus on rainstorm preparedness in CRH-affected areas
		$URI_i < UHI_i$	Focus on heatwave preparedness in CRH-affected areas
Low	$URHI_i \leq URHI_2$	—	CRH impacts are negligible, no immediate action required

Table 3: The measures for mitigating rainstorms and heatwaves

Type	Measure	Frequency of occurrence
Traditional measure	Drainage facility	26
	Building with elevated ground floor	23
	Levee	18
	Rain barrel	16
	Shade facility	12
	High reflective/radiant paving	9
Eco-DRR point measure	Street trees	35
	Bio-retention pool	34
	Roof garden	26
	Water mist	24
	Rain garden	21
Eco-DRR linear measure	River widening	33
	Rainwater harvesting system	27
	Flood embankment	25
	Green envelope	24
	Ecological street	20
	Ecological riverbank	18
Eco-DRR areal measure	Permeable pavement	32
	Natural wetland	25
	Retention lake	22
	Protective forest	17
	Green spaces adding	16

3.4.2 The Functionality and Spatial Suitability of Measures

The effectiveness of these measures in mitigating rainstorms and heatwaves depends on the presence and extent of their respective functional processes. These measures provide climate-regulating ecosystem services, primarily stormwater regulation for rainstorms (e.g., interception, infiltration, evaporation, retention, pumping, avoidance^②) and temperature regulation for heatwaves (e.g.,

transpiration, shading, insulation, ventilation).

Eco-DRR measures depend on ecosystem services, but their feasibility is contingent on urban spatial characteristics. Spatial suitability of the measures was evaluated based on land use characteristics, spatial scale, and ownership^[56]. To identify suitable locations for Eco-DRR implementation, the analysis required road network data, building vectors, river systems, and land-use datasets. Spatial overlay analysis was used to identify suitable spaces within area of CRH extreme risk, guiding the implementation of Eco-DRR and traditional measures (Table 4).

By linking the Toolbox with CRH extreme risk assessments, the Eco-DRR design framework translates the understanding of ecosystem services, functionality and spatial suitability into concrete measures implementation—a critical gap identified in current practice. It clarifies the linkages between Eco-DRR strategies and CRH extreme risk (Fig. 2), addressing a key limitation in current Eco-DRR applications for CRH extremes.

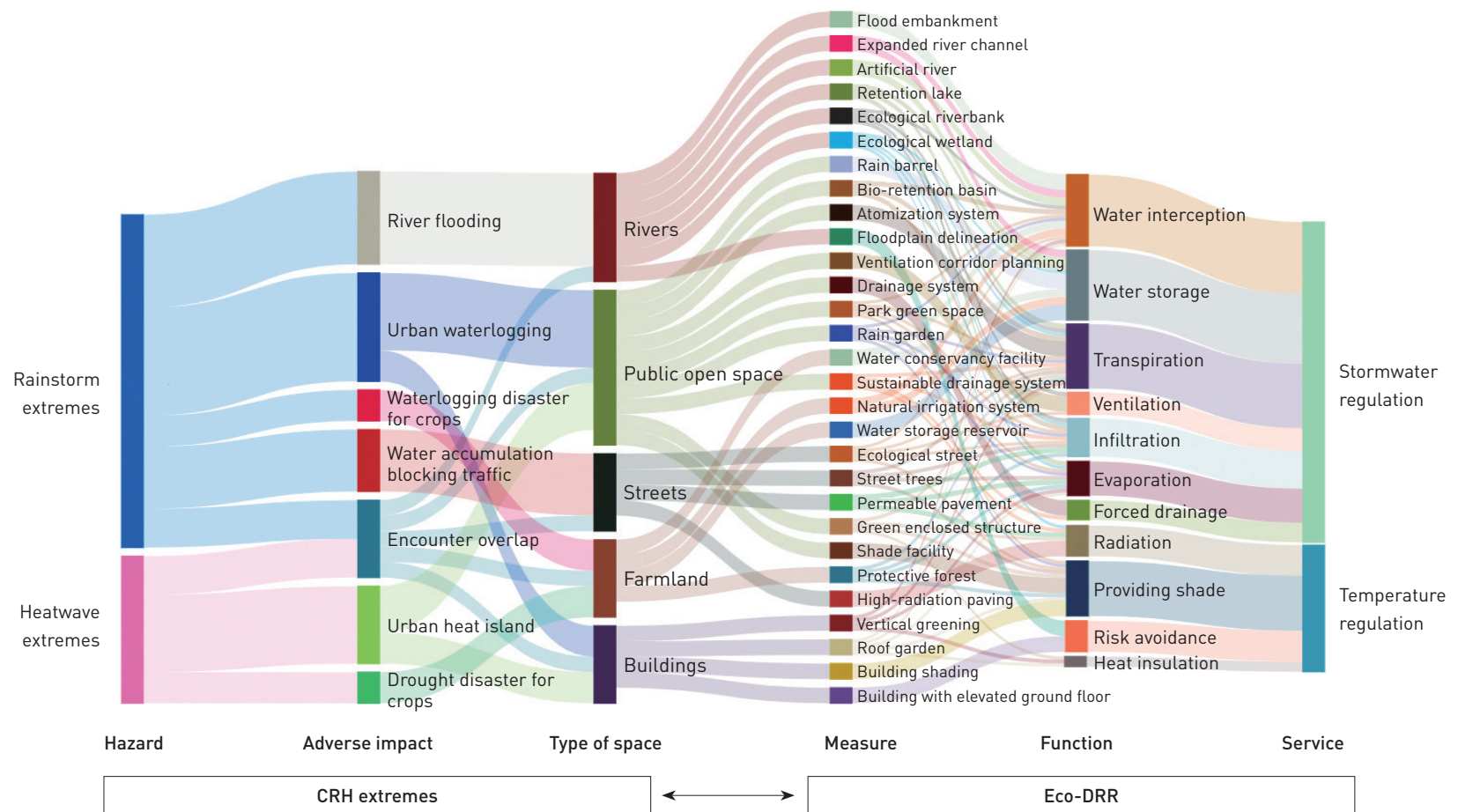
4 Application of the Toolbox for a Demonstration Site

