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Operationalising storage–discharge balance to enhance pluvial flood resilience: modelling and planning strategies in flat and sloping urban areas

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ABSTRACT

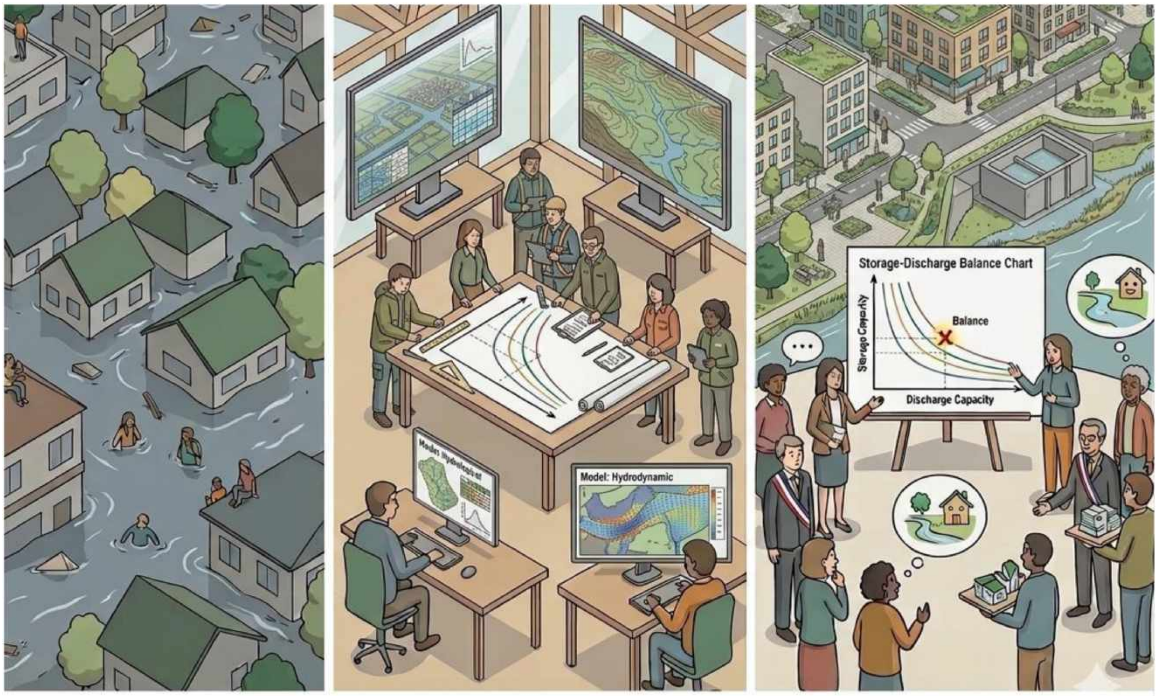
Storage and discharge are two fundamental solutions to strengthening pluvial flood resilience. Recent studies reveal that many urban catchments operate under a persistent storage–discharge imbalance, driven by urban densification. This 'imbalance' raises concerns in hydrologic, economic, spatial, and social aspects. This research aims to quantify the balanced relationship between storage capacity and discharge capacity (storage discharge balance, SDB) for pluvial flood protection and provide planning strategies for different urban topographies. We suggest and apply a quantification method using different modelling tools, hydrological and hydrodynamic models, in two cases with distinct physical and socioeconomic characteristics: one in a flat polder area in Nanjing, China, and the other in a sloping hilly area in Feldbach, Austria. By comparing these cases, insights are gained into the modelling methods, results, and proposed strategies for each context. The use of the SDB chart mapping framework supports the identification of both short- and long-term targets, as well as dynamic pathways toward enhanced flood resilience. These insights will facilitate multidisciplinary dialogue on key constraining factors, thereby enabling the co-creation of an actionable solution. While the quantitative findings are context-dependent, the novel approach can be applied to other cities to facilitate their resilience planning.

Key words: balance, discharge, flood resilience, modelling, planning, storage

HIGHLIGHTS

- Storage and discharge are two complementary fundamental solutions to building threshold capacity of pluvial flood resilience.
- Storage capacity and discharge capacity for flat and sloping areas are defined differently.
- The use of hydrological and hydrodynamic models depends on local contexts, especially the spatial topography.
- Mapping the SDB chart helps to determine targets and strategies for resilience planning.

GRAPHICAL ABSTRACT



INTRODUCTION

Background

Pluvial flooding has become an increasingly frequent and disruptive urban hazard under climate change (Miller & Hutchins 2017), making the enhancement of urban systems to cope with intense rainfall a crucial challenge in resilience planning. At its core, pluvial flood protection relies on two complementary fundamental solutions: *storage capacity*, the ability of the urban system to temporarily detain or retain stormwater, and *discharge capacity*, the ability to convey runoff away through gravity-driven or pump-assisted drainage infrastructure (Mejía-Morales *et al.* 2023). Both capacities are indispensable for building the *threshold capacity* of pluvial flood resilience, the capability to prevent damage by designing and constructing a system that can withstand rainfall events up to a defined protection level (Chen *et al.* 2021; de Graaf-van Dinther & Ovink 2021; Chen & Cheng 2022; CCICED 2024; Esraz-Ul-Zannat *et al.* 2024). In the context of engineering system resilience, planning this threshold capacity represents a proactive strategy to maintain functionality and prevent system failure under design-basis stressors, acting as a critical buffer before more adaptive or transformative resilience capacities are required (Zevenbergen *et al.* 2020; Nahiduzzaman *et al.* 2026).

However, in practice, a persistent imbalance has emerged in which discharge capacity has been systematically expanded at the expense of storage, a pattern traced back to the rapid infrastructure build-out of the industrial era (Schuetze & Chelleri 2011). Urban densification has further accelerated the recession of the previous (typically natural) storage through soil sealing (Junk *et al.* 2013; Zhang *et al.* 2026) and the replacement of floodplains and wetlands with engineered structures such as concrete dykes and reservoirs (Sohn *et al.* 2020). Such imbalance may lead to problems. Excessively depending on discharge capacity would shift the flood problem to downstream areas, causing increased fluvial flooding burdens there and raised spatial justice concerns (Liao *et al.* 2019). Moreover, it forgoes the opportunities to (re-)use the water or space for other benefits, such as improving water quality, increasing biodiversity, supply during periods of drought, and mitigating the urban heat island effect (Li *et al.* 2024). Although pumps are essential in areas with flat terrain and extensive manmade drainage systems, they can exacerbate issues by overloading levees and often cause damage to levees (Paup *et al.* 2025). On the other hand, building more storage capacity requires either above-ground or underground spaces, alternative designs for buildings, infrastructure, and urban spaces. Nature-based, blue–green drainage solutions tend to provide storage capacity and reduce runoff, alongside other significant co-benefits (Wu & Willems 2025). But retrofitting could demand huge investments (Lancia *et al.* 2020).

