

Process-based assessment of stormwater resilience in university building public spaces: causal drivers and improvement priorities in Guangzhou University Town

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Abstract

Extreme rainfall is increasingly disrupting the operational continuity of high-density campus environments, but stormwater resilience in university building public spaces remains insufficiently explained from a process-based perspective. This study develops a multi-criteria framework to assess how campus public spaces identify risks, maintain functions, buffer stormwater pressure, and recover after stormwater events. Five anonymized universities in Guangzhou University Town were evaluated using an integrated FDM-DANP-VIKOR approach (FDM, Fuzzy Delphi Method; DEMATEL, Decision-Making Trial and Evaluation Laboratory; DANP, DEMATEL-based Analytic Network Process; VIKOR, Visekriterijumska Optimizacija I Kompromisno Resenje). FDM was used to screen indicators, DEMATEL-DANP to identify causal relationships and network weights among criteria, and VIKOR to determine improvement priorities under resource constraints. From 37 candidate indicators, 18 were retained and organized into six criteria: Risk Identification and Grading, Stormwater Protection Facility Support, Runoff Drainage Performance, Pedestrian Space Performance, Water-Sensitive Retention Capacity, and Recovery Assessment and Feedback. The results show that Risk Identification and Water-Sensitive Retention Capacity act as upstream causal drivers, while Recovery Assessment and Feedback, Pedestrian Space Performance, and Runoff Drainage Performance represent the main evaluative priorities. The VIKOR results further classify the five campuses into differentiated improvement types. These findings support evidence-informed campus stormwater-resilience governance that moves beyond isolated drainage repairs and static rankings toward process-chain-based renewal strategies.

Keywords: stormwater resilience; university building public spaces; process-based resilience; FDM-DANP-VIKOR; Guangzhou University Town

1. Introduction

Under the combined effects of climate change and rapid urbanization, extreme rainfall events are intensifying stormwater pressure in high-density built environments (Miller and

33 Hutchins, 2017; Kundzewicz et al., 2014; Hou et al., 2025). From the perspective of
34 hydraulic engineering and urban stormwater governance, pluvial flooding is no longer merely
35 a matter of insufficient drainage capacity or localized ponding. Rather, it is an operational-
36 continuity problem jointly shaped by rainfall-runoff processes, surface-flow concentration,
37 drainage obstruction, inadequate detention and infiltration, spatial barriers, and delayed
38 recovery (Hammond et al., 2015; Zevenbergen et al., 2008; Butler et al., 2017). When a
39 stormwater event exceeds a site's capacity for drainage, detention and infiltration, and
40 organizational response, hydrological pressure can further translate into reduced spatial
41 accessibility, interruptions to public services, and constraints on everyday activities
42 (Hammond et al., 2015; Zhou et al., 2022; Dong et al., 2022; Rosenzweig et al., 2018).
43 Building entrances, connecting corridors, open ground floors, semi-outdoor transitional
44 spaces, low-lying walkways, and public nodes are critical interfaces through which
45 hydrological pressure can become operational disruption. Accordingly, investigating the
46 stormwater resilience of university building public spaces is not a general assessment of
47 campus spatial quality; it is a fine-grained examination of the capacity of the built
48 environment to maintain and restore functions under stormwater disturbance.

49 Teaching, residential, dining, library, sports, and public-service functions are highly
50 concentrated, and the daily activities of students and staff depend on continuously accessible
51 pedestrian systems and university building public spaces (Abu-Ghazze, 1999; Dong et al.,
52 2023; Hajrasouliha, 2017; Zhang et al., 2024). At the same time, building density, the
53 proportion of impervious paving, topographic variation, drainage configuration, and the
54 distribution of semi-outdoor spaces jointly influence runoff pathways, ponding locations, and
55 pedestrian safety during intense rainfall (Zuo et al., 2025; Rong et al., 2021; Zha et al., 2024;
56 Xu et al., 2025). Under normal conditions, building public spaces serve as resources for
57 circulation, staying, and social interaction. Under stormwater disturbance, however, they may
58 become vulnerable links where runoff converges, water accumulates, surfaces become
59 slippery, sheltered connections are interrupted, and routes are obstructed (Zuo et al., 2025;
60 Gorzka et al., 2025). Once a local entrance is blocked, a corridor is interrupted, or a low-lying
61 route becomes inaccessible, a localized stormwater problem may escalate into systemic
62 impacts, including constrained access to classes, difficulty reaching everyday services, and
63 delayed post-event recovery (Hammond et al., 2015; Zhou et al., 2022; Dong et al., 2022;
64 Gorzka et al., 2025).

65 Studies of campus space have examined open-space quality, walking behavior, spatial
66 connectivity, environmental perception, and quality of campus life, demonstrating that the

67 built environment significantly affects student behavior and spatial experience (Dong et al.,
68 2023; Hajrasouliha, 2017; Zhang et al., 2024; Lau et al., 2014). Urban stormwater and
69 waterlogging research has explored rainfall-runoff processes, drainage capacity, flood
70 exposure, road connectivity, and infrastructure failure, revealing how intense rainfall affects
71 the operation of urban systems (Miller and Hutchins, 2017; Hammond et al., 2015; Zhou et
72 al., 2022; Dong et al., 2022). Nevertheless, a clear disconnect remains between these two
73 bodies of research. The former generally assumes stable weather and routine use and seldom
74 explains how public-space functions deteriorate when pluvial flooding occurs. The latter
75 focuses mainly on urban districts, road networks, drainage networks, or blue-green
76 infrastructure and rarely reaches the fine-scale operational interface of university building
77 public spaces. Consequently, there is still no systematic explanation of how stormwater
78 processes affect the continuity of campus operations through building entrances, semi-
79 outdoor spaces, pedestrian routes, and public nodes.

80 This gap is particularly evident in campus stormwater-governance practice. Current
81 responses to intense rainfall on campuses often depend on risk alerts, temporary detours,
82 localized closures, drainage repairs, and post-event maintenance. Although these measures
83 can alleviate visible risks, they do not answer more consequential decision questions: Which
84 spatial capacities are antecedent drivers of stormwater resilience? Which capacities primarily
85 represent downstream resilience performance? Which campuses or spatial nodes should be
86 renewed first when resources are limited? Without identifying the influence relationships
87 among criteria and the mechanisms through which effects are transmitted, improvement
88 strategies can remain confined to isolated repairs or static weight-based rankings and fail to
89 distinguish causal drivers from evaluative priorities.

90 Resilience theory provides a process-oriented perspective on this problem. However,
91 when resilience assessment remains at the level of general concepts or static indicators, it
92 often fails to address adequately the relationships among a specific spatial object, a particular
93 disturbance, and actual governance boundaries (Meerow and Newell, 2019; Sharifi, 2016;
94 Rus et al., 2018; Meerow et al., 2016). For university building public spaces, stormwater
95 resilience is not the isolated outcome of drainage-facility performance, spatial quality, or a
96 single management measure. It is a process capacity jointly produced by pre-event risk
97 identification, in-event functional maintenance, hydrological buffering, and post-event
98 recovery feedback. An integrated framework is therefore needed to identify core indicators,
99 explain causal transmission, calculate evaluation weights, and determine improvement
100 priorities simultaneously.

101 To address this gap, this study defines the stormwater resilience of university building
102 public spaces as a process capacity encompassing pre-event risk identification, in-event
103 functional maintenance, hydrological buffering, and post-event recovery feedback, and
104 develops an integrated FDM-DANP-VIKOR evaluation framework. Rather than simply
105 combining several models, the framework links indicator screening, identification of causal
106 drivers, calculation of network weights, and campus improvement ranking into a continuous
107 decision process. Specifically, FDM screens core indicators using aggregated expert ratings;
108 DEMATEL identifies causal influence relationships among the criteria; DANP derives
109 evaluation weights under network dependence; and VIKOR determines improvement
110 priorities from multi-criteria performance gaps. Based on five anonymized case universities
111 in Guangzhou University Town, this study addresses the following research questions:

112 RQ1: How can the stormwater process resilience of university building public spaces be
113 operationalized as a multi-criteria evaluation framework linking pre-event risk identification,
114 in-event functional maintenance, hydrological buffering, and post-event recovery feedback?