Jiangchuan Road, situated in southwestern Minhang District, Shanghai, lies along the north bank of the mid-upper reaches of the Huangpu River (Fig. 3). The Huangpu River shoreline spans approximately 10 km along the site, with three secondary tributaries extending 12.74 km in length. The terrain is predominantly flat, with elevations ranging from 2.2 m to 9.3 m

② Avoidance refers to the process of preventing or minimizing the impact of floods on sensitive areas.

Table 4: The spatial types suitable for Eco-DRR measures

Type of space	Scale	Description
Red space	Point	Buildings
Gray space	Areal	Paved land like parking lots and squares
	Linear	Paved land like streets and roads
Blue space	Areal	Surface water like lakes
	Linear	Surface water like rivers
Green space	Areal	Vegetated spaces for recreational/farming use
Brown space	Areal	Undeveloped land, abandoned grounds, vacant lots, etc.



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Fig. 2 The mapping diagram of Eco-DRR and CRH extremes.

above sea level. The Jiangchuan Road demonstration site covers an area of about 30 km². The site experiences frequent CRH extreme events due to its humid subtropical climate and high annual rainfall. Historically, the site has suffered from an average of two typhoons annually, peaking at five instances. Its complex climatic and urban

characteristics complicate the implementation of Eco-DRR and traditional measures. Consequently, the Jiangchuan Road area was chosen to evaluate the suitability and effectiveness of the Toolbox in addressing CRH extremes under challenging conditions.

5 Results

5.1 CRH Extreme Events in Shanghai

According to the records, 24 compound CRH events were identified in Shanghai between 2010 and 2023, suggesting a relatively stable interannual frequency, with an annual average of 1 to 3 events. Temporally, these events primarily occurred between May and September. The analysis revealed an increasing trend in annual cumulative duration, notably surpassing 70 days in the past three years (Fig. 4). Identification of these extreme events revealed a 50% increase in the annual frequency and duration of CRH extreme events in Shanghai between 2010 and 2023, with severity and growth trends surpassing those observed in the Pearl River Delta^[13]. This study compiled extreme rainstorm and heatwave event records

Fig. 3 Demonstration site (source: Minhang District Administrative Division, map No. HUS [2020] 048).



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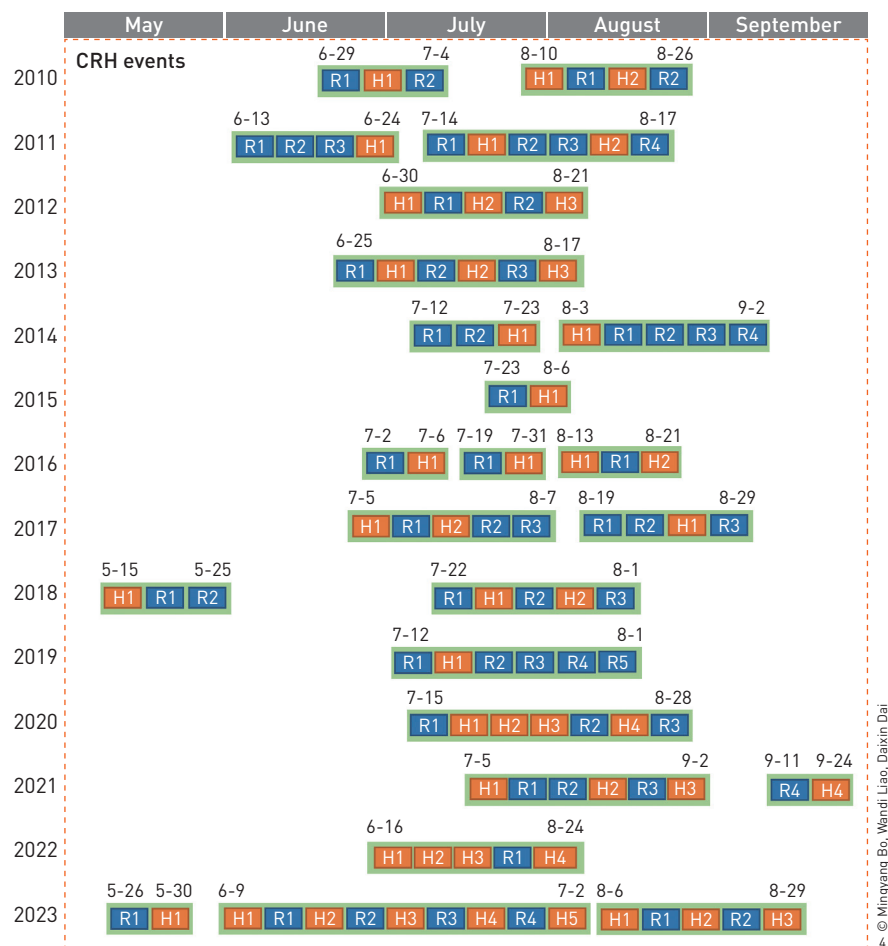