Despite growing recognition of the importance of balancing storage and discharge, the field still lacks an operational method to quantify *how much of each* is required to meet a defined pluvial flood protection level under specific topographic and hydro-climatic conditions. Such a deficiency makes strategic planning difficult and hinders interdisciplinary collaboration. This is the central methodological gap that motivates this study.

Existing approaches

The scientific literature has acknowledged the need to combine storage and conveyance in urban flood management. Conceptual frameworks such as the Three-Point Approach (3PA) explicitly promote the integration of storage and discharge measures across the full spectrum of rainfall events, ranging from frequent, low-intensity storms to rare, high-impact extreme events (Fratini *et al.* 2012) and has been applied in multiple cities to support interdisciplinary learning and strategy development (van de Ven *et al.* 2024; Randall *et al.* 2025). However, it does not provide a quantitative decision-making support specifying the required volumes of each measure under a given flood protection target.

In parallel, urban drainage research has long addressed the combined use of detention and conveyance through design-storm-based sizing, scenario analysis, and simulation–optimisation approaches. Studies have explored how detention basins, on-site storage, and pipe capacity can jointly reduce peak flows, surcharge, and flood volumes, often using hydrologic and/or hydrodynamic models coupled with optimisation algorithms to identify cost-effective system configurations (Schmitt *et al.* 2002; Wang *et al.* 2021; Liu *et al.* 2026). Such approaches have been widely implemented in software such as SWMM-based optimisation frameworks (Mugume *et al.* 2015) and integrated urban drainage models (Bach *et al.* 2014; Asadzadeh *et al.* 2026), and have advanced the understanding of detention–conveyance trade-offs at the design stage (Ngo *et al.* 2018). Despite becoming increasingly sophisticated, these models are primarily used to simulate system behaviour under predefined configurations (Qi *et al.* 2021), rather than to solve the inverse problem of identifying required capacity combinations. In practice, models are applied iteratively – testing scenarios such as pipe enlargement, detention measures, or network redesign (Locatelli *et al.* 2015; Qi *et al.* 2021) – without explicitly mapping the functional relationship between storage and discharge across return periods.

More recent studies have extended this line of work by incorporating blue–green and hybrid grey–green measures, multi-objective optimisation, and resilience-oriented performance metrics (Leng *et al.* 2021; Beceiro *et al.* 2022; Yang *et al.* 2023; Hunt *et al.* 2024; Cansian *et al.* 2025; Junior & Oliveira 2026). However, these studies mainly focus on the effectiveness of individual interventions (e.g., green roofs, detention basins, or other sustainable drainage systems portfolios) under specific scenarios (Wu *et al.* 2025). While they demonstrate that storage-oriented or hybrid solutions can reduce runoff and provide multiple co-benefits, they do not address the prior strategic question of how much storage versus discharge capacity is required to meet a defined protection level (Neumann *et al.* 2024; Sciuto *et al.* 2025). As a result, they lack a system-level framework for identifying feasible or optimal balances between these two fundamental mechanisms (Ferrans *et al.* 2022).

Moreover, the gap is further complicated by topography. Flat urban areas lack hydraulic gradients and often depend on pump-driven drainage, making temporary storage a critical component of flood protection. Sloping urban catchments, by contrast, tend to rely more on gravity-driven conveyance, where increasing discharge capacity may appear effective but can be constrained by downstream water levels or surface flow dynamics. There has been little comparative analysis of how storage–discharge relationships and associated planning strategies differ between flat and sloping urban contexts using a unified analytical framework.

Policy and planning context

At the policy level, the importance of the storage–discharge balance (SDB), the strategic combination of required storage capacity and discharge capacity to meet flood protection objectives, is increasingly recognised.

In the EU, this orientation is reflected in legal frameworks, such as the Floods Directive (European Parliament and Council of the European Union 2007) and the revised Urban Wastewater Treatment Directive (UWWTD) (European Parliament and Council of the European Union 2024). Broader EU strategies further promote nature-based solutions (NbS) as part of climate adaptation and resilience agendas (European Commission 2013, 2021, 2025; European Commission and Directorate-General for Environment 2020). Similar shifts are evident at national and local levels, typically shown in the Dutch principles of '*never shift problem*' and the '*retain-store–discharge*' (Chen *et al.* 2021). Austrian strategies emphasising retention basins and floodplains (ÖWAV 2015; ÖVGW and ÖWAV 2025), and China's Sponge City approach.

Recent policy developments further underscore this trend. In the Netherlands, a Parliamentary Letter in 2022 on water- and soil-based planning reinforced the principle of '*no passing the buck*' ('*niet afwentelen*') to future generations (Ministerie van Infrastructuur en Waterstaat 2022) and the need to create '*space for water*' ('*ruimte voor water*'); increasing hydroclimatic extremes necessitates increased regional storage and/or discharge capacity (Ministerie van Infrastructuur en Waterstaat 2022). Sponge City Programme requires respectable storage capacity (typically around 20–30 mm) (Chan *et al.* 2018; Chen 2020). While, recent devastating pluvial flood events, such as the 2021 Zhengzhou flood and the 2023 Beijing flood have prompted renewed emphasis on strategies with '*combination of storage and discharge*' (State Council 2021; General Office of the Ministry of Housing and Urban-Rural Development 2024). Local municipalities are now exploring how to operationalise an effective *balance* between storage and discharge (Chen & Cheng 2022; General Office of Nanjing Municipal Government 2022; Xinwu District People's Government 2023).

However, practical guidance on translating storage–discharge targets to local conditions in a holistic and transparent manner remains lacking. Existing planning frameworks tend to promote principles or target indicators – such as runoff reduction percentages, retention depths, or infiltration standards – without explicitly linking these targets to discharge constraints or downstream system impacts. Consequently, they risk reinforcing a fragmented approach in which storage and discharge are addressed separately, rather than as interdependent components of a single system. This may lead to suboptimal or even maladaptive outcomes, such as over-reliance on discharge capacity that transfers flood risks downstream, or storage targets that are spatially or economically infeasible, as elaborated in the background.

Objective and novelty

This paper aims to propose an operational method for quantifying and visualising the SDB required to achieve defined pluvial flood protection levels. The method translates flood protection targets into quantitative combinations of storage and discharge capacity and is explicitly designed to be adaptable to contrasting topographic conditions. The application of this method to two case studies further enables a comparative, topography-specific analysis, illustrating how modelling requirements, storage–discharge relationships, and feasible resilience planning strategies differ across contrasting physical settings.