115 RQ2: Within this evaluation framework, which criteria constitute causal drivers of
116 stormwater resilience, which constitute evaluative priorities, and do the two sets coincide?

117 RQ3: Under resource constraints, how can causal relationships, evaluation weights, and
118 performance gaps be integrated to identify resilience-improvement priorities and
119 differentiated renewal pathways for university building public spaces in Guangzhou
120 University Town?

121 This study aims to support evidence-informed diagnostic evaluation, identification of
122 vulnerable links, and prioritization of improvements for the stormwater resilience of
123 university building public spaces.

124 **2. Literature Review**

125 **2.1. Operational Characteristics and Research Foundations of University Building** 126 **Public Spaces**

127 University building public spaces form the spatial foundation of everyday campus
128 operations. Their value lies not only in landscape quality but also in their combined functions
129 of circulation, staying, social interaction, and access to services (Abu-Ghazze, 1999; Dong
130 et al., 2023; Speake et al., 2013). Research on healthy campuses, campus spatial quality, and
131 walking activity has shown that open spaces, green environments, spatial connectivity,
132 sidewalk conditions, and street-design quality affect students' user experiences and walking
133 behavior (Hajrasouliha, 2017; Zhang et al., 2024; Lau et al., 2014; McFarland et al., 2008).

However, most existing studies of campus public spaces focus on spatial quality, behavioral associations, and health benefits under stable conditions and offer limited explanations of how spatial functions deteriorate under disturbance (Hipp et al., 2016; Sugiyama et al., 2008). During stormwater events, campus operations are affected less by the static quality of open space than by whether building entrances remain accessible, main routes remain connected, semi-outdoor spaces provide buffering, and critical nodes permit safe passage (Gorzka et al., 2025). This study therefore conceptualizes university building public spaces as a spatial system with process-oriented operational properties and examines their functional continuity under stormwater disturbance.

2.2. Stormwater Disturbance and Functional-Failure Mechanisms in Building Public Spaces

Urban flood research shows that the effects of intense rainfall are not limited to water depth and inundation extent; they also disrupt urban-system operations through service interruptions, transport obstruction, and reduced accessibility (Miller and Hutchins, 2017; Hammond et al., 2015). Road-network studies further indicate that increased rainfall intensity reduces network connectivity and that compound failures can transform disruption to a small proportion of roads into broad network-level functional degradation (Zhou et al., 2022; Dong et al., 2022).

These insights are highly relevant to campus stormwater research. Although a campus is smaller than an urban road network, its teaching buildings, dormitories, dining halls, libraries, and public-service facilities similarly depend on continuous routes and critical nodes (Han and Gao, 2025). When building entrances, low-lying passages, or semi-outdoor transitional spaces are inundated, localized ponding may rapidly become obstructed access to classes, reduced accessibility to public services, and increased pressure on emergency management (Zuo et al., 2025; Gorzka et al., 2025). Although urban road connectivity has received substantial attention, the mechanisms by which public-space nodes of university buildings lose function during stormwater events remain insufficiently examined.

A missing explanatory link therefore remains between stormwater disturbance and building public space: how hydrological risk is transformed into spatial operational failure.

2.3. Process-Based Resilience Theory and a Framework for Spatial Operational Response

Resilience theory offers a process-oriented perspective for explaining spatial operations under stormwater disturbance (Francis and Bekera, 2014; Hosseini et al., 2016). Classical

167 disaster-resilience frameworks emphasize that system resilience is reflected not only in the
168 speed of post-disaster recovery but also in reduced failure probability, reduced consequences
169 of failure, and enhanced capacity to organize resources (Bruneau et al., 2003; Cimellaro et
170 al., 2010; Kammouh et al., 2019). Research on disaster-resilience indicators further suggests
171 that resilience assessment should account for multidimensional conditions, including
172 infrastructure, institutions, society, and community capacity, and should support comparisons
173 among locations through benchmark indicators (Cutter et al., 2010; Cimellaro et al., 2016;
174 Sharifi, 2020). Urban-resilience scholarship also cautions that any discussion of resilience
175 must specify resilience for whom, to what disturbance, and over what temporal and spatial
176 scope (Meerow and Newell, 2019; Meerow et al., 2016).

177 Translating this theory to university building public spaces requires a clear definition of
178 the object of resilience and its process boundaries (Wardekker et al., 2010; Barreiro et al.,
179 2024). This study concerns neither citywide resilience nor the resilience of a single facility.
180 Instead, it examines whether university building public spaces can identify risks, buffer
181 stormwater pressure, maintain basic circulation, and complete recovery and learning before,
182 during, and after intense rainfall. Process-based resilience can therefore be organized into
183 three linked stages: pre-event identification and preparedness, in-event absorption and
184 functional maintenance, and post-event recovery and feedback (Butler et al., 2017; Bruneau
185 et al., 2003; Folke, 2006).

186 Water-sensitive urban design (WSUD) and low-impact development (LID) provide
187 important physical support for stormwater process resilience (Wong and Brown, 2009; Burns
188 et al., 2012; Ashley et al., 2013). Previous studies have reviewed stormwater-management
189 terms and practices such as SUDS (Sustainable Urban Drainage Systems), LID, BMPs (Best
190 Management Practices), and WSUD, showing that decentralized measures, source control,
191 and ecological detention are important directions in modern urban drainage management
192 (Fletcher et al., 2015; Barbosa et al., 2012; McFarland et al., 2019; Meerow and Newell,
193 2017). Campus-scale studies likewise demonstrate that LID measures can reduce runoff,
194 attenuate peak flows, and improve stormwater-management performance (Rong et al., 2021;
195 Zha et al., 2024; Qin et al., 2013; Tan et al., 2024). Nevertheless, these studies generally
196 evaluate hydrological performance as their endpoint and do not fully explain how such
197 facilities support the operational continuity of building entrances, main routes, and public
198 nodes (Raymond et al., 2017; Kabisch et al., 2016).

199 The principal value of a process-based resilience framework is therefore its capacity to
200 connect hydrological regulation, spatial circulation, and recovery feedback (Demuzere et al.,

201 2014; Lovell and Taylor, 2013; Senes et al., 2021; Gill et al., 2007). This study includes LID
202 and water-sensitive retention capacity in the evaluation system, not as isolated engineering
203 outcomes, but as upstream capacities that support spatial functional maintenance and post-
204 event recovery.

205 **2.4. Application of Multi-Criteria Decision-Making to Stormwater-Resilience**

206 **Assessment**

207 Transforming a process-based resilience framework into an operational evaluation tool
208 requires the simultaneous treatment of indicator screening, interpretation of relationships
209 among criteria, and determination of improvement priorities. Flood-risk management
210 generally involves trade-offs among multiple stakeholders, objectives, and criteria; MCDM
211 has therefore been widely applied to risk assessment, alternative ranking, and resource
212 allocation (de Brito and Evers, 2016; Huang et al., 2011). For the stormwater resilience of
213 university building public spaces, the challenge lies not only in the number of indicators but
214 also in the interdependence among criteria: risk identification affects facility maintenance,
215 Water-Sensitive Retention Capacity affects drainage loads, and Pedestrian Space
216 Performance is jointly constrained by upstream conditions. Allocating resources solely
217 according to weight rankings may overlook antecedent drivers, whereas focusing only on
218 causal factors may fail to address the circulation, safety, and recovery performance most
219 directly perceived by users (Zheng et al., 2026; Jamali et al., 2021).