Fig. 4 The identification result of CRH extreme events in Shanghai.

within the CRH temporal window, for subsequent machine learning analysis and spatial risk assessment.

5.2 Machine Learning Model Outputs

Prior to constructing the RF model, multicollinearity among explanatory variables was assessed with the Variance Inflation Factor (*VIF*). All *VIF* values fell below 5, confirming negligible

multicollinearity. For the modeling performance, 150 trees yielded optimal results through empirical testing. Further optimization involved tuning the number of split variables, with 4 and 5 selected for rainstorm and heatwave estimation, respectively.

As shown in Table 5, both rainstorm and heatwave prediction models exhibited robust performance across key metrics, including accuracy, precision, *F1* score, and Area Under the ROC (Receiver Operating Characteristic) Curve (*AUC*). Accuracy quantifies the proportion of correct predictions, while precision measures the reliability of positive-case identification. The *F1* score, as the harmonic mean of precision and recall, reflects overall classification effectiveness. The *AUC* evaluates the class discrimination capability. The RF models demonstrated strong predictive validity, as evidenced by their high scores across these metrics.

5.2.1 Driving Factors of CRH Extremes

Table 6 presents a comparison of variable importance rankings for CRH extremes derived from the RF models, exhibiting comparable importance across models. Distance from coastline and building density emerged as the primary driving factors for rainstorms, with elevation and slope, through their influence on moisture transport, acting as secondary drivers. Land cover, underlying surface, and building density were identified as dominant factors for extreme heatwaves, followed by elevation and average temperature.

Table 5: Model performance metrics

RF Model	Accuracy	Precision	<i>F1</i> score	<i>AUC</i>
Rainstorm	0.824	0.843	0.887	0.783
Heatwave	0.816	0.839	0.892	0.778

Table 6: Comparison of the relative importance of variables between rainstorm and heatwave extremes

Factor classification	Variable	Rainstorm		Heatwave	
		Relative importance	Rank	Relative importance	Rank
Climate factor	Average precipitation	9.23%	5	4.04%	11
	Average temperature	2.18%	11	9.25%	5
	Typhoon intensity	2.03%	12	4.11%	10

(Continued)

Table 6: Comparison of the relative importance of variables between rainstorm and heatwave extremes (Continued)

Factor classification	Variable	Rainstorm		Heatwave	
		Relative importance	Rank	Relative importance	Rank
Topographic factor	Elevation	8.02%	6	9.56%	4
	Slope	13.28%	3	6.58%	7
	Aspect	3.53%	10	3.78%	12
Hydrological factor	River density	6.57%	8	5.25%	9
	Distance from coastline	18.51%	1	8.86%	6
Landform factor	Land cover	11.67%	4	15.74%	1
	Underlying surface	6.86%	7	14.95%	2
	Road density	4.56%	9	5.34%	8
	Building density	13.56%	2	12.54%	3

Eliminating these less influential driving factors is a basic step to refine the prediction accuracy and validity of the RF estimation models. In both the rainstorm and heatwave RF models, factors (typhoon intensity and aspect) ranking in the bottom 30% by relative importance were removed. Consequently, 10 out of 12 driving factors were included for constructing the RF models for rainstorm and heatwave extreme estimation. Figure 5 illustrates the correlations between CRH extremes and the retained explanatory variables, along with their respective weights. These weights, derived from relative importance scores, represent the impact degree of each variable on CRH extremes.

