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Stormwater detention basin design: a review of traditional approaches and current challenges

Mariacrocetta Sambito[a], Ana Maria Rotaru[b], Eleonora Dallan[c], Paola Mazzoglio[d], Dario Treppiedi[e], Marco Lompi[f], Panagiotis Asaridis[b], Noemi Maglia[b] and Anita Raimondi[b]

[a]Engineering and Architecture Department, University of Enna "Kore", Enna, Italy; [b]Department of Civil and Environmental Engineering, Politecnico di Milano, Milano, Italy; [c]Department of Land, Environment, Agriculture and Forestry, University of Padova, Padua, Italy; [d]Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy; [e]Department of Engineering, University of Palermo, Palermo, Italy; [f]Department of Civil and Environmental Engineering, University of Florence, Florence, Italy

ABSTRACT
Flood risk and associated damages are increasing worldwide due to more intense extreme rainfall events and ongoing urbanization, challenging the adequacy of conventional, stationary stormwater design. This paper presents a critical review and synthesis of methods for the design and operation of stormwater detention basins, with emphasis on climate change adaptation. We first examine traditional 'design-storm' and storage-based approaches, outlining their simplifying assumptions (e.g. fixed hyetograph shapes, constant runoff coefficients, constant outflows, etc.) and the implications for underestimating flood risk in non-stationary contexts. We then survey advances that address these limitations: risk-based and multi-objective optimization frameworks, hydrodynamic modelling, analytical–probabilistic formulations that accommodate multiple operating rules and pre-filling, and emerging tools including real-time control and AI-driven prediction. Building on recent evidence of changing extreme precipitation, we review pathways to incorporate future rainfall into design (delta-change scaling, non-stationary frequency analysis, and climate-model-informed projections) and discuss requirements for downscaling and bias correction when coupling hydrological models with projections. Finally, we highlight the central role of damage assessment to link hazard, exposure, and vulnerability, enabling cost–benefit evaluation of detention basin alternatives. The paper consolidates methodological guidance for practitioners: use updated/non-stationary rainfall information, prefer ensemble-driven hydrological–hydraulic modelling, and embed damage evaluation in design.

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1. Introduction

In recent decades, the number of flood events and the associated losses have increased globally, highlighting the urgency of effective and robust engineering solutions for stormwater management. Two macro-drivers amplify this trend: (i) a demonstrated increase in the intensity of short-duration extreme rainfall linked to a warming climate, and (ii) urbanization and land consumption that reduce infiltration capacity and accelerate runoff (Francipane *et al.* 2021, Fowler and Ali 2022). As a result, drainage networks are more frequently stressed by intense storms that generate hazardous peak discharges and volumes within short response times. In this context, detention basins represent fundamental tools to mitigate hydrological risks and manage runoff. However, traditional design methodologies, based on static analyses and stationary assumptions, often fail to capture the complex dynamics that characterize contemporary hydrological events, such as the increase in intense rainfall and the change in land use (Durdu *et al.* 2023, ISPRA 2023). As illustrated in Figure 1, in 2023, one-third of the European river network exceeded the 'high' or 'severe' flood threshold, underlining the urgency of adapting design solutions to the new climate conditions. This evidence strengthens the need for updating stormwater design to account for non-stationarity and operational flexibility.

Beyond their conventional role in flood mitigation, stormwater detention basins have increasingly been promoted as multi-functional infrastructures capable of simultaneously controlling runoff and improving water quality (Hogan and Walbridge 2007, McPhillips and Walter 2015). When properly designed and operated, detention basins can act as pollutant sinks, allowing suspended sediments, nutrients, and heavy metals to settle or degrade before the outflow reaches downstream water bodies (Ferrara and Witkowski 1983, Shishegar *et al.* 2018). This dual purpose (flood control and pollutant load reduction) is particularly relevant in urban environments, where impervious

CONTACT Mariacrocetta Sambito mariacrocetta.sambito@unikore.it Engineering and Architecture Department, University of Enna "Kore", 94100 Enna, Italy