220 To address this problem, this study adopts an integrated FDM-DANP-VIKOR approach
221 (Zhang et al., 2021; Li et al., 2021; Zhu et al., 2017). FDM screens core indicators when
222 expert judgments are fuzzy and uncertain; DEMATEL identifies the criteria that act as causal
223 drivers within the system; DANP converts these network dependencies into evaluation
224 weights and reveals which criteria receive priority in the overall evaluation (Si et al., 2018;
225 Zheng et al., 2026); and VIKOR develops a compromise ranking between group utility and
226 individual regret to identify improvement priorities under resource constraints (Opricovic and
227 Tzeng, 2004; Mardani et al., 2016).

228 **3. Materials and Methods**

229 **3.1. Research Framework and Methodological Pathway**

230 To address multi-indicator screening, causal interpretation, and improvement
231 prioritization in the assessment of stormwater resilience in university building public spaces,
232 this study employs a three-stage hybrid FDM-DANP-VIKOR decision framework. Inputs

include the initial indicators derived from the literature and field observations, expert judgments of indicator suitability and influence relationships among criteria, and performance scores for five universities across six criteria. Outputs include a set of core indicators, the causal structure among criteria, network weights, and campus-level improvement priorities. Each stage addresses a distinct decision question: FDM determines which indicators should be retained; DEMATEL-DANP identifies causal drivers and evaluative priorities; and VIKOR determines which universities should receive priority for improvement under resource constraints (Zheng et al., 2026; Zhang et al., 2021; Xiong et al., 2017). This arrangement avoids equating a weight-based ranking directly with the order of governance interventions and prevents the analysis from focusing exclusively on upstream causes while neglecting actual operational performance.

In this way, the questions of whether an indicator is valid, how the system operates, how performance should be evaluated, and where resources should be directed form a continuous chain of reasoning (Zheng et al., 2026; Zhu et al., 2017; Zhu et al., 2022).

The evaluation boundary should be clarified. This study is limited to the process-based resilience capacities of university building public spaces themselves. The terminal drainage systems of the universities in Guangzhou University Town are connected to the municipal drainage network, and campus drainage performance is partly constrained by regional hydrological conditions, such as the capacity of the external network and backwater effects from receiving rivers. These external conditions are therefore treated as common constraints facing all five universities. The analysis focuses on capacities within campus spaces that can be evaluated and improved in relation to risk identification, functional maintenance, water-sensitive buffering, and recovery feedback.

The five case universities were anonymized and coded A1-A5 (Table 1). The correspondence between institutional names and codes was used only for data verification during the research process and is not disclosed in the manuscript.

Table 1. Profiles and public-space functions of the five case universities.

Case information	Case photos
Case A1 Development and use period: opened in 2004 as part of Guangzhou University Town. Spatial attribute: waterfront ecological type / low-density comprehensive campus. Public-space function: low-lying entrances, open lawns, underpass or parking access, and dormitory-teaching walking links.	

Case information	Case photos
Case A2 Development and use period: Construction began in October 2003; officially put into use in August 2004. Spatial attribute: axial-organization type / high-density teaching campus. Public-space function: teaching-building entrances, axial roads, bicycle parking, tree-lined paths and pedestrian transfer nodes.	
Case A3 Development and use period: Ground-breaking on Oct. 18, 2003; first put into use with Guangzhou Higher Education Mega Center in 2004. Spatial attribute: grid-structure type / industry-oriented campus. Public-space function: grid-based teaching clusters, inner courtyards, water-edge spaces, entrances and service-node connections.	
Case A4 Development and use period: Land allocated in 2003; first students enrolled in September 2004. Spatial attribute: compact-enclosed type / high-pedestrian-flow campus. Public-space function: dense entrances, enclosed plazas, narrow covered corridors and high-flow teaching-living connections.	
Case A5 Development and use period: Constructed during 2003–2005; first entered in September 2004; overall relocation completed in 2005. Spatial attribute: water-green composite type / comprehensive open campus. Public-space function: open pedestrian corridors, water-green edges, plazas, building entrances and campus activity nodes.	
Sources: campus construction and use information is compiled from official university history and campus-introduction pages and Guangzhou University Town historical records.	

Sources: campus construction and use information is compiled from official university history and campus-introduction pages and Guangzhou University Town historical records.

The initial indicators were developed jointly through a literature search and field observation of operational problems. The search covered studies published from 2010 to 2026 on urban flood resilience, water-sensitive design, campus built-environment evaluation, and MCDM methods (Dong et al., 2023; de Brito and Evers, 2016; Prashar et al., 2023). Field observations supplemented this evidence with actual stormwater problems at building entrances, pedestrian routes, low-lying nodes, and semi-outdoor spaces on representative campuses in Guangzhou University Town. The process yielded 37 initial indicators, which were assigned to six criteria within the process-based resilience framework: Risk Identification and Grading (C1), Stormwater Protection Facility Support (C2), Runoff Drainage Performance (C3), Pedestrian Space Performance (C4), Water-Sensitive Retention Capacity (C5), and Recovery Assessment and Feedback (C6). C1 and C2 primarily correspond to pre-event preparedness; C3 and C4 correspond to in-event absorption and

functional maintenance; C5 acts on the formation and transmission of stormwater pressure; and C6 corresponds to post-event recovery and feedback. The complete initial indicator pool and literature sources are provided in Supplementary Table S1. The research procedure is shown in Figure 1.

3.2. Expert Sample and Data-Quality Control

Purposive sampling was used to assemble a mixed panel of 30 experts covering theoretical assessment, spatial-design experience, and stormwater-governance practice. The FDM stage obtained 30 valid questionnaires, which were used primarily to evaluate indicator suitability. The DEMATEL-DANP stage obtained 25 valid questionnaires, which were used to assess the degree of direct influence among the six criteria. The VIKOR stage obtained 28 valid questionnaires, which were used to evaluate the performance of the five universities across the six criteria. All questionnaires were completed by members of the same expert panel to ensure a consistent knowledge base across the three stages. The panel profile is presented in Table 2.

Table 2. Profile of the expert panel ($N = 30$).

Statistical characteristics	Category	N	Percentage (%)
Expert type	University experts	22	73.33
	Social/industry experts	8	26.67
Main professional background	Spatial design, architecture, landscape and planning	19	63.34
	Hydrology, water resources, municipal drainage and sponge-city engineering	7	23.33
	Ecology, GIS/spatial analysis and public governance	4	13.33
Research/practice experience	≤ 5 years	4	13.33
	6–15 years	6	20.00
	> 15 years	20	66.67

Note. GIS, Geographic Information System.

3.3. Implementation of the Hybrid Decision Model

During FDM indicator screening, experts evaluated the suitability of each indicator in the initial system on a 1-10 scale (Zhang et al., 2021; Tseng et al., 2022; Zhu et al., 2025). For each indicator j , lower and upper ratings were separately summarized by their minima, geometric means and maxima to form conservative and optimistic triangular fuzzy numbers. The fuzzy parameters and all 37 crisp scores S_j (G_j in Table 3) were calculated as:

$$C_j = (C_{Lj}, C_{Mj}, C_{Uj}), O_j = (O_{Lj}, O_{Mj}, O_{Uj}) \quad (1)$$

$$S_j = G_j = \frac{O_{Mj} C_{Uj} - O_{Lj} C_{Mj}}{(O_{Mj} - O_{Lj}) + (C_{Uj} - C_{Mj})} \quad (2)$$

295 In Table 3, $Z_j = C_{Uj} - O_{Lj}$ and $M_j = O_{Mj} - C_{Mj}$. Questionnaire most-likely ratings,
 296 distinct from M_j , were not used in this calculation.

297 After ranking crisp values in descending order, the threshold was defined by the score at
 298 the selected cutoff rank t :

$$\alpha = S_{(t)} \quad (3)$$

299 An indicator was retained when $S_j \geq \alpha$; indicators below α were removed, thereby
 300 producing the core evaluation-indicator set.