5.2.2 Probability Estimation Maps of Rainstorm and Heatwave Extremes

The RF models were applied to estimate extreme rainstorm and heatwave probabilities across Shanghai. Results reveal a “core-periphery” spatial distribution for both extremes. Figure 6 demonstrates significant overlaps between high-probability rainstorm and heatwave zones. While extreme rainstorms predominantly affect inland areas, including Jiading, Qingpu, Songjiang, Minhang, southern Baoshan, and western Pudong, extreme heatwaves are primarily concentrated in central urban districts such as Jing’an, Yangpu, Baoshan, Putuo, Changning, Xuhui, and northern Minhang. These

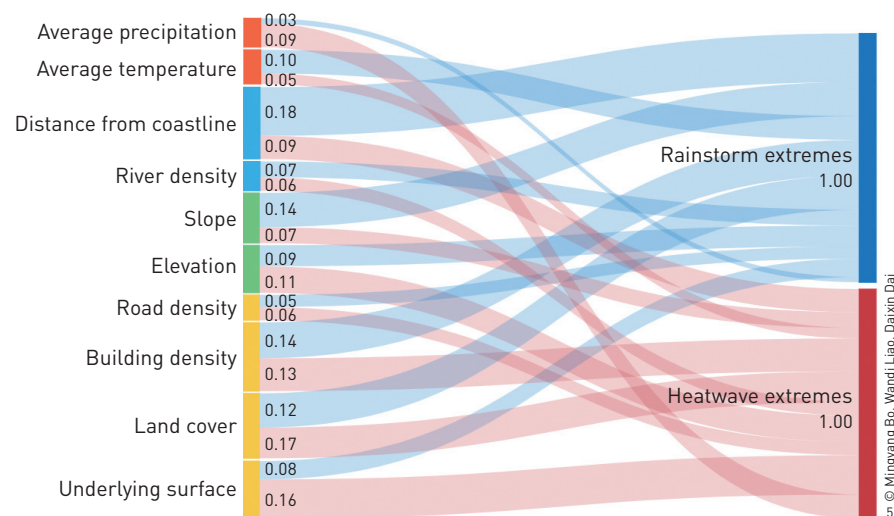


Fig. 5 The correlations of CRH extremes with each explanatory variable in the RF model.

patterns align with historical records, confirming the model’s high predictive accuracy.

5.3 Spatial Distribution of CRH Extreme Risk

Through the transformation and computation outlined in Section 3.3, the spatial distribution of CRH extreme risk in Shanghai

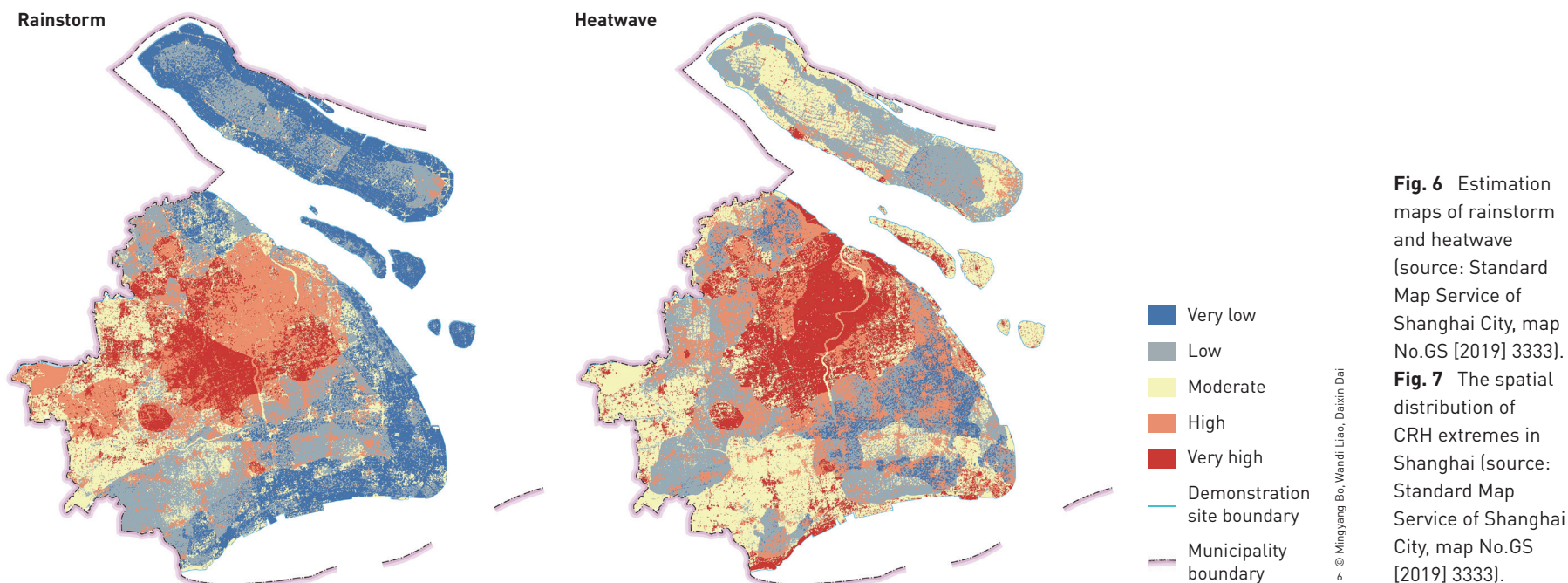


Fig. 6 Estimation maps of rainstorm and heatwave [source: Standard Map Service of Shanghai City, map No.GS [2019] 3333]. **Fig. 7** The spatial distribution of CRH extremes in Shanghai [source: Standard Map Service of Shanghai City, map No.GS [2019] 3333].