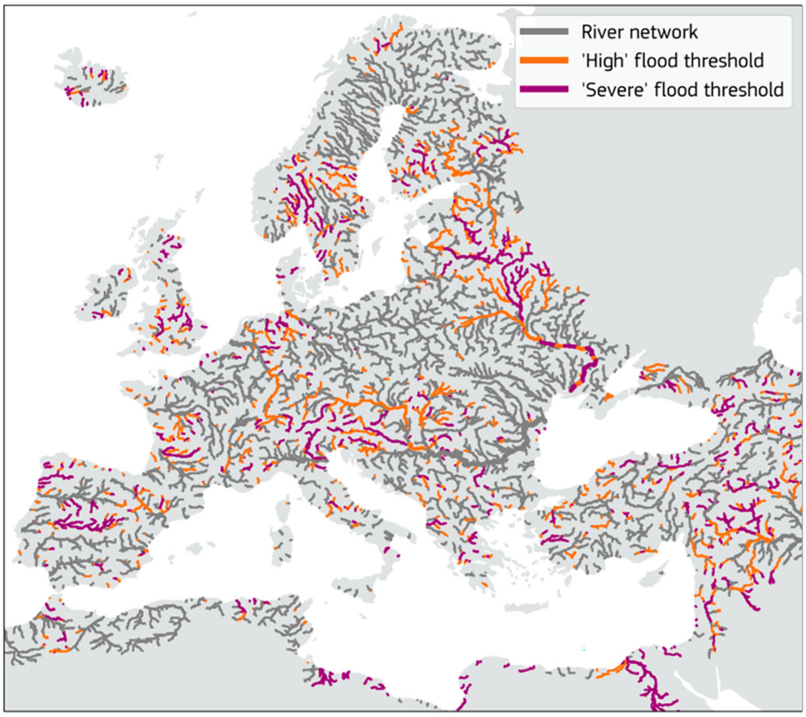

Figure 1. Map of Europe and nearby areas showing where river flow exceeded the 'high' (5-year return period) and 'severe' (20-year return period) flood thresholds on any day in 2023. Rivers with upstream areas larger than 1000 km^2 are shown in grey and are coloured orange when river flow exceeds the 'high' flood threshold and purple when the 'severe' flood threshold is overcome. Data source: EFAS. Credit: CEMS/C3S/ECMWF (Copernicus Climate Change Service 2024).

surfaces generate both rapid runoff and high pollutant concentrations. By temporarily storing stormwater and regulating its release, detention basins reduce peak discharges while also enhancing sediment deposition and pollutant removal processes, contributing to the restoration of hydrological and ecological balance in urban catchments.

Addressing all these challenges requires an integrated approach, capable of taking into account the complex interactions between territory, infrastructure and hydrological dynamics. Established methodologies, while representing an important basis, need to be integrated with more advanced and adaptable tools, capable of responding to complex future scenarios and to the growing needs of communities' resilience and sustainability. The adoption of numerical models and simulation techniques, combined with a critical analysis of the specific characteristics of the catchment area, offers new possibilities to improve the design of retention basins and adapt them to rapidly changing urban contexts.

In light of these issues, the main objective of this study is to provide a critical assessment of traditional methods of stormwater detention basin design, analysing the most recent advances and innovative approaches with particular reference to the challenges posed by climate change and urbanization, in order to provide a comprehensive and integrated framework to address these issues effectively. Specifically, the study aims to:

(i) Critically review the traditional design methods for stormwater detention basins, highlighting their simplifying assumptions and limitations in representing non-stationary hydrological processes.
(ii) Synthesize recent advances in stormwater detention basin design and management, including risk-based, analytical-probabilistic and multi-objective optimization approaches, as well as recent artificial intelligence applications.
(iii) Investigate the integration of the impact of climate change into design rainfall and discharge estimation.
(iv) assess the contribution of hydrodynamic models in improving the accuracy of basin design, evaluating flood dynamics, and supporting scenario-based analyses;
(v) emphasize the role of flood damage assessment as a decision-support tool for evaluating cost-effectiveness and prioritizing flood-mitigation strategies.