301 During DEMATEL causal analysis, experts used a five-point scale from 0 to 4 to assess
 302 the direct pairwise influence among the core criteria (Si et al., 2018; Zheng et al., 2026;
 303 Gabus and Fontela, 1972; Tzeng et al., 2007). The judgments of N experts were first
 304 aggregated to construct the initial average direct-influence matrix:

$$A = \frac{1}{N} \sum_{k=1}^N A^k$$

$$= \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \quad (4)$$

305 Matrix A was then normalized to obtain the direct-influence matrix D :

$$\alpha = \max \left(\max_{1 \leq i \leq n} \sum_{j=1}^n A_{ij}, \max_{1 \leq j \leq n} \sum_{i=1}^n A_{ij} \right) \quad (5)$$

$$D = \frac{A}{\alpha} \quad (6)$$

306 Under the convergence condition for the matrix series, the total-influence matrix T was
 307 derived using the identity matrix I :

$$\begin{aligned} T &= D + D^2 + D^3 + \cdots + D^k \\ &= D(I + D + D^2 + \cdots + D^{k-1})[(I - D)(I - D)^{-1}] \\ &= D(I - D^k)(I - D)^{-1} \\ &= D(I - D)^{-1}, \text{ when } k \rightarrow \infty, D^k = [0]_{m \times m} \end{aligned} \quad (7)$$

308 The total-influence matrix can be expressed as follows:

$$T_c = \begin{bmatrix} T_c^{11} & \dots & T_c^{1j} & \dots & T_c^{1n} \\ \vdots & & \vdots & & \vdots \\ T_c^{i1} & \dots & T_c^{ij} & \dots & T_c^{in} \\ \vdots & & \vdots & & \vdots \\ T_c^{n1} & \dots & T_c^{nj} & \dots & T_c^{nn} \end{bmatrix} \quad (8)$$

309 The row and column sums of T_c yield the dispatching and receiving influences, from
310 which prominence and relation are calculated:

$$r = (r_i)_{n \times 1} = \left[\sum_{j=1}^n t_{ij} \right]_{n \times 1} = (r_1, \dots, r_i, \dots, r_n) \quad (9)$$

$$s = (s_i)_{n \times 1} = (s_j)_{1 \times n}' = \left[\sum_{i=1}^n t_{ij} \right]_{1 \times n} = (s_1, \dots, s_j, \dots, s_n)' \quad (10)$$

$$r_i - s_i \quad (11)$$

$$r_i + s_i \quad (12)$$

311 Here, $r_i + s_i$ represents the overall strength of association of criterion i ; a positive $r_i - s_i$
312 indicates a cause criterion, whereas a negative value indicates an effect criterion (Gabus and
313 Fontela, 1972).

314 During DANP weight derivation, the six criteria were treated as nodes in a single
315 network. The total-influence matrix was normalized by row and transposed to obtain the
316 column-stochastic supermatrix. Repeated squaring yielded its fourth power, whose first
317 column was used to approximate the criterion weights (Zheng et al., 2026; Jamali et al., 2021;
318 Zhu et al., 2017; Xiong et al., 2017). The calculation procedure is as follows:

$$t^r_{ij} = \frac{t_{ij}}{\sum_{k=1}^6 t_{ik}} \quad (13)$$

$$W = (T^r)^T \quad (14)$$

$$w_i \approx (W^4)_{i1} \quad (15)$$

319 In the final VIKOR-ranking stage, the five representative universities in Guangzhou
320 University Town were treated as alternatives, and a performance matrix F was constructed
321 from the DANP weights and expert performance scores. Performance values were computed
322 from the 28 experts' questionnaire ratings. The ideal solution f_j^* and negative-ideal solution

323 f_j^- were then determined from the performance matrix, and the distance d_{ij} between each
 324 alternative and the ideal state was calculated.

$$S_i = \sum_{j=1}^n w_j d_{ij} = \sum_{j=1}^n w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \quad (16)$$

$$R_i = \max_j \{w_j d_{ij}\} = \max_j \left\{ w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right\} \quad (17)$$

325 The compromise-ranking value Q_i was then calculated:

$$Q_i = v \frac{(S_i - S^*)}{(S^- - S^*)} + (1 - v) \frac{(R_i - R^*)}{(R^- - R^*)} \quad (18)$$

326 A value of $v = 0.5$ assigns equal importance to group utility and individual regret (de
 327 Brito and Evers, 2016; Opricovic and Tzeng, 2004; Mardani et al., 2016; Chen et al., 2022).
 328 Because Q is interpreted here as the aggregate distance from the ideal state, a smaller Q
 329 indicates better overall resilience performance. From the perspective of improvement priority,
 330 universities with larger Q values should be improved first. Ranking robustness was assessed
 331 using both the acceptable-advantage and acceptable-stability conditions.

332 4. Results and Discussion

333 4.1. Formation of a Process-Oriented Resilience Framework

334 The FDM screening results revealed clear differences in indicator suitability across the
 335 37 initial candidates. Crisp values ranged from 6.449 to 9.395, indicating that the expert panel
 336 clearly differentiated the need to retain individual indicators. Considering score separation,
 337 $\alpha \approx 8.505$ was selected as the screening threshold at the 0.334 gap between I25 ($S_j = 8.505$)
 338 and I35 ($S_j = 8.171$) (Figure 2).

339 After screening, 18 indicators with $S_j \geq \alpha$ were retained, whereas 19 indicators below
 340 the threshold were excluded. The retained indicators covered all six criteria: Risk
 341 Identification and Grading (C1), Stormwater Protection Facility Support (C2), Runoff
 342 Drainage Performance (C3), Pedestrian Space Performance (C4), Water-Sensitive Retention
 343 Capacity (C5), and Recovery Assessment and Feedback (C6). C1 retained three indicators,
 344 C2 retained three, C3 retained four, C4 retained three, C5 retained three, and C6 retained two
 345 (Tables 3 and 4).

346 Table 3. FDM screening results.

Indicator	C_L	C_U	O_L	O_U	O_M	$M - Z$	G	Consensus Met	Criterion
I1 Flood-prone space identification	7	9	8	10	9.748	0.770	8.631	Yes	C1
I2 High-risk path identification	7	9	9	10	9.516	1.785	9.000	Yes	C1
I3 Historical stormwater-event record	5	8	7	10	8.938	1.093	7.626	No	—
I4 Graded Stormwater Risk Representation	6	10	8	10	9.561	-0.411	8.870	Yes	C1
I5 Rainstorm warning and notification	4	9	6	10	8.273	-1.060	7.380	No	—
I6 Alternative route guidance plan	6	8	8	10	8.912	2.009	8.000	No	—
I7 Emergency plan for key nodes	5	8	7	10	8.553	1.011	7.516	No	—
I8 Coordinated response mechanism	5	8	7	10	8.099	1.024	7.363	No	—
I9 Drainage facility maintenance	6	10	8	10	9.378	-0.351	8.756	Yes	C2
I10 Entrance waterproofing and anti-slip measures	7	9	8	10	9.681	0.703	8.622	Yes	C2
I11 Rain-shelter connection provision	4	9	6	10	8.140	-1.031	7.292	No	—
I12 Water-sensitive facility provision	7	10	9	10	9.816	0.396	9.341	Yes	C2
I13 Ponding extent and depth	7	10	9	10	9.755	0.459	9.307	Yes	C3
I14 Runoff conveyance organization	6	10	8	10	9.688	-0.591	8.990	Yes	C3
I15 Drainage operation continuity	5	10	8	10	9.378	-0.322	8.749	Yes	C3
I16 Control capacity for flood-prone locations	7	9	9	10	9.877	1.724	9.000	Yes	C3
I17 Rainy-day main-route accessibility	6	9	8	10	9.451	0.849	8.509	Yes	C4
I18 Continuity of rain-sheltered passage	4	10	6	10	8.204	-2.166	7.511	No	—
I19 Detour-cost controllability	5	9	7	10	8.660	-0.032	7.837	No	—
I20 Peak-period path capacity	5	8	7	10	8.304	1.083	7.423	No	—
I21 Barrier-free passage continuity	5	8	7	10	8.768	1.017	7.586	No	—
I22 Pedestrian-vehicle conflict control	4	8	6	10	7.563	0.030	6.776	No	—
I23 Rain-shelter buffer capacity	6	9	8	10	9.502	0.903	8.517	Yes	C4
I24 Entrance waiting-area shelter	4	9	6	10	7.998	-1.021	7.204	No	—
I25 Ground anti-slip safety	6	9	8	10	9.437	0.847	8.505	Yes	C4
I26 Core-node operational continuity	6	8	8	10	9.030	2.008	8.000	No	—
I27 Support service provision	4	7	6	8	7.329	0.961	6.449	No	—
I28 Rainwater retention and peak attenuation	7	10	9	10	9.816	0.217	9.368	Yes	C5
I29 Infiltration and conveyance efficiency	7	10	9	10	9.816	0.519	9.324	Yes	C5
I30 Facility-system coordination	7	10	9	10	9.877	0.218	9.395	Yes	C5
I31 Differentiated passage support	5	8	7	10	8.354	1.181	7.426	No	—
I32 Drainage and functional recovery time	6	9	8	10	9.561	0.632	8.593	Yes	C6
I33 Spatial reopening recovery	6	8	7	10	8.727	0.878	7.600	No	—
I34 Ground safety restoration	6	8	8	10	9.206	2.009	8.000	No	—
I35 Post-rain inspection and desilting	5	9	7	10	9.175	-0.285	8.171	No	—
I36 Closed-loop repair rectification	4	10	6	10	8.727	-2.103	7.850	No	—
I37 Review feedback and data accumulation	6	10	8	10	9.495	-0.351	8.820	Yes	C6