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was mapped exhibiting a “central concentration, peripheral dispersion, and local aggregation” pattern (Fig. 7). High *URHI* zones, indicating higher CRH risk, concentrate in central urban areas and surrounding new towns. Medium *URHI* zones were categorized as areas with dominant rainstorm or heatwaves risk. High-risk areas for rainstorms are predominantly distributed in the western region of the city, characterized by a dense river network, while high-risk areas of heatwaves are primarily found in the eastern periphery surrounding the

urban core. Low *URHI* zones, such as Chongming Island and southeastern coasts, exhibit minimal CRH extreme risk. Overall, this pattern suggests a risk gradient from high-risk urban cores to peripheral zones.

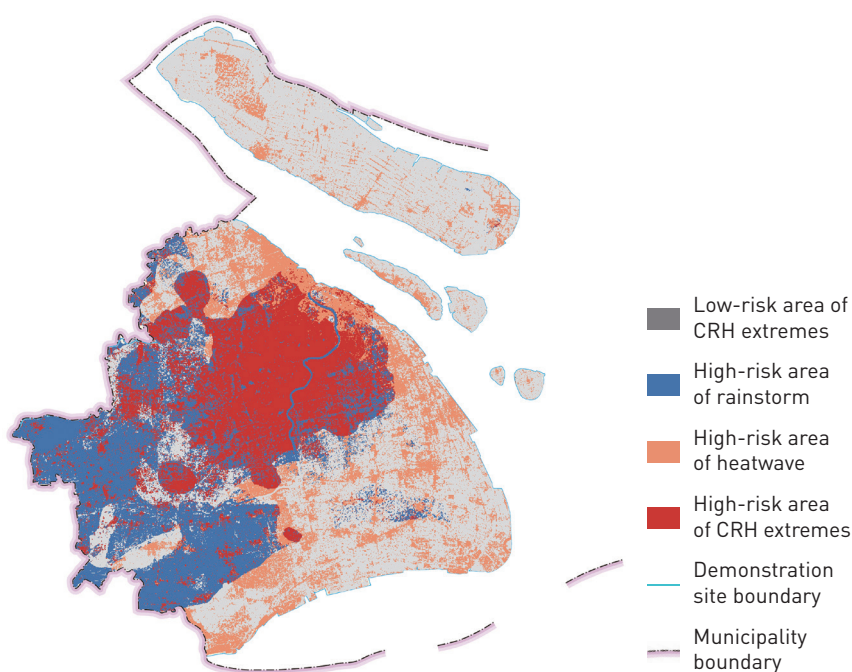
5.4 Toolbox Development

5.4.1 Function Comparison Between Eco-DRR and Traditional Measures

Eco-DRR measures vary in their capacity to deliver ecosystem functions, resulting in differing effectiveness in mitigating CRH extreme risk. This study compared various Eco-DRR and traditional measures by type and functional role (Table 7). The results revealed that Eco-DRR measures often provide multiple ecosystem functions, whereas traditional measures typically serve single functions. This highlights the superior spatial compatibility of Eco-DRR measures in addressing rainstorms and heatwaves.

5.4.2 Toolbox Development Based on Functionality and Spatial Suitability

A toolbox for mitigating CRH extreme risk for Shanghai context was developed based on functionality (the synergy between stormwater management and temperature regulation) and spatial suitability (compatibility with identified spatial types) (Fig. 8). By leveraging spatial compatibility assessments, the toolbox can guide the selection of context-appropriate measures, assisting planners and designers in integrating Eco-DRR measures with traditional measures.



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Table 7: Function comparison between Eco-DRR and traditional measures for rainstorm and heatwave extremes