Building on this overview, Section 2 covers the fundamentals and drawbacks of standard stormwater detention design methods. Section 3 then discusses a range of advanced solutions. Sections 4, 5, and 6 specifically explore the integration of climate change projections, hydraulic modelling, and damage assessment, illustrating how these interconnected components strengthen detention basin design in the context of evolving environmental conditions. The final section synthesizes key conclusions and outlines actionable insights for advancing research and improving real-world implementation.

2. Traditional design methods

Although stormwater detention basins can act as multipurpose structures, their design objectives are typically restricted to meeting prescribed hydraulic performance criteria. These criteria generally involve reducing the peak discharge for a specified return period. In this section we describe the traditional hydrologic design methods and the simplified assumptions on which they are based.

The three main equations governing the process in stormwater detention basins are:

The balance equation:

$$Q_I(t) - Q_O(t) = \frac{dW(t)}{dt} \tag{1}$$

The discharge equation:

$$Q_O = Q_O[H(t)] \tag{2}$$

The storage function:

$$W = W[H(t)] \tag{3}$$

where: Q_I: inflow rate, Q_O: outflow rate, H: water depth, W: stored volume and t: time.

Traditionally, determining the required storage W in basin design requires knowledge of the inflow hydrograph $Q_I(t)$, which is typically derived from hydrologic modelling of the contributing watershed. The methods used to generate these hydrographs involve different levels of simplification, depending on the objectives of the design and on the amount of data and computational effort that practitioners can afford.

A common approach for estimating the inflow hydrograph is the use of design-storm methods. These methods generate an artificial rainfall event that corresponds to a chosen annual exceedance probability, meaning the likelihood that a storm of that magnitude will be equalled or exceeded in a given year. The synthetic event is then transformed into runoff to obtain the hydrograph used for basin sizing (Hong *et al.* 2006, Lee and Kwak 2008).

The design-storm procedure begins by selecting rainfall statistics from IDF (intensity–duration–frequency) or DDF (depth–duration–frequency) curves, which relate rainfall intensity or depth to storm duration and exceedance probability. These curves are derived from historical observations and are typically fitted using stationary extreme-value models such as the Generalized Extreme Value distribution (Koutsoyiannis *et al.* 1998). Once the rainfall depth or intensity has been obtained for the chosen duration and exceedance probability, it is distributed in time by constructing a synthetic hyetograph, usually based on a standardized temporal pattern.

In the most basic form, the storm is represented by a constant-intensity hyetograph, which assumes that rainfall intensity does not change during the event. This simplification ignores the strong temporal variability observed in real storms, particularly convective ones (Wright *et al.* 2012, Cristiano *et al.* 2017). To address this, other methods introduced variable hyetograph shapes, such as triangular distributions, the Chicago hyetograph (Keifer and Chu 1957), and the SCS Type II pattern (USDA-SCS 1975). These methods allow the user to specify the position of the rainfall peak within the event. However, the choice of peak timing is not trivial. Several studies show that shifting the rainfall peak earlier or later in the event can lead to large differences in the resulting hydrograph (Alfieri *et al.* 2008, Balbastre-Soldevila *et al.* 2019). The catchment response is especially sensitive to this timing when its concentration time is short, because peak inflow can increase or decrease depending on whether the rainfall maximum aligns with the fastest runoff pathways (Emmanuel *et al.* 2015). Observational analyses confirm that real convective storms show high variability in temporal structure, including multipeaked patterns, rapid intensification, and late-peak dynamics (Wright *et al.* 2012). As a consequence, using a single deterministic storm can bias inflow hydrographs, especially for small urban catchments.