Table 4. Preliminary evaluation framework for process-based stormwater resilience in university building public spaces.

Dimension	Criteria	Indicator
Pre-Event Preparedness	C1. Risk Identification and Grading	Flood-prone space identification (I1) High-risk path identification (I2) Stormwater Risk Grading Representation (I4)
	C2. Stormwater Protection Facility Support	Drainage facility maintenance (I9) Entrance waterproofing and anti-slip measures (I10) Water-sensitive facility provision (I12)
In-Event Absorption and Functional Maintenance	C3. Runoff Drainage Performance	Ponding extent and depth (I13) Runoff conveyance organization (I14) Drainage operation continuity (I15) Control capacity for flood-prone locations (I16)
	C4. Pedestrian Space Performance	Rainy-day main-route accessibility (I17) Rain-shelter buffer capacity (I23) Ground anti-slip safety (I25)
	C5. Water-Sensitive Retention Capacity	Rainwater retention and peak attenuation (I28) Infiltration and conveyance efficiency (I29) Facility-system coordination (I30)
Post-Event Recovery and Feedback	C6. Recovery Assessment and Feedback	Drainage and functional recovery time (I32) Review feedback and data accumulation (I37)

These screening results show that the final evaluation system is not a general assessment of campus spatial quality. Rather, it is a process-capacity framework centered on whether building public spaces can remain operational during stormwater events.

The five highest-ranked crisp values highlight the importance of water-sensitive detention and infiltration and ponding control. Facility-System Coordination (I30), Rainwater Retention and Peak Attenuation (I28), Water-Sensitive Facility Provision (I12), Infiltration and Conveyance Efficiency (I29), and Ponding Extent and Depth (I13) ranked in the top five. I30, I28, and I29 all belong to C5, indicating high aggregated suitability ratings for indicators of hydrological detention and regulation. This study further embeds C5 within the operational process of university building public spaces and emphasizes its support for the functional continuity of entrances, circulation routes, and public nodes.

4.2. Causal Transmission Structure of Process-Based Stormwater Resilience

After the core indicators were screened, DEMATEL was used to reveal causal transmission relationships among the six criteria. The prominence ($R + S$) and relation ($R - S$) values are reported in Table 5. The average gap ratio of the expert judgments was 0.82%, below the 5% tolerance threshold, indicating satisfactory convergence in assessments of direct influence among the criteria.

Table 5. DEMATEL results at the criterion level.

Criteria	Prominence ($R + S$)	Relation ($R - S$)	Causal type
C1 Risk Identification and Grading	9.558	1.412	Cause
C2 Stormwater Protection Facility Support	9.341	0.482	Cause
C3 Runoff Drainage Performance	10.096	0.119	Cause
C4 Pedestrian Space Performance	8.966	-2.277	Effect
C5 Water-Sensitive Retention Capacity	9.152	0.736	Cause
C6 Recovery Assessment and Feedback	10.716	-0.473	Effect

369

370 The DEMATEL results reveal a clear structure comprising upstream support,
 371 intermediate transformation, and downstream response. In terms of relation, C1, C5, C2, and
 372 C3 were classified as cause criteria, whereas C4 and C6 were classified as effect criteria.
 373 Thus, the process-based stormwater resilience of university building public spaces is not
 374 determined by a single facility or spatial condition. It is formed through continuous
 375 interactions among risk-information identification, hydrological-load buffering, drainage and
 376 protective transformation, circulation performance, and recovery feedback.

377 Within this structure, C1 and C5 constitute the principal upstream support conditions. C1
 378 had the highest relation value ($R - S = 1.412$), indicating that the identification of flood-
 379 prone spaces and high-risk routes, together with graded risk representation, provides the
 380 spatial basis for subsequent facility maintenance, drainage organization, and circulation
 381 safeguards (Rosenzweig et al., 2018; de Moel et al., 2009; Apel et al., 2009). C5 ranked
 382 second in relation ($R - S = 0.736$), showing that stormwater detention, infiltration and
 383 drainage, peak-flow attenuation, and facility coordination can reduce runoff loads before
 384 stormwater pressure reaches critical circulation spaces (Burns et al., 2012; McFarland et al.,
 385 2019; Qin et al., 2013). The two criteria provide upstream support through information
 386 identification and physical buffering, respectively: the former identifies where risks are
 387 located, whereas the latter determines how stormwater pressure can be reduced in advance.
 388 This finding is consistent with the antecedent roles of anticipation, preparedness, and
 389 resource organization in disaster-resilience research (Bruneau et al., 2003; Cutter et al., 2010)
 390 and with the source-control and decentralized-detention logic of water-sensitive urban design
 391 and LID (Wong and Brown, 2009; Fletcher et al., 2015).

392 C2 and C3 mediate the transformation from upstream support to spatial performance.
 393 The relation value of C2 was 0.482, indicating that drainage-facility maintenance, entrance
 394 floodproofing and slip resistance, and the provision of water-sensitive facilities translate pre-
 395 event preparedness into direct protective capacity (Barreiro et al., 2024; Barbosa et al., 2012;
 396 McFarland et al., 2019). The relation value of C3 was 0.119, close to the cause-effect

boundary, indicating that C3 is influenced by C1 and C5 while also affecting C4 and C6. In other words, C3 is the critical pathway through which hydrological-regulation capacity becomes spatial operational performance. Previous flood studies have shown that ponding and road disruption affect accessibility and network connectivity (Hammond et al., 2015; Zhou et al., 2022; Dong et al., 2022); this study extends that logic to the scale of university building public spaces.

The downstream outcomes are represented mainly by C4 and C6. C4 had the lowest relation value ($R - S = -2.277$), indicating that main-route accessibility during rainfall, sheltered-buffer capacity, and ground-surface slip resistance depend strongly on upstream identification, detention and infiltration, protection, and drainage conditions (Gorzka et al., 2025; Böcker et al., 2013). Inadequate identification of risk locations, poor drainage maintenance, disorganized runoff conveyance, or weak Water-Sensitive Retention Capacity ultimately manifests as route obstruction, slippery surfaces, interrupted shelter, and reduced access to building entrances. C4 is therefore not an isolated measure of spatial quality, but an observable outcome of the capacity to maintain spatial functions under stormwater disturbance. Research on campus public spaces has shown that spatial connectivity and route conditions affect routine walking and spatial experience (Hajrasouliha, 2017; Zhang et al., 2024; Lau et al., 2014; Saelens and Handy, 2008); the present findings further demonstrate that these everyday spatial qualities become functional-maintenance capacities during stormwater events.