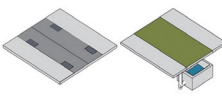
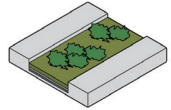
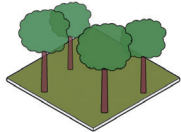
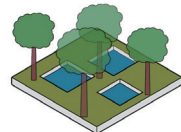
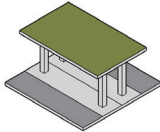
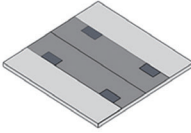
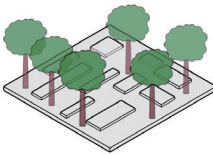
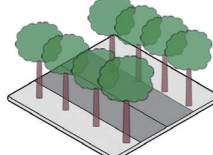
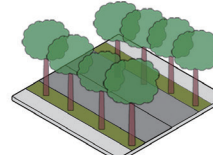
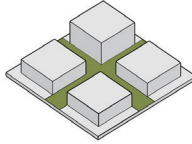
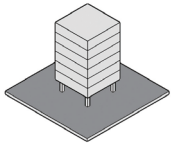
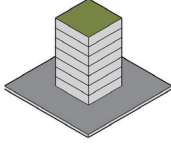
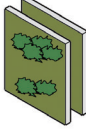
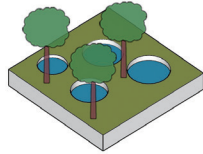
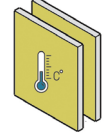
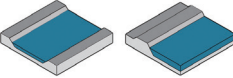
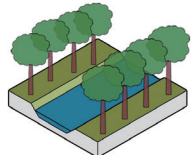
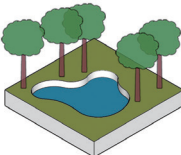
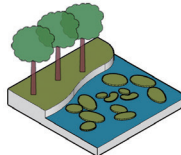
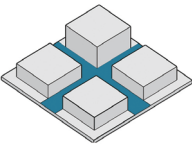
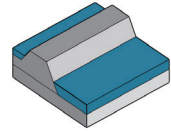
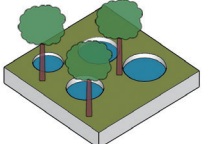
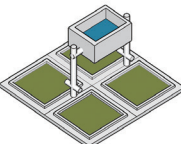

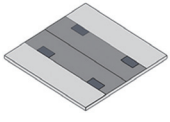
Type	Measure	Functions for stormwater regulation						Functions for temperature regulation			
		Intercep- tion	Infiltra- tion	Evapora- tion	Reten- tion	Pump- ing	Avoid- ance	Transpira- tion	Shad- ing	Insula- tion	Ventila- tion
Traditional measure	Drainage facility					●					
	Building with elevated ground floor				●						
	Levee	●									
	Rain barrel						●				
	Shade facility								●		
	High reflective/radiant paving										●
Eco-DRR Point measure	Street trees		●	●				●	●		
	Bio-retention pool	●	●					●			
	Roof garden	●		●				●	●	●	
	Water mist							●			
	Rain garden	●	●	●				●	●	●	
Eco-DRR linear measure	River widening	●			●						
	Rainwater harvesting system	●	●			●		●			
	Flood embankment	●			●						●
	Green envelope			●				●	●	●	
	Ecological street	●	●	●				●	●		●
	Ecological riverbank	●		●				●			●
Eco-DRR areal measure	Permeable pavement		●					●		●	
	Natural wetland		●	●	●			●		●	●
	Retention lake			●	●			●			
	Protective forest	●	●	●				●	●		
	Green spaces adding	●	●	●				●	●		

5.4.3 Toolbox Implementation Process and Guideline

The Toolbox implementation process included three steps: 1) Eco-DRR measure selection: tailor measures to the site's CRH extreme risk level and spatial suitability; 2) integration: combine selected Eco-DRR measures with traditional measures as a package

to enhance multi-functionality; and 3) assessment: assess the combinability and integrity of the package, following the guidelines and scales outlined in Table 7.

Following established guidelines^[57], supplementary measures for a given site can be selected by addressing three types of gaps: 1)

Classification		Traditional stormwater management measures	Eco-DRR measures			Traditional cooling measures
Spatial type	Gray areal-space	 Drainage facility Rain barrel	 Sustainable drainage facility	 Green space adding	 Rain garden	 Shade facility
	Gray linear-space	 Drainage facility	 Permeable pavement	 Street trees	 Greenbelt	 Ventilation corridor
	Red space	 Building with elevated ground floor	 Roof garden	 Vertical greening	 Bio-retention pool	 Cooling construction material
	Blue space	 Expanded river channel Flood embankment	 Ecological riverbank	 Retention lake	 Natural wetland	 Ventilation water corridor
	Green and brown space	 Water conservancy facility	 Water storage reservoir	 Natural irrigation system	 Protective forest	 High reflective/radiant paving

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Fig. 8 Toolbox for mitigation of CRH extremes.

Functionally, add interception/retention measures to sites with temperature regulation to boost cooling, or add infiltration where interception/retention exists to aid groundwater recharge; 2) spatially, introduce linear measures where only point-based stormwater regulation exists to improve conveyance/connectivity, or add measures at the missing scales if point, linear, and areal measures are not all covered; and 3) typologically, incorporate complementary measures if only Eco-DRR or traditional types exist to ensure synergies. Following this process, appropriate measures are compiled into a package, providing context-specific support for Eco-DRR design.

6 Eco-DRR Design for the Demonstration Site

6.1 Eco-DRR Design Optimization Through the Toolbox

Guided by the established toolbox and guidelines, a package

of measures was proposed for the demonstration site. Eco-DRR measures were prioritized in the eastern area with high CRH extreme risk. Stormwater measures were targeted along the Huangpu River and communities in areas with high rainstorm impact, whereas cooling interventions were prioritized in the western areas with high heatwave impact. Spatial types further informed measure selection. This spatially explicit approach ensures context-specific recommendations for Eco-DRR design (Fig. 9).