Once rainfall is specified, converting it into an inflow hydrograph requires a rainfall-runoff model. Simplifications are generally also introduced in the rainfall-runoff transformation, depending on the model that is considered (i.e. lumped, semi-distributed or physically based distributed). The complexity of these models varies greatly, being easily manageable from lumped models (i.e. the entire catchment is considered as a single unit), while definitely more significant for physically based models (i.e. the basin is discretized, and the hydrological processes are better modelled). The simplest and still most common model is the Rational Method (Kuichling 1889), which assumes: spatially uniform rainfall, time-invariant runoff production, and a linear catchment response. A more physically informed alternative is the SCS Curve Number (CN) method (USDA-SCS 1972), widely used in event-based design.

Generally, 'design storm' methods are used for preliminary design analysis, and the volume obtained by their application needs to be verified throughout a continuous simulation. Continuous simulations consistently find that basins sized using design storms provide substantially less protection than expected (Elliott and Trowsdale 2007). However, continuous simulations are not always performed since they require the availability of long-term records of rainfall data and often involve high computational efforts (Heaney and Wright 2021).

The final step in the traditional workflow is storage–outflow routing. Equations (1)–(3) can be integrated in a closed form only for simplified storage functions and discharge laws. As an example, this is the case when a constant outflow rate or a linear storage-outflow relationship is considered, as well as when basins with regular geometry are designed. In practice, stormwater detention basins may be characterized by complex outlet structures, changing outflow conditions, and non-uniform geometry, which can hardly be considered in an analytical solution. For this reason, the equations are usually solved numerically within hydrological–hydraulic models, often through storage–outflow routing methods (Tung 2004).

A significant limitation of these traditional methods is the assumption that the storage capacity is completely available at the beginning of a storm event, disregarding the potential for partial pre-filling from previous rainfall events (Raimondi and Becciu 2015). This simplification can lead to an overestimation of the actual available storage capacity, increasing the likelihood of overflow.

Beyond hydrological simplifications, traditional approaches also overlook economic, environmental, and social factors that increasingly influence the performance and acceptance of flood-mitigation infrastructure. Numerous studies show that flood-mitigation infrastructure is still predominantly designed using hydraulic criteria, while life-cycle costs, environmental burdens, and social co-benefits receive only marginal consideration (Zhou 2014, Yang and Zhang 2021, Ferdowsi *et al* 2024, Sun *et al.* 2024). Although life-cycle assessment research demonstrates that construction and maintenance costs, energy use, and embodied impacts can significantly influence the overall sustainability of flood-control solutions, such aspects are still seldom integrated into standard detention basin design procedures (Brudler *et al.* 2016). Similarly, broader indicators such as pollutant removal efficiency, ecological impacts, and recreational or aesthetic value are often assessed only qualitatively or after design, despite growing support for integrated social–economic–environmental evaluation frameworks in stormwater planning (Khalaji *et al.* 2025). Consequently, detention basins are still most commonly designed predominantly on the basis of hydraulic performance, with limited attention to broader sustainability objectives or to the long-term costs associated with their construction, operation, and upkeep (Duan *et al.* 2016).

A further limitation is the assumption that detention basins operate passively with fixed outlet structures. In practice, most systems are still designed as static facilities, even though numerous studies demonstrate that active or real-time control can substantially improve both flood mitigation and water-quality performance (Brasil *et al.* 2021, Altobelli *et al.* 2024). The absence of management and operational considerations in traditional design therefore limits the ability of these systems to respond dynamically to varying hydrological conditions, system-wide interactions, and future climate scenarios.

3. Advances in stormwater detention basin design and management

The proper design of a detention system is extremely challenging due to several factors, such as technical and environmental characteristics and, mainly, its impact on the hydrological response of the basin. Since traditional methods neglect economic, environmental, and social factors related to the design of a detention basin, advanced approaches have been proposed in recent years for stormwater detention basin design and management. These innovative approaches try to overcome the limitations related to hydrological assumptions, economic and environmental considerations, and the computational burden associated with continuous simulation.

Risk-based approaches have emerged as alternatives to the ‘design storm’ methods, offering more comprehensive solutions for single and multiple detention basins. Travis and Mays (2008) proposed a discrete dynamic programming technique to determine the ideal locations and geometry for each basin. Yazdi and Salehi Neyshabouri (2012) coupled the MIKE-11 simulation model with the NSGA-II multi-objective optimization model to provide optimal Pareto solutions between the two conflicting objectives of minimizing the investment costs of flood mitigation measures and the potential damages of the floodplain.