The main novelty of this work lies not in the conceptual recognition that storage and discharge must be balanced, but in the operationalisation of this balance through a quantitative, topography-specific framework, as well as a visual SDB chart that supports target setting and pathway planning (Babovic & Mijic 2019). The proposed method provides actionable information on required storage and discharge volumes for facilitating interdisciplinary dialogues among urban planners, water managers, policy/decision makers, and developers. It enables the follow-up spatial arrangement and design of storage capacity, using, e.g., grey–green hybridised infrastructures (GGI) (Water Europe 2021), to enhance urban flood resilience and reduce the risk of socioeconomic losses by extreme rainfall events (Voskamp & Van de Ven 2015). It can also serve as a policy instrument for applying resilience principles at the earliest stages of the planning process, especially given that the policy demand to make water and subsurface leading in spatial and resilience planning (Ministerie van Infrastructuur en Waterstaat 2022) proves difficult to realise in practice (CCICED 2025). While specific numerical outcomes of this study are context-dependent, the framework itself is transferable and can be adapted to other cities facing increasing pluvial flood risk under climate change.

METHODS

Definition

We propose definitions for some key concepts as follows:

Pluvial flood resilience refers to the capacity of an urban or regional system to anticipate, absorb, accommodate, and recover from flooding caused by intense precipitation, while maintaining or rapidly restoring essential functions (Ambily *et al.* 2024; Esraz-Ul-Zannat *et al.* 2024). Engineering systems definitions vary in temporal scope, treating resilience either as a lifecycle property of interdependent infrastructure (Zhang *et al.* 2025), or in relation to a specific perturbation (Sinha *et al.* 2023). Building on disaster risk reduction (Rana 2020), this paper uses static (time-independent) resilience (Simonovic & Arunkumar 2016) and focuses specifically on the building of threshold capacity of pluvial flood resilience that enables systems to withstand pluvial flood events without critical failure or damage (de Graaf-van Dinther & Ovink 2021), through both short-term reactive and incremental long-term adaptation measures (Kelder *et al.* 2025).

Discharge capacity is the maximum rate at which an urban drainage system can remove stormwater through gravity-driven (self-draining) and/or pump-assisted (mechanical) discharge. Depending on the scale of the pre-defined system, the value of discharge capacity can be decided by the maximum pumping capacity for discharging runoff outside of the system, or by the maximum drainage capacity of sewer pipes.

Storage capacity refers to the **required** storage volume in an urban drainage system to achieve a certain flood protection level, usually under a certain design frequency (return period), given a certain discharge capacity.

Frequency is the targeted design level, normally expressed in terms of rainfall or runoff event frequency, either as an annual probability of exceedance or its inverse, the return period. For example, a 100-year storm has an annual probability of exceedance of 1% (1/100). The probability of experiencing such a centennial flood during a lifetime is about 55%, assuming a life expectancy of 80 years; While the probability of experiencing a once-in-30-year event reaches as high as 93% in the same person's lifetime.

Storage–Discharge–Frequency (SDF) curves present the relationship between storage capacity and discharge capacity under certain return periods of rainfall or runoff events for a given drainage basin.

SDB: The most feasible and attractive combination(s) of storage capacity and discharge capacities, determined systematically and strategically to attain a targeted pluvial flood protection level under a certain design frequency.

SDB chart: A chart that builds on SDF curves to help identify the feasible range of possibilities as 'suggested SDB status' and to facilitate the strategic planning of pathways that move from status quo to short-term targets, and ultimately long-term target.

Urban drainage basin: Delineated homogeneous urban area (size often 10^3–10^6 m^2) with one coherent drainage system, leading to one outlet.

Urban catchment: A heterogeneous mixture of natural and artificial surface coverage where runoff drains into a river or other types of receiving water bodies.

Conceptual models and modelling assumptions

Considering the distinct physical conditions of the urban drainage basin, we use different quantification methods with various modelling assumptions for flat and sloping areas: a hydrological model for flat areas, and a hydrodynamic model for sloping areas. In the flat areas, the main driver for the discharge of runoff to external receiving water bodies is the pumping capacity. Given the small spatial scale of the urban drainage basin and typical concentration times on the order of 10–15 min, the 1-h temporal resolution used in the long-term hydrological simulations effectively captures the accumulation of runoff in the receiving water body. We thereby assume all runoff initially accumulates in the 'open water' reservoir (OW) (Figure 1(a)) and the discharge capacity of sewer system is irrelevant (see Table 1). The proportion of the runoff volume that (a) cannot be immediately discharged by the pumps and (b) exceeds the standard surface water elevation level determines the required storage capacity (Brolsma & Vergroesen 2020).

In sloping areas, the discharge capacity typically relies on gravity flow through sewers and open water courses. However, under extreme scenarios, the pipe flow capacity may be constrained by the elevated water levels in receiving water bodies. When floodwater depth and flow velocity exceed critical thresholds, this surface flooding poses significant risks to human safety and economic activities (Evans *et al.* 2024). To prevent such hazardous conditions, adequate on-site detention capacity is required to temporarily store excess runoff. This requirement directly determines the necessary storage capacity within the system. In the case study of a sloping area, the discharge capacity is defined as the maximum actual flow rate at the sewer system outlets, while the required storage capacity is represented by the maximum flood volume (Figure 1(b)). We note that this formulation equates required storage with the maximum instantaneous flood volume rather than with sited, engineered storage capacity; it is intended as a heuristic that enables consistent cross-case comparison, and the implications of this simplification are discussed in the section *Limitation of the research*.

In both cases, stormwater infiltration is already embedded in the runoff modelling process; therefore, the existing infiltration capacity is not included in the required storage capacity reflected in the resulting SDF curves. The detailed assumptions and key parameters are summarized in Table 1, and the modelling and construction processes of SDF curves are illustrated in Figure 2.

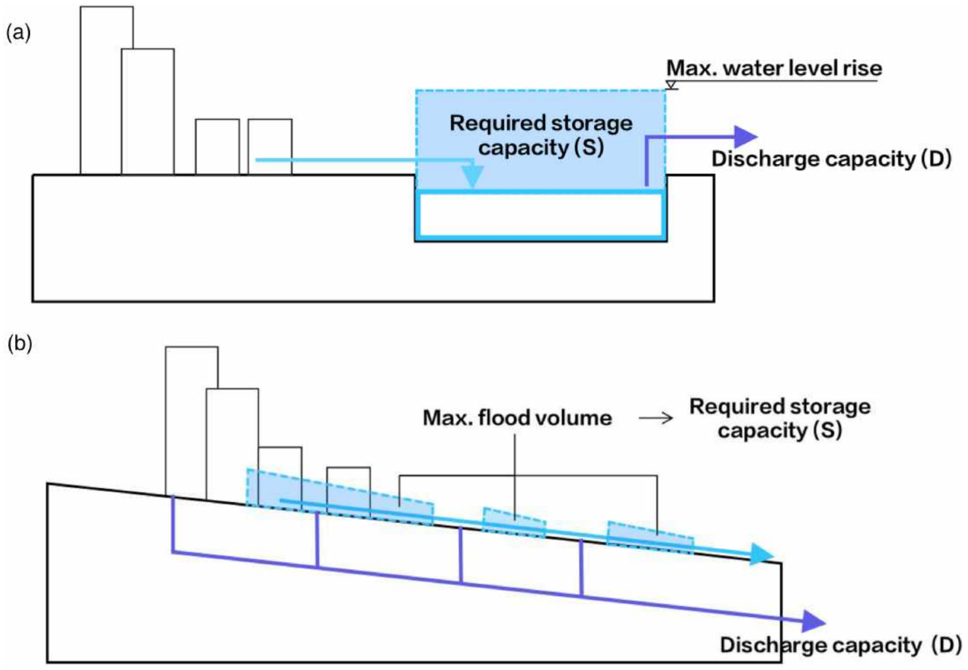


Figure 1 | Simplified conceptual model for flat (a) and sloping (b) areas before SDB analysis.