For example, ecological riverbanks and ecological streets (linear measures) were added for point-only stormwater regulation to improve conveyance or connectivity. Bio-retention pools and shrubbery in the streets were incorporated to supplement interception and retention functions, enhancing the systemic resilience of the site (Fig. 10).

Risk level	Medium	High		Medium
Hazard type	Rainstorm	Rainstorm + heatwave		Heatwave
Suitability	Suitable for traditional stormwater management measures	Suitable for Eco-DRR measures		Suitable for cooling measures
Gray areal-space	Drainage facility Rain barrel	Drainage facility Infiltration field Infiltration box	Rian garden Green space adding	Shade facility Water mist
Gray linear-space	Drainage facility Rainwater harvesting system Rainwater tank	Street trees Permeable pavement Shrubbery in street	Grass/herbs in street Infiltration box Water square	Ventilation corridor Water mist
Red space	Building with elevated ground floor Infiltration trench	Roof garden Vertical greening Rainwater tank	Vertical greening Bioswale Retention pond	Cooling construction material Water roof Air conditioning
Blue space	River widening Flood embankment	Ecological riverbank Retention lake Helophyte filter	Flood embankment Helophyte filter Natural wetland	Ventilation corridor
Green and brown space	Water conservancy facility	Community farm Water storage reservoir Protective forest	Green space adding Constructed wetland Natural irrigation system	High reflective/radiant paving Shade facility

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Fig. 9 Measures used in the Eco-DRR design for the demonstration site. **Fig. 10** Optimization for Eco-DRR design of the demonstration site (source: Minhang District Administrative Division, map No. HUS [2020] 048).



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6.2 M&E Plan and Planning Strategy for Eco-DRR Design

Monitoring and evaluating the effectiveness of Eco-DRR design schemes is challenging. This research employed an urban

stormwater model coupled with SWMM (a 1D model for a drainage system) and LISFLOOD-FP (a 2D hydrodynamic model) to verify the site's performance before and after implementing the Eco-DRR

design scheme^[48] using the same model parameters and rainfall data. The simulation results revealed two critical improvements: 1) the number of inundation points within the demonstration site during extreme rainstorms decreased from 15 to 5, and 2) both inundation extent and depth were substantially reduced under same extreme rainstorm conditions. The stormwater simulation results indicated that Eco-DRR measures have great effects in improving urban stormwater resilience and reducing flooding risk. Furthermore, future studies could utilize climate simulation software such as ENVI-met to validate the effectiveness of Eco-DRR designs in mitigating heatwave extremes and also conduct M&E plan for cooling effects achieved through Eco-DRR implementations.

Eco-DRR planning strategies, rooted in coordinated ecological space planning and disaster prevention planning^[58], constitute the foundation for detailed design, which establishes a structured implementation framework across five core components: risk assessment–planning objectives–support system–spatial configuration–management measures. Leveraging the RF model for CRH risk assessment developed in this study, planners and designers are recommended to apply an empirical analysis in Shanghai under the Eco-DRR design framework. District-specific resilience objectives are established for sub-districts and categorized into “+ ecology” and “+ disaster prevention” strategies, promoting horizontal coordination between ecological spaces and disaster mitigation systems and advancing NbS into territorial spatial planning for reducing disaster risk. These planning strategies thus facilitate the practical applications of the Eco-DRR design framework in climate-resilient planning and design.

7 Discussion

7.1 Temporal and Spatial Compounding Features of CRH Extremes

This study revealed the temporal and spatial compounding features of CRH extremes in Shanghai. CRH extreme events in Shanghai are frequently linked to the subtropical high-pressure cyclones, which causes persistent heatwaves often followed by extreme rainfall^[13,59]. Summer CRH events arise from enhanced atmospheric convection and moisture convergence, leading to subsequent extreme precipitation^[49]. The predominant driving factors of CRH extremes in the context of coastal megacities are urbanization, distance from coastline, and topographic factors. Urbanization intensifies CRH extreme risk through spatial compounding and aggregation effects^[13]. The interplay between urban rain islands and heat islands^[14] amplifies

extreme precipitation via intensified urban islands and elevated anthropogenic heat^[60]. Distance from coastline and topographic factors correlate with heightened rainstorm frequency, producing two clusters^[61]: one near the Pudong New Area core (about 20 km from the coastline) and another in Minhang and Qingpu (about 50 km from the coastline). This spatial divergence arises because urbanization and terrain undulation delay sea-breeze fronts, displacing moisture convergence zones inland^[61–62].