Although C6 was also classified as an effect criterion ($R - S = -0.473$), it had the highest prominence ($R + S = 10.716$). It is therefore not merely a terminal outcome, but a critical link connecting pre-event, in-event, and post-event processes. Post-event recovery depends on risk-identification results, operational records collected during rainfall, drainage-recovery time, and mechanisms for reviewing problem locations (Cimellaro et al., 2010; Barreiro et al., 2024). From the perspective of continuous improvement, recovery assessment and accumulated data in turn support the next cycle of risk identification, facility maintenance, and water-sensitive renewal (Butler et al., 2017; Folke, 2006). C6 thus shifts stormwater resilience from a one-off event response to a continuous improvement process and embodies the roles of recovery, learning, and adaptive adjustment in process-based resilience.

The prominence results further show that C6 ($R + S = 10.716$) and C3 ($R + S = 10.096$) occupy central positions in the system. C6 represents post-event recovery, review,

and data accumulation and is closely related to all preceding stages, whereas C3 occupies the intermediate position through which hydrological regulation is translated into spatial operational performance. C4 had the lowest prominence ($R + S = 8.966$), indicating that although it is the most strongly affected criterion, it exerts relatively little feedback influence on other criteria and therefore functions mainly as an outcome. The causal network among the criteria is shown in Figure 3.

4.3. Causal Drivers and Evaluative Priorities

After the causal relationships among the criteria were established, the DANP results revealed their weights under network dependence. Considered together, DEMATEL and DANP expose an important characteristic of stormwater resilience in university building public spaces: causal drivers and evaluative priorities do not fully coincide (Zheng et al., 2026; Zhang et al., 2021; Zhu et al., 2017). Causal drivers indicate which criteria can induce changes in other system capacities, whereas evaluative priorities indicate which criteria best represent resilience performance in the overall assessment. The global weights derived from the DEMATEL total-influence matrix T are presented in Table 6.

Table 6. DANP global weights of the criteria.

Rank	Criteria	Global weight
1	C6 Recovery Assessment and Feedback	0.1943
2	C4 Pedestrian Space Performance	0.1917
3	C3 Runoff Drainage Performance	0.1718
4	C2 Stormwater Protection Facility Support	0.1534
5	C5 Water-Sensitive Retention Capacity	0.1456
6	C1 Risk Identification and Grading	0.1433

C6 received the highest global weight (0.1943), followed by C4 (0.1917) and C3 (0.1718); C2, C5, and C1 followed in descending order. This ranking indicates that expert evaluations of campus stormwater-resilience performance focused most strongly on post-event recovery and learning, maintenance of circulation during rainfall, and the stability of runoff and drainage. In other words, C6, C4, and C3 most directly represent whether campus spaces can remain functional, recover, and improve continuously during and after stormwater events, and thus constitute the evaluative priorities. This interpretation is consistent with the theoretical emphasis of process-based resilience on functional maintenance, recovery speed, and adaptive learning (Bruneau et al., 2003; Francis and Bekera, 2014; Hosseini et al., 2016; Meerow and Newell, 2019).

DEMATEL relation values, however, identify C1 and C5 as the more pronounced upstream causal drivers. C1 determines where risks are located, how risk levels are

459 represented, and which routes and nodes should be identified in advance. C5 determines how
460 stormwater pressure is reduced in advance through detention, infiltration, peak-flow
461 attenuation, and facility coordination. Although neither criterion ranks highest by weight,
462 both affect downstream performance in C3, C4, and C6 through the causal chain. The
463 relatively low weight of C1 therefore does not imply low management value, and the lower
464 weight of C5 relative to C6 and C4 does not mean that Water-Sensitive Retention Capacity
465 can be postponed. These criteria are antecedent conditions of system operation rather than its
466 most visible performance outcomes.

467 This difference is not a contradiction between methods; it reflects the complementary
468 explanatory tasks of DEMATEL and DANP (Zheng et al., 2026; Jamali et al., 2021).
469 DEMATEL maps expert-rated influences among criteria, whereas DANP determines the
470 importance of a criterion to the overall evaluation under network dependence. The factors
471 that make campus stormwater resilience function are therefore not identical to those that
472 make it evaluate well. The former are oriented toward enabling conditions, information
473 identification, and hydrological buffering; the latter toward in-event accessibility, post-event
474 recovery, and continuous feedback. Recognizing both sets of factors prevents two decision
475 biases: treating highly weighted downstream symptoms as the sole targets of repair, and
476 improving upstream facilities without addressing the circulation and recovery outcomes most
477 directly perceived by students and staff.

478 DANP weights should therefore be interpreted together with the DEMATEL causal
479 pathways rather than as a simple ranking. C6 and C4 indicate how campus stormwater
480 resilience ultimately manifests; C1 and C5 indicate where improvement should begin; and C3
481 and C2 provide intermediate channels through which upstream conditions become spatial
482 operational performance. For campus renewal, the highly weighted C6 and C4 can serve as
483 performance objectives and monitoring priorities, whereas the causal C1 and C5 should serve
484 as starting points for reform and antecedent targets for resource investment. This
485 interpretation further shows that LID and water-sensitive facilities are not isolated
486 engineering outcomes in the proposed framework, but upstream mechanisms supporting
487 spatial operational continuity, drainage stability, and recovery efficiency (Burns et al., 2012;
488 Raymond et al., 2017; Senes et al., 2021).

489 **4.4. Campus-Specific Priorities for Resilience Improvement**

490 To translate criterion weights into campus-level improvement priorities, the DANP
491 global weights were combined with performance ratings provided by 28 experts for five

universities in Guangzhou University Town, producing a six-criterion performance matrix. The purpose was not to assign absolute labels of superiority or inferiority, but to identify the campuses that require earlier intervention under resource constraints and their principal deficiencies. Table 7 reports the mean performance scores, group-utility values (S_i), individual-regret values (R_i), and compromise-ranking values (Q_i).

Table 7. VIKOR performance matrix and improvement-priority ranking of the five universities.

University	C1	C2	C3	C4	C5	C6	S_i	R_i	Q_i
A1	8.143	6.893	7.321	6.536	8.964	6.857	0.333	0.100	0.242
A2	8.893	8.071	7.107	9.036	5.643	7.857	0.151	0.087	0.084
A3	6.929	7.607	8.107	6.893	5.929	6.464	0.408	0.117	0.350
A4	5.429	4.750	4.429	4.250	3.143	5.536	1.000	0.194	1.000
A5	8.214	7.500	8.679	7.357	9.357	7.643	0.140	0.067	0.000

The compromise ranking ordered the five case universities from best to worst overall performance as follows: A5 ($Q_i = 0.000$) > A2 ($Q_i = 0.084$) > A1 ($Q_i = 0.242$) > A3 ($Q_i = 0.350$) > A4 ($Q_i = 1.000$). The corresponding order of resilience-improvement priority was A4 > A3 > A1 > A2 > A5. A4 had the lowest performance on every criterion and the highest S_i and R_i values. It was therefore classified as systemically vulnerable and should receive the highest intervention priority under resource constraints.

The compromise solution was tested for stability. The acceptable-advantage condition requires the difference in Q between the first- and second-ranked alternatives to be no less than DQ . In this study, the difference between A5 and A2 was 0.084; the acceptable-advantage condition was therefore not satisfied.

The acceptable-stability condition requires the top-ranked alternative also to rank first by S or R . A5 ranked first by both S and R , and therefore satisfied this condition. Because the acceptable-advantage condition was not met, the final VIKOR compromise set was {A5, A2, A1}. A5, A2, and A1 should thus be interpreted as a relatively high-performing group rather than as alternatives with an absolute hierarchical distinction. To explain further the sources of deficiency in each case and support the subsequent typology and differentiated renewal strategies, the weighted gap values of the five cases were decomposed by criterion (Table 8).