Table 1 | Assumptions and parameters used in the two types of topographic areas

Assumptions or parameters	Flat area	Sloping area	Unit
Discharge capacity	The capacity of the pumping station that drains this district to pump out the excess water. Discharge from an open water reservoir (OW) to the outside is only limited by a predefined pumping capacity.	The maximum of the total flow rate of the sewer system divided by the entire case area. Changes in discharge capacity are introduced by modifying the geometry of the sewer network, thereby altering the potential flow rate.	mm/d, mm/hr, or L/(s•ha).
Required storage capacity	Calculated by multiplying the open water area in the model by the maximum rise of water level above the standard level for a certain flood event, then dividing by the entire case area.	The maximum total flood volume occurring at a single moment during the entire process, normalized by the total area of the case study.	mm or m^3/ha
Rainfall input	Long-term hourly data (e.g., 10 years); preferably corrected for future climatic conditions.	Design storm events with different duration and storm shape, with time step of 1–5 min and a duration of at least 1 h. Historic or synthetic storm profile and known return period. Preferably corrected for future climatic conditions.	mm
Frequency (Return period)	Return period of exceedance of a runoff event. For each of the storage depths, the return period can be estimated as: $T = t_{total}/(\text{rank} + 1)$, where t_{total} is the number of years of input data.	Return period of exceedance of the design storm events.	year
Sewer system	Discharge capacity of sewer system is irrelevant. All runoff from land drains directly, without delay into the open water reservoir.	For each return period, different pipe system scenarios are generated to represent different discharge capacities.	–
Scenarios	Various socioeconomic, land use, and climate change scenarios could be taken into account by changing the parameters of model input, although the case study in this paper does not consider different scenarios.		

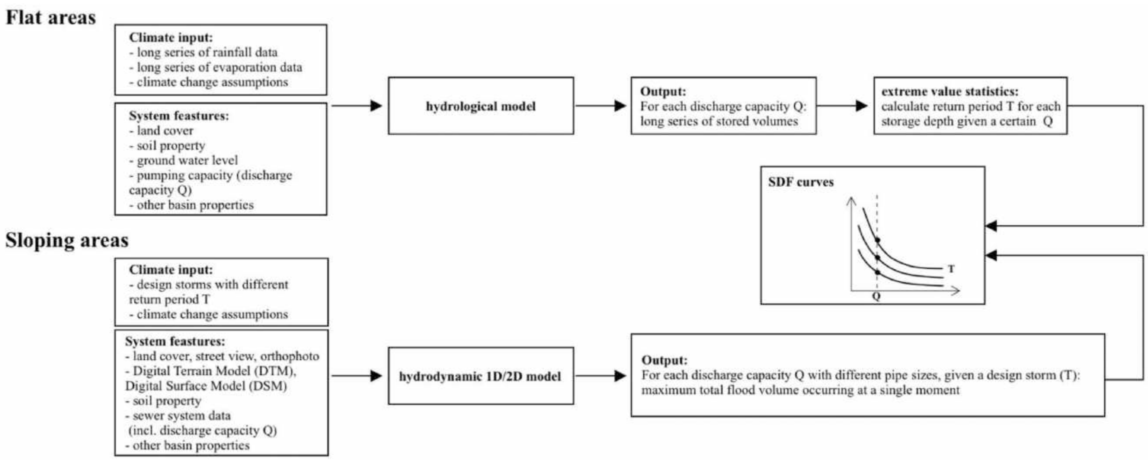


Figure 2 | The modelling process of SDF curves in the two areas.

SDB chart mapping

Building on SDF curves (Brolsma & Vergroesen 2020; Chen 2020), we standardise the quantification of target storage–discharge (S-D) combination for both flat and sloping areas into an SDB chart (Figure 3), defining the feasible range of the possibilities as 'suggested SDB status' for the long-term target. The underlying physical reality is that, under a certain target return period protection level, the more discharge capacity the system has, the less storage capacity is required, resulting in an inverse proportional function curve (dashed line in Figure 3). For multiple reasons, the domain of feasible storage–discharge combinations is limited. For example, the discharge capacity is (to be) limited to a value that does not contribute to