Extending this line of research, Moridi and Yazdi (2017) developed a multi-objective optimization framework for the coordinated operation of multi-reservoir systems, formulated as a nonlinear non-convex problem solved via the ε-constraint method and mixed-integer linear programming (MILP). Their approach minimized downstream flood damages and hydropower losses, demonstrating that coordinated reservoir operation can substantially reduce or even eliminate flood impacts.

Similarly, Karamouz *et al.* (2009) proposed a coupled optimization and hydrology model to identify cost-effective combinations of permanent and emergency flood control measures, integrating flood damage estimation and optimal crop allocation. Later, Ahmadi *et al.* (2010) introduced robust optimization schemes for deterministic and stochastic reservoir operation, incorporating inflow uncertainty and multi-sector water allocation using evolutionary algorithms. These studies highlight the evolution of optimization-based methods in flood and water management, progressively integrating hydraulic, economic, and operational perspectives. However, most of these approaches rely on stationary hydrological conditions and do not explicitly address non-stationary rainfall regimes or climate change impacts, which are key aspects of the present study.

Bellu *et al.* (2016) developed a flexible framework model to optimize the dimensioning and site selection of a detention basin. The approach was based on three interconnected modules, i.e. hydrologic, geomorphologic, and environmental. Such an approach was also proposed by Albertini *et al.* (2022), who proposed an integrated framework for dimensioning an in-line detention dam that integrates geomorphic, probabilistic, and economic modelling in an optimization problem. They combined (i) a probabilistic approach for the assessment of flood outflows from a detention dam; (ii) geomorphological methods for areas at risk of flooding; and (iii) economic analyses (cost of construction and damages) to look for the optimal design of the detention dam.

Another crucial advancement is the integration of hydraulic modelling in detention basin design. Hydrodynamic models allow for a more detailed simulation of flood dynamics, helping engineers refine detention basin geometry and understand the interactions between basins and downstream river networks, allowing for the performance of damage assessment under different scenarios.

To optimize the beneficial effects in terms of flood risk reduction and the impact on the environment and communities; stormwater detention facilities should not only be properly designed but also managed, evaluating the impacts and the damage assessment on the downstream catchment (De Paola and De Martino 2013). A new trend in the management of stormwater detention basins is their multiuse purpose, to face the different challenges posed by climate change, such as the reduction of flood risk, water storage and supply during dry weather periods, and sediment removal (Park *et al.* 2014). The design and management of stormwater detention basins with a multi-objective target, that is, considering different goals, sometimes in contrast to each other's needs, requires the definition of a multi-objective function. This has the aim of making stormwater detention basins versatile for different uses under different conditions, such as the alternation of long drought periods and extreme rainfall events as effects of climate change.

New methods based on the use of artificial intelligence are also arising for the optimal design and management of stormwater detention basins (Park *et al.* 2012). Yang *et al.* (2019) optimized the effectiveness of flood control systems, minimizing variations and peaks in water level and the number of duty pumps. Similarly, real-time control can improve the performance of stormwater detention basins (Gaborit *et al.* 2013, Sharior *et al.* 2019). Shishegar *et al.* (2019) proposed an integrated optimization and rule-based approach for predictive real-time control of urban stormwater management systems. They designed a dynamic real-time control framework for stormwater management basins, integrating quality control rules into quantity control optimization algorithms to provide optimal performance for the stormwater management systems in terms of peak flow reduction and water quality improvement.

A promising alternative proposed in the literature to both demanding continuous simulations and simplified methods for the design and modelling of stormwater detention basins is represented by the so-called analytical-probabilistic approach, suitable to be used under different climatic scenarios and management rules. Developed at first in the nineties by Adams and Papa (2001), it was then applied to stormwater detention basins by several authors, both with quantitative (Guo 2001, Guo 2004, Manfreda *et al.* 2021, Aldrees and Dan'azumi 2023) and qualitative targets (Chen and Adams 2007, Raimondi and Becciu 2017, Wang *et al.* 2023). The analytical-probabilistic approach allows, once the variable of interest is analytically defined, the derivation of its probability distribution function from the probability distribution functions of the input variables.