Table 8. Decomposition of weighted gaps ($w_j \cdot d_{ij}$) by criterion.

University	C1	C2	C3	C4	C5	C6
A1	0.031	0.054	0.055	0.100	0.009	0.084
A2	0.000	0.000	0.064	0.000	0.087	0.000
A3	0.081	0.021	0.023	0.086	0.080	0.117
A4	0.143	0.153	0.172	0.192	0.146	0.194
A5	0.028	0.026	0.000	0.067	0.000	0.018

518 Based on S_i , R_i , and the decomposition of weighted gaps, the five universities were
519 grouped into four resilience-improvement types. These categories are not static labels; they
520 connect VIKOR performance gaps with the causal relationships identified above to determine
521 whether intervention should begin with upstream conditions, intermediate transformation
522 pathways, or downstream performance. The first type is systemically vulnerable, represented
523 by A4. This university had the highest S_i , R_i , and Q_i values and large weighted gaps across
524 all six criteria, indicating that its deficiencies extend throughout pre-event identification, in-
525 event protection and drainage, stormwater buffering, circulation maintenance, and post-event
526 feedback. It should therefore receive priority in establishing the basic resilience chain,
527 including risk identification, grading of critical entrance nodes, drainage-facility
528 maintenance, provision of water-sensitive detention and infiltration facilities, and post-event
529 documentation (Butler et al., 2017; Barreiro et al., 2024; Prashar et al., 2023).

530 The second type is constrained by downstream outcomes, represented mainly by A3 and
531 A1. The largest deficiency for A3 was C6, indicating weaknesses in post-event recovery,
532 review, and data accumulation. The largest deficiency for A1 was C4, indicating that main-
533 route accessibility, continuity of sheltered buffers, and ground-surface safety during
534 stormwater disturbances require improvement. Governance for these campuses should work
535 backward from downstream outcomes to their upstream causes. A3 should not merely
536 accelerate post-event repairs; it should establish risk-location files, ponding-location records,
537 and recovery-time tracking so that recovery feedback supports the next cycle of risk
538 identification (Cimellaro et al., 2010; Folke, 2006). A1 should not focus only on localized
539 paving, slip resistance, and shelter facilities; it should also improve the identification of high-
540 risk routes, runoff-conveyance arrangements, and detention and infiltration measures at
541 critical circulation nodes (Gorzka et al., 2025).

542 The third type has a localized deficiency in water-sensitive capacity and is represented
543 by A2. Although its overall performance was relatively strong, its principal deficiency was
544 concentrated in C5. Rather than comprehensive reconstruction, improvement should target
545 public spaces with high proportions of impervious paving, concentrated inflows, or adjacency
546 to pedestrian routes. Permeable paving, rain gardens, sunken green spaces, linear drainage,
547 and connections to the existing drainage network should be optimized to strengthen water-
548 sensitive buffering (Rong et al., 2021; Zha et al., 2024; Xu et al., 2025; Qin et al., 2013).

549 The fourth type requires maintenance and optimization and is represented by A5. Its
550 overall process-based stormwater resilience was relatively strong, and its main remaining gap
551 was concentrated in C4. Its renewal strategy should therefore shift from large-scale

552 reconstruction toward routine maintenance, targeted monitoring, and localized micro-
553 renewal, with particular attention to the continuity and safety of heavily used pedestrian
554 routes, building entrances, semi-outdoor transitional spaces, and public nodes during intense
555 rainfall (Meerow and Newell, 2017; Raymond et al., 2017; Zellner and Massey, 2024).

556 Overall, A4 requires systematic reinforcement; A3 and A1 require upstream mechanisms
557 to be traced from their downstream deficiencies; A2 requires stronger C5 capacity; and A5 is
558 suited to a maintenance-and-optimization strategy. Considered together with the DEMATEL
559 and DANP results, these findings show that improvement should move beyond a single
560 campus ranking or isolated facility repairs toward differentiated renewal decisions organized
561 around the process chain. For decision makers, VIKOR identifies where intervention is most
562 urgent, weighted-gap decomposition identifies the criteria in which deficiencies are
563 concentrated, and DEMATEL-DANP explains the causal drivers through which those
564 deficiencies should be addressed.

565 **4.5. Management Implications**

566 The findings have three implications for improving stormwater resilience on university
567 campuses. First, campus stormwater governance should clarify causal drivers rather than
568 focus solely on isolated ponding repairs. Although C1 and C5 did not receive the highest
569 weights, they occupy upstream positions in the process chain and determine whether
570 subsequent drainage organization, circulation safeguards, and recovery feedback can function
571 effectively. Risk maps, grading of priority entrances, identification of critical routes, water-
572 sensitive detention and infiltration nodes, and pre-event inspections of drainage facilities
573 should therefore be treated as basic governance conditions rather than as auxiliary measures
574 appended to engineering repairs (Barreiro et al., 2024; McFarland et al., 2019; de Moel et al.,
575 2009).

576 Second, evaluative priorities should be translated into performance objectives and
577 management-monitoring priorities. DANP identified C6, C4, and C3 as the key criteria in the
578 overall evaluation. Universities must therefore demonstrate not only that facilities have been
579 installed, but also that main routes remain accessible during intense rainfall, entrances and
580 ground surfaces remain safe, and drainage recession and functional recovery can be
581 documented and tracked. Circulation continuity, recovery time, the number of closed routes,
582 recurrence frequency of ponding locations, and closed-loop feedback from students and staff
583 can serve as routine indicators for campus stormwater-resilience management (Cimellaro et
584 al., 2010; Kammouh et al., 2019; Cutter et al., 2010).

585 Third, improvement priorities should be determined jointly from the VIKOR ranking,
586 weighted-gap decomposition, and causal network. A4 is systemically vulnerable and should
587 first establish the basic resilience chain. A3 and A1 are constrained by deficiencies in
588 Recovery Assessment and Feedback and Pedestrian Space Performance, respectively, and
589 should work backward from downstream outcomes to upstream causes. A2's principal gap
590 lies in C5 and should be addressed through localized infiltration, detention, and linear-
591 drainage optimization. A5 performs well overall and is better suited to maintaining its
592 resilience through routine maintenance, targeted monitoring, and localized micro-renewal.
593 Campus renewal should therefore ask not only which university ranks lower, but also which
594 upstream conditions create its deficiencies and which highly weighted outcomes require
595 continuing monitoring.

596 **5. Conclusions**

597 Taking universities in Guangzhou University Town as its empirical setting, this study
598 addresses inadequate operational continuity in building public spaces during stormwater
599 events by developing an integrated FDM-DANP-VIKOR decision framework for process-
600 based resilience assessment and continuous improvement. Previous campus-space research
601 has shown that open space, spatial connectivity, and built-environment quality affect student
602 walking, spatial experience, and campus-use performance (Zhang et al., 2024; Lau et al.,
603 2014), while urban flood research has shown that road disruption, reduced accessibility, and
604 declining network connectivity amplify operational risks (Hammond et al., 2015; Dong et al.,
605 2022). When the unit of analysis shifts to university building entrances, semi-outdoor spaces,
606 pedestrian routes, and public nodes, however, further explanation is needed of how
607 stormwater pressure becomes spatial functional degradation and how different resilience
608 capacities interact. This study therefore defines stormwater resilience in university building
609 public spaces as a continuous process capacity encompassing pre-event identification, in-
610 event functional maintenance, hydrological buffering, and post-event feedback. Through a
611 hybrid MCDM model, the concept is advanced from a static indicator framework to a
612 decision tool that simultaneously explains causal drivers, the structure of evaluative priorities,
613 and the order of campus improvements.