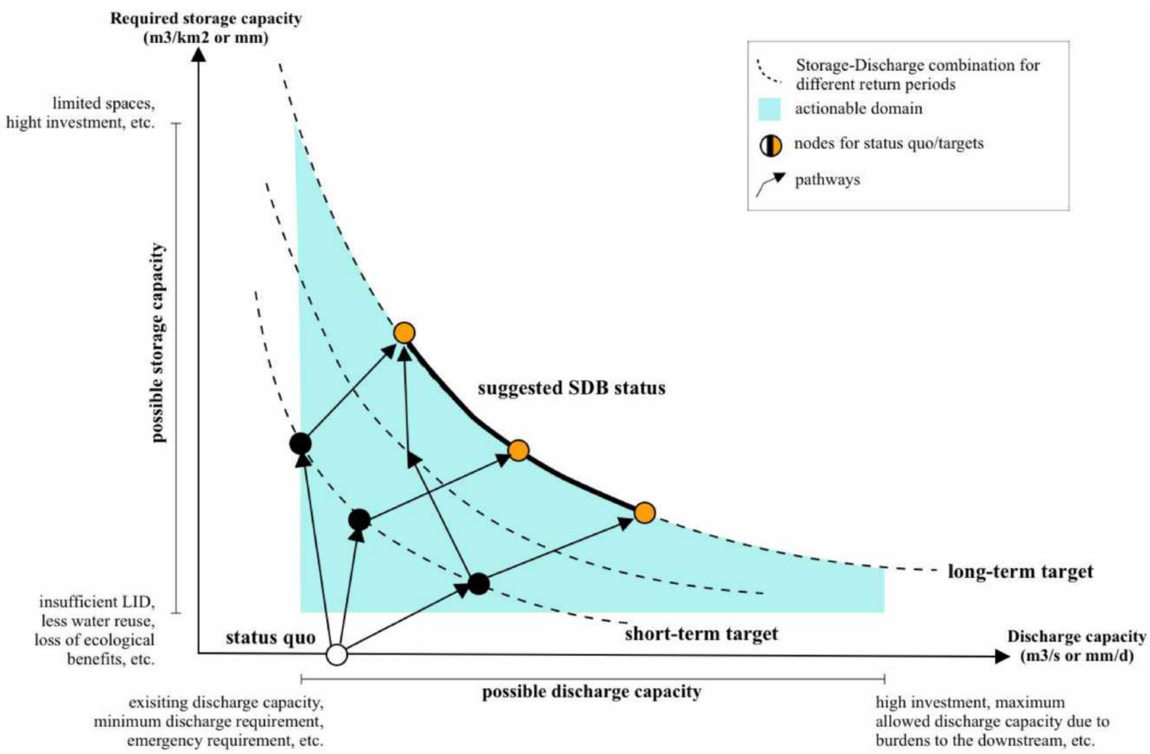


Figure 3 | SDB chart, including short- and long-term targets, storage–discharge (S-D) combination, actionable domain based on the constraint factors, and suggested SDB status, for planning pathways of flood resilience.

flooding problems downstream of the discharge point. Another example is that the discharge capacity should not be too low, as the resulting storage capacity will increase exponentially with extremely low discharge capacities. Other hydrologic, economic, spatial, and social reasons can also limit the domain of acceptable combinations. These constraint factors are enumerated and discussed in the discussion chapter.

Since the *y*-axis represents additional storage capacity required beyond the existing situation, the status quo is represented by a hollow dot on the *x*-axis corresponding to the current discharge capacity. This reference point can then be compared with the feasible range of combinations (suggested SDB status, shown as a solid black line) with a specific return period that can be used to provide a specific safety level in the long run. Consequently, the actionable domain, shown in cyan–blue in Figure 3, provides the basis for strategically planning flood-resilience pathways, guiding transitions from the status quo to short-term and ultimately long-term targets.

CASE STUDY AND MODEL SETUP

The 'flat' case study is part of Qinhuai District, Nanjing City, China, with a dense population and a high percentage of closed pavement, situated in a flat polder area with a total area of 4.4 km^2. The 'sloping' case study area of Feldbach, Austria, is 1.0 km^2, located in a catchment which extends to a hillside. The elevation variation is 15 m (ranging from 5 to 20 m) in the Nanjing case and 100 m (ranging from 280 to 380 m) in the Feldbach case. With distinct spatial structure and fabrics (Figure 4), the two cases both suffered from pluvial flooding events in recent history. Climate in Nanjing is slightly different from that in Feldbach, respectively *Cfa* and *Cfb* in the Köppen climate classification. A comparison of the design storms is presented in Table 2.

A lumped hydrological model, i.e., Urban Water Balance Model (Brolsma & Vergroesen 2020), is used in the flat polder area in Nanjing, China (Chen *et al.* 2021). The maximum discharge capacity is derived from the total capacity of all pumping stations that convey runoff to the Qinhuai River. A 10-year hourly rainfall data are used as input, and eight return periods are simulated (0.2, 1, 2, 5, 10, 20, 50, and 100 years) to map the SDB chart. For each discharge capacity, the relationship between required storage and return period is fitted using a natural logarithmic function of the form $S = a \times \ln(T) + b$,

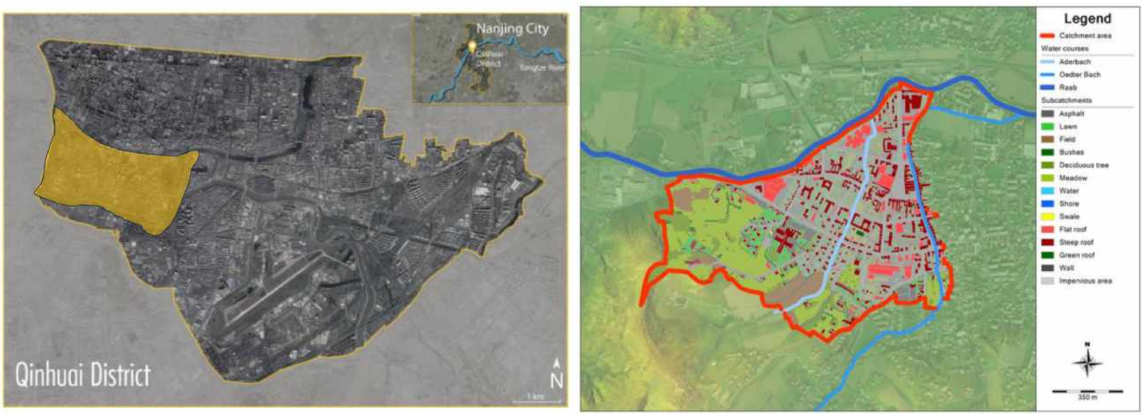


Figure 4 | Locations and spatial fabrics of the two case areas in Nanjing (left, in yellow) and Feldbach (right).

Table 2 | Rainfall depth (mm) comparison of design storm over 1 h under different return periods: Nanjing vs. Feldbach

Return period	Nanjing	Feldbach
1	37.7	23.2
5	62.8	37.6
10	73.7	43.9
30	90.8	54.5
100	109.6	66.7

following established practice (Brolsma 2022). These fitted relationships are then evaluated at a set of predefined return periods to obtain storage values. Quantitative calibration was hindered by limited monitoring data, as documented by Chen *et al.* (2021). Nevertheless, qualitative validation demonstrated that the hydrological model was able to reproduce the timing and severity of the most significant historical pluvial flood events observed between 2009 and 2018.

For the case with sloping topography in Feldbach, Austria, we use an integrated 1D–2D hydrodynamic drainage model with the software PCSWMM (Reinstaller *et al.* 2024; Funke *et al.* 2025). Discharge capacity is calculated by dividing the maximum total flow rate at the seven sewer outlets by the total area of the study catchment. Changing discharge capacity is achieved by uniformly modifying sewer pipe diameters across the network, thereby scaling the ideal flow capacity of all pipes by 0%, −50%, −100% (approximated by setting the flow limit to 0.1 L/s), +50%, and +100%. Euler Type II design rainfall with time step of 1 min and a duration of 1 h is used and five return periods are simulated for the Feldbach case. This means that each dot in the SDB chart corresponds to a manually configured sewer system scenario. Due to the computational demands of 2D hydrodynamic simulation, a limited number of discrete discharge–storage combinations are available (five discharge scenarios under return period 1, 5, 10, 30, and 100 years). The PCSWMM 2D model was calibrated and validated against multiple evidence sources, including observed flood extents, water levels derived from photographs and videos, and official flood and fire brigade reports, as described by Funke *et al.* (2025) and Reinstaller *et al.* (2024).