The main advantages of analytical-probabilistic approaches, if compared to traditional methods, are that they can include multiple management rules (Tang *et al.* 2018), consider the possibility of prefilling the storage capacity from previous rainfalls, model the chain of previous rainfall events (Raimondi *et al.* 2023a , Maglia and Raimondi 2025), and can be used at different time and spatial scales. These characteristics make them particularly suitable for adapting to various climatic scenarios and for integrating long-term climate projections (Balistrocchi *et al.* 2013, Raimondi *et al.* 2023b, 2023c).

Moreover, the integration of AI-based predictive models with analytical-probabilistic approaches enhances forecasting capabilities. By leveraging machine learning and deep learning techniques, inflow and outflow dynamics can be more accurately modelled, facilitating robust short-to-long-term stormwater management strategies (Tang *et al.* 2018, Puoti *et al.* 2023).

The advancements outlined in this section illustrate how innovative methodologies address the inherent limitations of traditional design methods. By incorporating risk-based decision-making, hydraulic modelling, real-time optimization, and probabilistic approaches, modern stormwater detention basin design can achieve greater accuracy, resilience, and sustainability.

While many innovative approaches are reshaping stormwater detention basin design, this paper focuses primarily on the impact of climate change on detention basin performance, the role of hydraulic models in improving design accuracy, and damage assessment as a tool for evaluating effectiveness. The discussion in the following sections explores these aspects in greater depth, demonstrating how climate-adaptive hydraulic and damage models can lead to more efficient stormwater management strategies.

4. Detention basin design under a changing climate

One of the input variables that must be carefully evaluated during the design of a stormwater detention basin is the design discharge, which is the flow crossing a given cross-section with a certain return period. This value depends on the design rainfall, i.e. the precipitation falling in the upstream river basin with a specific duration and return period. Some of the current challenges in the estimation of the design discharge are related to the observed (and expected) changes in the rainfall regimes. This section presents an overview of how to include the impact of climate change on the design rainfall (section 4.1) and discharge (section 4.2) for adaptation strategies.

4.1. Future rainfall scenarios

Several different rainfall frequency analysis approaches can be used to evaluate the design rainfall in stationary conditions (i.e. without considering the impact of climate change), depending on the richness of measurements available in the area.

When long time series are available, the design value is usually computed by using only at-site rain gauge measurements. In the presence of short and fragmented records, or when a larger sample is necessary to reliably estimate very high return periods, the lack or shortage of at-site data is compensated by using regionalization techniques, i.e. techniques targeted to pool data from sites that are close to or similar to the one investigated, relying thus on the concept of trading space for time (Svensson and Jones 2010, Claps *et al.* 2022).

From an operational point of view, in some cases (Svensson and Jones 2010), these estimates could be obtained from official nationwide methodologies, while in other cases, at-site frequency analyses must be specifically performed by using the time series acquired up to the present. Even if the second approach is more demanding and relies on the decision made by the designer, it could allow for an evaluation that considers all the available records, which is sometimes not granted when using the first approach. Official methodologies, in fact, are usually updated every 10 years (or more) and thus miss the extremes recorded in the most recent years. In recent years, indeed, the frequent occurrence of record-breaking rainfall events highlights the need to provide practitioners with updated estimates. Several research works have been conducted to update these estimates on a regional scale (see e.g. Caporali *et al.* 2008, Forestieri *et al.* 2018, Libertino *et al.* 2018, Deidda *et al.* 2021 for Italy) or at the national scale (Shehu *et al.* 2023 for Germany, Iliopoulou *et al.* 2024 for Greece). Some of these studies have been translated into operational tools, while others are at the research stage and have not yet been formally adopted. Nevertheless, in several regions and countries, efforts to update design methodologies are actively underway.