614 The first principal outcome is a context-adapted evaluation framework. FDM retained 18
615 core indicators from 37 initial candidates and assigned them to six criteria: Risk Identification
616 and Grading, Stormwater Protection Facility Support, Runoff Drainage Performance,
617 Pedestrian Space Performance, Water-Sensitive Retention Capacity, and Recovery

618 Assessment and Feedback. The result demonstrates that stormwater resilience in university
619 building public spaces is neither a general assessment of campus open-space quality nor an
620 evaluation of individual drainage facilities. It is a process capacity jointly constituted by risk
621 information, facility protection, hydrological regulation, circulation maintenance, and
622 recovery learning. Whereas disaster-resilience indicator research characterizes baseline
623 conditions and infrastructural and institutional capacities at a broad level (Cutter et al., 2010),
624 this study situates resilience indicators in specific operational settings of university building
625 public spaces, enabling systematic identification and comparison of obstructed entrances,
626 interrupted routes, slippery surfaces, facility failures, and delayed recovery.

627 The DEMATEL-DANP results further reveal the systemic relationships underlying
628 stormwater resilience in university building public spaces. DEMATEL shows that C1 and C5
629 provide upstream support, C2 and C3 perform intermediate transformation, and C4 and C6
630 represent downstream operational outcomes. C1 had the highest relation value, indicating that
631 identifying flood-prone spaces and high-risk routes and representing graded risks are
632 preconditions for facility maintenance, drainage organization, and circulation safeguards. C6
633 had the highest prominence, showing that recovery feedback is not an auxiliary task after an
634 event, but a critical mechanism connecting the next cycle of risk identification, facility
635 maintenance, and spatial renewal. DANP identified C6, C4, and C3 as the core evaluative
636 criteria. Together, these results show that causal drivers and evaluative priorities do not fully
637 coincide: C1 and C5 better explain how the system is activated and supported, whereas C6,
638 C4, and C3 better represent how operational outcomes are evaluated. This distinction is not
639 contradictory; it demonstrates that campus stormwater-resilience governance must build
640 upstream enabling conditions while also addressing downstream performance. The finding
641 translates the resilience logic of reducing failure probability and consequences and shortening
642 recovery time (Bruneau et al., 2003) into an interpretable identification-buffering-
643 transformation-maintenance-feedback chain for university building public spaces, while
644 responding to calls for clear definitions of the object, temporal process, and spatial boundary
645 of urban resilience (Meerow and Newell, 2019).

646 The VIKOR results translate the evaluation framework into campus-level improvement
647 priorities. Overall performance was ranked $A5 > A2 > A1 > A3 > A4$, producing the reverse
648 order of improvement priority: $A4 > A3 > A1 > A2 > A5$. Because the acceptable-advantage
649 condition was not fully satisfied, A5, A2, and A1 are better interpreted as a relatively high-
650 performing group than as an absolute hierarchy. Weighted-gap decomposition classified the
651 five universities into four types: systemically vulnerable, constrained by downstream

652 outcomes, locally deficient in water-sensitive capacity, and requiring maintenance and
653 optimization. The ranking therefore moves beyond the question of which campus performs
654 better and identifies where intervention is most urgent, where the principal deficiencies lie,
655 and through which causal pathway intervention should proceed. In particular, A4 requires
656 reinforcement across all six criteria and should first establish the basic resilience chain. A3
657 and A1 are constrained by deficiencies in Recovery Assessment and Feedback and Pedestrian
658 Space Performance, respectively, and should work backward from downstream problems to
659 upstream causes. A2 requires stronger water-sensitive retention capacity, whereas A5 should
660 maintain its resilience through routine maintenance, targeted monitoring, and localized
661 micro-renewal.

662 The theoretical contribution is twofold. First, this study extends the process-based
663 resilience perspective to the scale of university building public spaces and shows that
664 hydrological regulation, spatial circulation, and recovery feedback are not independent
665 management concerns, but components of a capacity chain that sustains spatial operations
666 during stormwater events. Second, it integrates FDM, DANP, and VIKOR into a continuous
667 decision framework in which indicator screening, causal explanation, network weighting, and
668 improvement prioritization are linked. MCDM has been widely used for alternative ranking,
669 risk assessment, and resource allocation in flood-risk management (de Brito and Evers,
670 2016); DEMATEL identifies causal relationships and critical pathways in complex systems
671 (Si et al., 2018); and VIKOR generates compromise rankings between group utility and
672 individual regret (Opricovic and Tzeng, 2004). The integrated approach further demonstrates
673 that, for campus stormwater governance characterized by multiple interacting factors, limited
674 resources, and heterogeneous renewal needs, evaluation methods should not only produce
675 weights and rankings but also distinguish what drives system improvement from what
676 represents performance priority. This distinction provides a more explanatory framework for
677 stormwater-resilience research in university building public spaces than static indicator
678 assessment alone.

679 In practice, the findings suggest that campus stormwater governance should move
680 beyond an emergency logic of identifying ponding locations and making localized repairs
681 toward whole-process resilience governance. LID and water-sensitive urban research has
682 demonstrated that low-impact development facilities reduce runoff, delay peak flows, and
683 improve stormwater-management performance (Rong et al., 2021; Zha et al., 2024; Fletcher
684 et al., 2015; Qin et al., 2013). If assessment stops at hydrological performance, however, it
685 cannot explain how campus spaces maintain basic operations during intense rainfall. Based

686 on the present findings, universities can treat C1 and C5 as starting points for antecedent
687 reform and C6, C4, and C3 as performance objectives and monitoring priorities. Campus
688 renewal should jointly address risk mapping, grading of priority entrances, main-route
689 accessibility, coordination between permeable paving and rain gardens, pre-event inspection
690 of drainage facilities, floodproofing and slip resistance at entrances, and a post-event data-
691 feedback loop. Strategies should also be differentiated according to the VIKOR ranking and
692 weighted-gap decomposition so that limited resources are directed first to the critical links
693 with the greatest influence on the process chain.

694 This study has several limitations that also indicate directions for future research. First,
695 the cases are concentrated in Guangzhou University Town, and the findings are most
696 applicable to campuses in humid, rainfall-intensive settings with clustered universities and
697 relatively similar municipal drainage conditions. Future work should test the stability of the
698 indicator system and relationships among criteria across different climate zones, campus
699 morphologies, and baseline drainage conditions (Kundzewicz et al., 2014; Hou et al., 2025).
700 Second, performance scores rely primarily on expert judgment. Future studies could
701 incorporate high-resolution ponding monitoring, SWMM (Storm Water Management Model)
702 simulation, movement trajectories of students and staff, and measured post-event recovery
703 times to improve the dynamic validity and verifiability of the evaluation (Zuo et al., 2025;
704 Tan et al., 2024; Salvatore et al., 2015). Finally, this study treats the external municipal
705 drainage network and regional hydrological conditions as common constraints. Future
706 research could analyze the coupling between internal campus spatial systems and urban
707 drainage systems and conduct multi-stage longitudinal evaluations to determine whether
708 resilience capacities actually improve after spatial renewal (Zevenbergen et al., 2008;
709 Fletcher et al., 2013).

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Figure legends

Figure 1. Methodological framework for evaluating process-based stormwater resilience.

Figure 2. FDM screening threshold and structure of the retained indicators.

Figure 3. DEMATEL causal transmission structure among the six criteria.

Data availability

De-identified individual expert-scoring files, processed FDM, DEMATEL-DANP and VIKOR datasets, survey instruments, variable definitions and coding, and spreadsheet calculation formulas are provided in Supplementary Materials 1. The accompanying survey and calculation documentation describes the available materials and processing steps. Expert names and affiliations have been removed to protect privacy. No custom code was used for the original analyses.

Ethics declaration

This study was conducted under the ethics approval for project RP/FCBS-02/2025, reviewed by the Research Committee of Macao Polytechnic University (Ethics Approval No. RP/FCBS-02/2025/E01). All methods were carried out in accordance with the Macao Polytechnic University Regulations on Research Ethics and Integrity.

Informed consent

Informed consent was obtained from all participants involved in the expert consultation. Participants were informed of the research purpose, the voluntary nature of participation, and the anonymized use of their responses for academic research.

917 **Competing interests**

918 The authors declare no competing interests. The funder had no role in the design of the study; in the
919 collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to
920 publish the results.

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