RESULTS

The hydrological and hydrodynamic models are able to map the required storage capacity according to a given discharge capacity and return period. The results of the two case studies are shown in Figure 5. The SDB chart result of Nanjing case (Figure 5(a)) is straight-line connections between discrete points, because there are more points per curve thanks to the convenience of hydrologic modelling. While in Feldbach case, in order to better illustrate the overall trend and curvature of the storage–discharge relationship under these data-sparse conditions, an exponential function was fitted to the points for each return period in Figure 5(b).

As expected, if the discharge capacity of the system increases, the required storage capacity for flood protection under a given return period decreases. However, the rate of reduction in required storage capacity diminishes as discharge capacity continues to grow, and this effect is less pronounced in the sloping area (Figure 5(b)). For example, for a 10-year event in the flat Nanjing polder, when discharge is reduced from 300 to 200 mm/d, the required storage increases from approximately 62 to 80 mm (+18 mm); a further reduction to 100 mm/d increases storage demand to about 106 mm (+26 mm). In contrast, the sloping Feldbach catchment exhibits a much more moderate response to reduced discharge capacity. Decreasing discharge from 30 to 20 mm/h increases required storage from roughly 18 to 22 mm (+4 mm), and a further reduction to 10 mm/h raises storage demand to approximately 26 mm (+4 mm). Such difference in curvature reflects topographic influences. In flat areas with limited pumping capacity, runoff keeps accumulating in the open-water reservoir. In sloping areas, by contrast, the maximum flood volume (i.e., the assumed required storage) is affected by the terrain. Even in the absence of

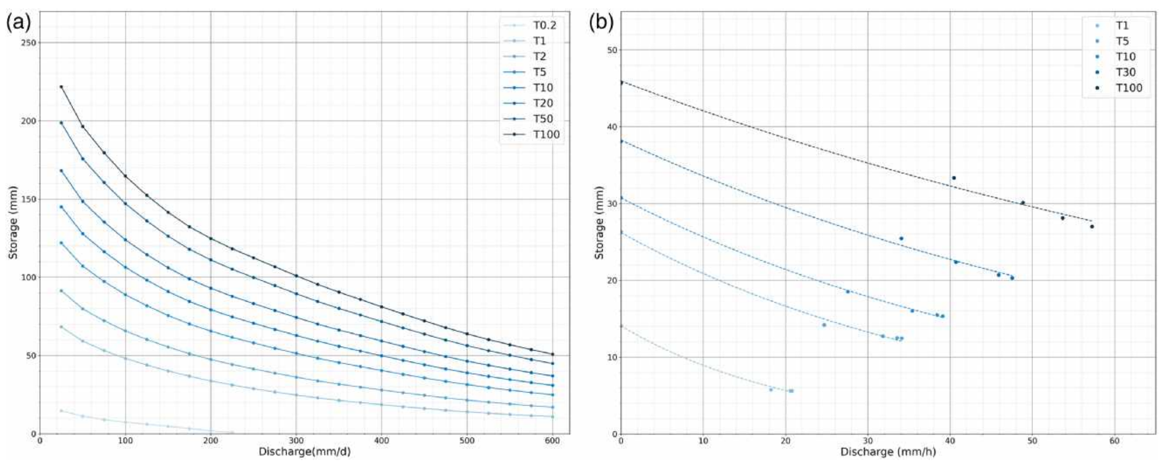


Figure 5 | The SDB curves for the Nanjing case (a) and the Feldbach case (b).

a sewer system, most flood runoff can drain to the receiving river through overland flow, resulting in a more linear storage–discharge relationship.

The ranges of the curves are different due to the varying assumptions regarding storage and discharge capacities in the two cases. In the flat area, the discharge capacity (pumping capacity) cannot be set to a small value because the required storage capacity would increase dramatically. However, in the sloping area, a near-zero discharge capacity (flow rate of pipe outlets) is assumed to simulate the absence of a sewer system. Moreover, regardless of how large the pipe system becomes, the actual discharge capacity is constrained, because even with enlarged pipes, the amount of runoff entering the sewer system is limited, e.g., by the sloping topography and inlet capacity. As a result, the required storage volume decreases asymptotically.

DISCUSSION

Function of the SDB chart

The SDB chart provides essential information for decision making of pathways on building pluvial flood resilience. The relationship between storage and discharge capacity for any given rainfall event with annual probability of exceedance could be depicted in the chart; Considering the practical constraints, all the possible solutions (actionable domain of possible actions) to the pluvial flooding problem are registered (see Figure 3, actionable domain). Therefore, standing on the status quo (the circle on the x-axis, Figure 3), this tool could facilitate the pathway planning with short-term and long-term targets. Reversely, the chart can also support backcasting from a defined long-term vision, helping to determine appropriate intermediate targets between the status quo and the long-term goal.

Once the design return period – the service level of the Technical Design Domain (Randall *et al.* 2025) – is defined, a corresponding curve in SDB chart can be identified as the long-term target for flood resilience. For example, Nanjing City has set a goal for its old district to be once-in-50-year flood-proof (Chen *et al.* 2021), so the T50 curve in Figure 6(a) is the target SDB status. By identifying the current discharge capacity (yellow dashed lines in Figure 6) and the short-term required storage capacity, both the status quo (hollow circle in Figure 6) and the short-term target (black dots in Figure 6) can be positioned. In Nanjing, for instance, the sponge city programme specifies a storage requirement of approximately 25 mm, which can serve as a short-term target for storage capacity (Chen *et al.* 2021). Within this framework, city officials, planners, and engineers in Nanjing can use the SDB chart to discuss whether to invest in new pumps or detention basins in parks, visualising how a combination of both might be more effective than relying on a single measure, which may yield diminishing returns. The same approach is applied to the Feldbach case, as illustrated in Figure 6(b).

With the visualisation of balanced status, the chart also allows for adaptive transitions along the pathway, as more information becomes available and capacities and constraints evolve over time. For example, if the capacity of the river allows for extra water without increasing the flood risk downstream, a city may initially focus on enhancing discharge capacity to mitigate pluvial flooding in the short term; while later on, when opportunities arise (e.g., a policy window) and resources become available (e.g., financial or technical capacity), disconnecting sewers and introducing more nature-based storage capacity