7.2 Applicability of the Toolbox

The Toolbox developed in this study incorporates functionality and spatial suitability considerations for Eco-DRR. Designed to bridge gaps between planners and engineers, it supports the selection and combination of measures, enabling users to adapt and update measure packages dynamically based on site-specific demands. Unlike existing tools such as SUSTAIN and SWMM (focused on urban stormwater management)^[63], the InVEST urban cooling model (targeting heatwave mitigation via urban trees)^[64], and the Landscape Treatment Designer (for wildfire prevention in urban forests)^[65], the Toolbox uniquely addresses compound climate extremes and supports multi-hazards mitigation. In contrast to tools like the Spatial Suitability Analysis Tool^[40], Adaptation Support Tool^[56], and BMP siting tool^[63], which are limited to small-scale interventions, or NbS suitability mapping, which applies only to large-scale measures^[41], the Toolbox integrates cross-scale adaptability to enhance planning and design processes. By positioning Eco-DRR as a complementary approach, rather than an alternative one, the tool promotes prudent decision-making^[66] and enhances stakeholder engagement^[67]. Furthermore, the Toolbox roughly addresses functionality and spatial suitability. Future research should expand on this by prioritizing cost-benefit analyses^[68], to broaden disaster risk reduction measure evaluations.

8 Conclusions

Eco-DRR holds significant potential for addressing multiple climate extremes, yet practical applications targeting CRH extremes remain limited. This study proposes an Eco-DRR design framework to mitigate and adapt to CRH extremes by integrating CRH extreme risk assessment with the Eco-DRR design toolbox. The CRH extreme risk assessment is developed using RF models, while the Toolbox is established through systematic review of domestic and international case studies on Eco-DRR and traditional measures for rainstorms and heatwaves. The study employs a demonstration site in Shanghai for CRH extreme risk assessment, and Eco-DRR design

implementation.

Three key conclusions emerge: 1) The spatial distribution of CRH extreme risk exhibits a “central concentration, peripheral dispersion, and local aggregation” pattern. High-risk areas of CRH extremes are primarily clustered in central urban areas and adjacent new towns. Urbanization is the dominant factor influencing this spatial distribution. 2) The Toolbox generates an integrated package comprising Eco-DRR and traditional measures tailored to demonstration sites, aligning with functional demands and spatial suitability requirements for CRH adaptation. 3) The CRH extreme risk assessment for Shanghai provides optimized, precise guidance for site-scale Eco-DRR design. An M&E plan and supportive planning strategies facilitate iterative feedback and practical applications on design improvements.

The framework aids urban planners and designers in selecting context-specific Eco-DRR and traditional measures for mitigating CRH extremes. The assessment method of CRH extreme risk is applicable across diverse geo-morphological contexts, and machine learning results exhibit variability in driver-factor evaluations. For instance, topographic factors may dominate the occurrence of CRH extremes in mountainous cities^[69]. However, by analyzing the temporal and spatial compounding features of CRH extremes separately, this study may have inherent limitations, potentially introducing bias in the assessment results. Future research could explore evaluation methods that integrate spatiotemporal compounding effects for a more comprehensive analysis^[36]. Besides, the study is limited by fragmented analytical approaches to spatiotemporal compounding of CRH extremes, and its assessment methods for spatial suitability and functional effectiveness remain relatively simplistic. Future research should expand the framework’s applicability to other compound climate extremes (e.g., drought-heatwaves, flooding) and integrate advanced modeling techniques^[30] (e.g., artificial neural networks, Bayesian models). Broader spatial integration of both private and public green spaces, coupled with analysis of CRH spatiotemporal evolution, could further refine blue-green infrastructure strategies^[35].

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面向极端雨热复合风险的生态防灾减灾设计框架与应用

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摘要

城市正面临日益严峻的极端雨热复合事件的威胁。然而, 现有研究与实践多将极端暴雨和热浪事件孤立分析, 缺乏系统性解决方案。尽管生态防灾减灾理论具有系统整合的潜力, 但其实际应用受限于多尺度风险评估与设计框架的缺乏。为此, 本研究提出了一个面向极端雨热复合风险、减缓与适应的生态防灾减灾设计框架。首先, 本研究识别了上海市的极端雨热复合事件, 并基于随机森林模型评估了其风险的空间分布。研究发现, 城市化进程加剧了此类复合风险, 极端雨热复合事件在梅雨季与夏季集中分布于中心城区, 呈现显著的时空集聚特征。随后, 本研究构建了“生态防灾减灾工具箱”, 并在江川路街道示范地块验证了设计框架的可行性。结果表明, 该工具箱通过措施筛选、整合、监测与使用后评估的结构化流程, 能够因地制宜地协同配置生态防灾减灾措施与传统工程措施。该设计框架不仅为极端雨热复合风险的系统评估提供了可操作路径, 更通过可复制的工具箱将生态防灾减灾理念融入城市气候适应实践, 从而提升城市应对此类极端气候复合事件的韧性。

关键词

生态防灾减灾; 极端雨热复合风险; 气候适应; 雨洪管理; 热缓解; 设计支持工具

文章亮点

- 该框架具备跨尺度减缓与适应雨热灾害复合风险的能力
- 基于随机森林模型识别上海市的雨热灾害复合事件并评估其空间分布特征
- 通过空间适配性分析提供整合生态防灾减灾与传统工程措施的工具箱

基金项目

上海市高峰学科建设项目 (编号: 22-3-YB-13)