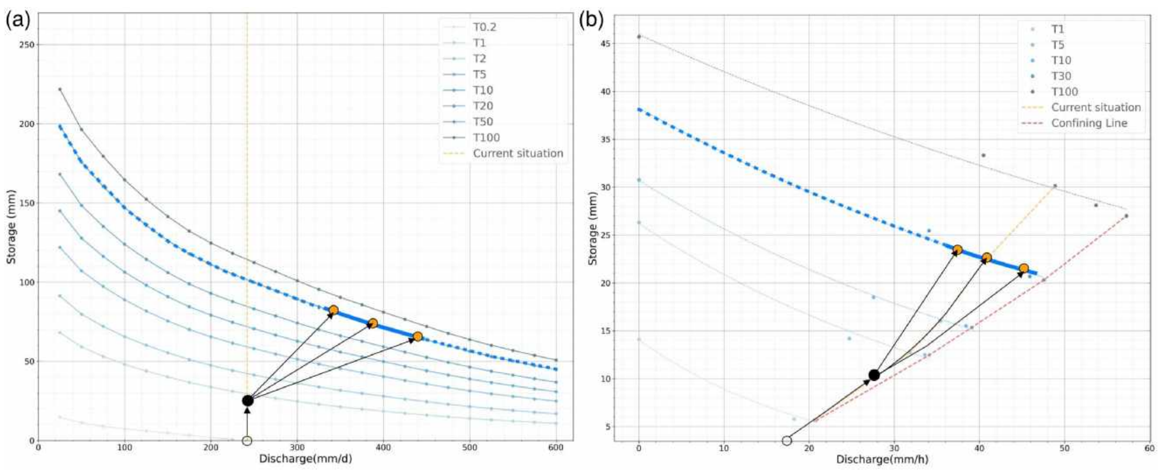


Figure 6 | SDB strategies for the Nanjing case (a) and the Feldbach case (b).

could become a preferred pathway. However, it is recommended to prioritise the creation of above-ground storage capacity over underground sewers, to enable more adaptability to future changes, and represents a no-regrets strategy for an uncertain future (Ommer *et al.* 2025).

Moreover, the SDB chart functions as an educational and heuristic tool which could provoke strategic conversations amongst diverse stakeholders. By visualising modelling results and clearly illustrating the relationship between storage and discharge capacity, the chart supports more effective communication with the key actors, including politicians, planners, engineers, and architects. It facilitates a shared understanding of the complementarity between the two solutions, as well as the flood risks associated with the current situation or alternative planning scenarios. Based on the chart, stakeholders can discuss and negotiate on constraint factors, co-shape the actionable domain, and deliberate on the short- and long-term pathways without losing sight of the broader picture. The actionable domain allows planners and landscape architects to use the range of balanced solutions to create a specific urban character, ranging from a 'water city' with abundant visible water to a 'dry city' where the presence of water is less outspoken. By incorporating unit costs for storage and discharge measures, and benefits, co-benefits and ecosystem services of the interventions, the chart can be translated into a cost function, enabling the exploration and comparison of cost-efficient adaptation strategies. Furthermore, the chart can work as an assessment tool to document the status quo and track how different cities or areas progress towards higher levels of flood resilience.

Constraint factors

Constraint factors, which determine the actionable domain, are crucial when making decisions to build long-term flood resilience (see Figure 3). These boundaries are not uniform; rather, they are determined by the interplay of regulatory, physical, and socioeconomic limits specific to a given location.

In both cases, increasing discharge capacity should be avoided, as it may place additional burdens on downstream cities, require significant investment, and increase the risk of water pollution when combined sewer systems exist. The **design maximum discharge capacity (Q_{max})** should be determined by analysing the interaction between urban runoff and upstream river-basin drainage to minimise the adverse downstream impacts. A typical Q_{max} value in Dutch practice is 11–13 mm/d (Biron 2004; van de Ven *et al.* 2024). This value reflects the 'natural' drainage capacity if the land would not be urbanized. This limit aligns with the Low Impact Development concept, requiring properties to maintain zero changes before and after development in the peak discharge rate of runoff for target storm intensities as regulated in US, Canada, Indonesia, etc. (Sohn *et al.* 2020). On the other hand, certain regulations impose a **minimum discharge capacity**; for example, Jiangsu Province, where Nanjing City is located, mandates 4 $m^3/(s \cdot km^2)$ or 345.6 mm/d (Jiangsu Provincial Government 2011), which sets the lower boundary. The SDB chart of Qinhuai, Nanjing (Figure 6(a)), however, tells us that this standard seems excessive; a smaller discharge capacity with slightly more storage capacity seems to provide a better balance. It should be noted that a larger pumping station alone is generally insufficient, as the hydraulic capacity of the stormwater drainage system conveying runoff to the station must also be increased (Brolsma & Vergroesen 2020).

Beyond discharge limits, some countries ask for the **minimum storage volume**, such as a typical 20 mm storage required by Sponge City programme in China (Chen 2020), and a detention volume of rainwater for new development (i.e., minimum 470 m^3 of storage volume per hectare required) in New South Wales, Australia (Sohn *et al.* 2020). Nanjing's Sponge City construction requires a 25.6 mm storage capacity (Chen *et al.* 2021). However, creating storage capacity either above ground or underground requires spaces, and different storage measures demand distinct types of spatial conditions (Liu *et al.* 2022). In high-density areas like Nanjing, **the availability of space and the feasibility of implementing adaptation measures** are dominant constraints; historical heritage protection in Qinhuai District may narrow down underground tanks or infiltration measures (Sass & Viles 2022). In other cities, high groundwater tables, less permeable soils, etc., also limit the options of creating nature-based underground storage capacity. In smaller cities like Feldbach, **financial feasibility** may serve as another key constraint, as the investment cost for storage or discharge infrastructure can be high for planning cycle(s) (Gold *et al.* 2022).

The local factors are further complicated by **ecological concerns** and **sociocultural values**. Discharging runoff, particularly from combined sewer systems, can have adverse ecological impacts on the receiving water bodies. Therefore, some cities impose limits on combined sewer overflow (CSO) frequency or pollutant loads (Kleidorfer & Rauch 2011; Hauser *et al.* 2026), which in turn place constraints on discharge capacity and encourage storage capacity. Community perceptions of nature, sense of place, cultural values, social cohesion, and other sociocultural factors can constrain the acceptance or implementation of certain measures (McNabb *et al.* 2024). Large-scale storage or discharge interventions may additionally entail land-use change or the displacement of residents and livelihoods, raising equity concerns that further shape what strategies are politically and socially feasible (Abu *et al.* 2024).

These constraint factors are not static boundary conditions; therefore, it is recommended to periodically revisit both the factors and the SDB chart within a defined planning cycle, considering climate change, economic and social developments in the area, and other evolving parameters. It is also recommended to discuss and identify the constraint factors in a co-creative manner with diverse stakeholders.

Implications for planning strategies

An interesting pattern emerges from the analysis: as discharge capacity increases, the rate at which the required storage capacity decreases becomes progressively smaller. Moreover, except for the smallest discharge capacities, the slopes of the curves are less than one, under most conditions in the Nanjing case and under all in the Feldbach case. This indicates that increasing discharge capacity by a given percentage results in a smaller percentage reduction in required storage capacity. In other words, expanding storage capacity may offer a more favourable substitution path than expanding discharge capacity. This comparison is unit-dependent: storage is expressed in mm and discharge in mm/h (or mm/d), so the curves describe a substitution relationship rather than a like-for-like comparison of effectiveness. Further confirmation would require analyses that explicitly account for the dimensional asymmetry between the two quantities (e.g., through cost-normalised or service-equivalent comparisons).

The Feldbach case illustrates this pattern particularly clearly. Due to the narrow range constrained by the current situation (yellow dashed line, Figure 6(b)) and the confining line (dark red dashed line, Figure 6(b)), even if the potential maximum pipe flow were doubled, the actual discharge capacity would increase by only 7 mm/h under T30, while the required storage capacity would decrease by 2 mm. This indicates that, above a certain event threshold, the discharge capacity has only a negligible effect on the flooding volume. This implies that in sloping areas, creating additional storage capacity is more effective than enlarging pipe geometries to improve pluvial flood resilience.

Viewing through the lens of 3PA (Fratini *et al.* 2012; Randall *et al.* 2025), increasing storage capacity with NbS can generate more co-benefits (González-García *et al.* 2025) in the Day-to-Day Domain while also reducing flow velocity of overland runoff in sloping areas, thereby mitigating potential damage in both the Technical design domain and extreme domain. This theoretical perception aligns with the modelling result, which shows storage-based drainage structures far outperform conveyance-based mechanisms regarding minimising flood damage (Sohn *et al.* 2020). We emphasise that threshold capacity is only one dimension of resilience in the extreme domain; coping, recovery, adaptive, and transformative capacities are also crucial considerations in a fuller assessment.

Storage capacity can be enhanced through both spatial and temporal strategies. Spatially, distributing storage across the system follows the principle of '*never shift problems*' and contributes to overall resilience. Canals provide both storage and drainage; local ponds add landscape value; and large-scale surface storage such as wetlands or reservoirs can function as centralised solutions, though these are often difficult to realise in dense urban settings. Where surface options are constrained, underground storage, such as Tokyo's underground reservoirs (Nakamura & Oosawa 2021), or parcel-scale measures, such as rain gardens, infiltration boxes and bioswales, can serve as effective alternatives for reducing flood loss and bring more co-benefits (Sohn *et al.* 2020). Moreover, restoring or 'daylighting' lost and culverted urban ponds or canals can further enhance storage capacity. To address water-supply challenges during dry spells, local towns and cities in both flat and hilly areas have traditionally used storage measures (Charlesworth *et al.* 2016; Xie *et al.* 2023). Temporal storage capacity can be created by emptying the storage facilities ahead of rainfall events supported by early warning systems and real-time control technologies (Connaughton *et al.* 2014; Busker *et al.* 2022; Cha *et al.* 2025). This anticipatory flood risk management approach enables the active operation of both grey infrastructure and NbS to maximise available storage before extreme rainfall (Young *et al.* 2021). Allowing water to pond on selected streets during extreme events can also increase contingent storage capacity. Incorporating multifunctionality into storage design is particularly beneficial, such as water squares in Rotterdam (Tillie & van der Heijden 2016) and the vertical bus parking complex with underground flood storage in Fuzhou (Fujian Southeast Net 2020). These examples show how storage (spatial, temporal, or multifunctional) can shift a system downward on the SDB chart (Figures 5 and 6), reducing storage demand without large increases in discharge infrastructure.

Discharge capacity nonetheless remains critical, especially in sloping areas and densely urbanised areas. For example, upstream drainage tunnels can intercept runoff from hinterland catchments and convey it directly to receiving water bodies, thereby bypassing vulnerable urban areas in Hong Kong (Chen & Lo 2026). The Kalvebod Brygge Cloudburst Tunnel and a large pumping station are designed to secure Frederiksberg and Copenhagen against flooding due to cloudbursts and heavy rains (Niras 2024; Wilcock & Ralph 2025). During high-intensity rainfall events (e.g. >30 mm/h), urban drainage systems and surface watercourses are often overwhelmed and unable to convey runoff effectively; Even under normal operating conditions, limited inlet capacity can cause excess runoff to bypass sewers and accumulate in low-lying areas (Yu & Coulthard 2015). Furthermore, surcharged drainage can significantly constrain the discharge capacity of gravitational sewer systems during intense rainfall events, typically when receiving water levels are elevated (Schmitt *et al.* 2002; Gold *et al.* 2022). Consequently, we have to include such extreme weather conditions in the design of our urban system, with the objective to minimize the economic, social, and ecological damage of a system that is failing because of overloading (Van De Ven *et al.* 2024). These correspond to the position of the confining line in the Feldbach curves (Figure 6(b)).

Limitation of the research

The research adopts a simplified dichotomy between storage and discharge, which supports quantification and facilitates strategic planning with diverse stakeholders. However, this framing should be understood as a heuristic device using a simplified conceptual method, rather than a comprehensive representation of all detailed adaptation options.

This paper focuses primarily on threshold capacity for pluvial flooding, without accounting for other resilience capacities during and after rainfall events, nor for interactions between pluvial, fluvial, and coastal flooding. In addition, the proposed method relies on several assumptions related to the hydrological and hydraulic processes that govern stormwater runoff. The two case studies use different approaches to quantify frequency, which may introduce uncertainty in cross-case comparisons. The observed difference in linearity between the two cases may therefore partly reflect these methodological choices in modelling and curve-fitting, rather than being attributable solely to topographic effects.

While model uncertainty inevitably influences absolute estimates of storage volumes or discharge capacities, including those derived from the uncalibrated model in Nanjing case, the objective of this study is not to predict exact flood depths or damages, but to systematically explore the relationship between storage and discharge under consistent assumptions. Future research could strengthen the framework by incorporating additional monitoring data, more advanced calibration strategies, and explicit uncertainty analysis, as well as by examining the applicability of SDB charts across multiple spatial scales.

CONCLUSIONS

The research focuses on searching for balancing storage and discharge capacity in flat and sloping areas. Flat areas normally exhibit clear discharge boundaries via pumps, whereas the sloping areas typically rely on gravity flow through pipes. The modelling methods need to be customized based on this context: hydrological models based on water balance suit flat areas in analysing the SDB due to their short processing time and capability to run long series of historical rainfall events with extreme value analysis as the tool to analyse the output; whereas hydrodynamic models outperform with regards to the capability of modelling routing and velocity, which is more important in pluvial flooding in sloping areas.

By applying various discharge capacities and calculating the corresponding storage requirements across a range of return periods, a SDB chart can be generated using appropriate tools tailored to different topographies. The SDB chart helps to determine short- and long-term targets, in order to define a dynamic pathway for enhancing flood resilience. Specific SDF curve shapes and quantitative findings depend on local conditions, but the framework and modelling approach is applicable to other cities.

The future work following this research includes (1) validating the effectiveness of the target storage–discharge combination on pluvial flood mitigation; (2) exploring how spatial arrangement of GGI affects the actual storage and discharge capacity; (3) testing how SDB charts for different spatial scales affect the overall performance in pluvial flood protection and provide policy recommendation on multi-scale flood resilience strategy.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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