As mentioned before, these techniques treat rainfall extremes as stationary, i.e. no observed variations are present in the time series. In recent decades, variations in extreme precipitation have been observed all over the world, especially at sub-hourly and sub-daily durations (Madsen *et al.* 2014, Libertino *et al.* 2019, Dallan *et al.* 2022, Gründemann *et al.* 2022, Mazzoglio *et al.* 2022, Jayaweera *et al.* 2023, Avino *et al.* 2024, Mazzoglio *et al.* 2025b), claiming the need to consider non-stationary frequency analysis for a better estimation of design rainfall (e.g. Pesce *et al.* 2025).

Variations in rainfall extremes are usually assessed by using two different types of measurements. To obtain precise at-site information about past observed variations in rainfall extremes, at-site data are usually considered. The changes in the past, present and future extreme precipitation and its frequency are instead usually assessed with projections obtained from Global Climate Model (GCM), which are then downscaled with Regional Climate Model (RCM), for impact assessment studies, under different scenarios. In recent years, among the various types of climate models, the convection-permitting models (CPM) have demonstrated to provide more realistic representations of short and intense precipitation compared to lower-resolution regional climate models (Prein *et al.* 2015, Kendon *et al.* 2017, Berthou *et al.* 2020, Fosser *et al.* 2020). The use of these climate models for estimating projected changes in extreme precipitations is receiving increased attention from the scientific community (e.g. Chan *et al.* 2023, Dallan *et al.* 2024a, 2024b, Lompi *et al.* 2025), but it is still in its infancy, and it requires multi-model ensemble approaches for a proper assessment of estimation uncertainties (Fosser *et al.* 2024, Correa-Sánchez *et al.* 2025), combined with a detailed accuracy assessment performed by means of a comparison, on the historical period, with at-site measurements (Correa-Sanchez *et al.* 2025, Mazzoglio *et al.* 2025a).

All the procedures to assess the impact of climate change on design rainfall can be classified into three categories: a delta change approach, with a scaling factor that is multiplied by the design rainfall of the current scenario, the application of a non-stationary frequency distribution, or its evaluation on the basis of climate projections.

In a few countries, the adaptation of design rainfall to climate is included in national guidelines (Martel *et al.* 2021) and usually follows the delta change approach. In most of the cases, a constant scaling factor is suggested to be applied. Sometimes the scaling factor depends on the duration or the return period of the precipitation; in others, the change depends on projections of precipitation according to the precipitation-temperature scaling relationship (Wasko *et al.* 2024, Treppiedi *et al.* 2025).

Extensive reviews exist on the general topic of incorporating non-stationarity and climate change into intensity-duration-frequency (IDF) curve estimation (Willems *et al.* 2012, Yan *et al.* 2021, Martel *et al.* 2021), and a recent one also covers the topic of regionalization (Schlef *et al.* 2023).

4.2. Catchment hydrological modelling

Quantifying future design discharges is essential to building reliable detention basins in a changing climate. In the past decades, many studies have investigated the impact of climate change on floods. For instance, Madsen *et al.* (2014) provide a comprehensive review focused on changes in extreme precipitation and floods in Europe. More recent studies have analysed the impact of climate change on floods at the European scale with trend analysis on observations (Bloeschl *et al.* 2019) or climate projections and hydrological models (Alfieri *et al.* 2015). Even if trend analysis can measure the statistical significance of the flood changes over time, hydrological models represent the interplay between climate projections and future design discharge assessments. Further highlighting the interplay between climate variability and hydraulic processes, Karamouz *et al.* (2011) proposed a probabilistic framework to assess floodplain variability, considering both river morphology and climate change impacts. Their approach combined hydraulic routing, copula-based joint probability analysis, and precipitation projections to quantify uncertainties in flood extent and depth under future climate scenarios. The study demonstrated that alterations in precipitation intensity and channel geometry substantially influence the magnitude and spatial distribution of floods, highlighting the need for adaptive floodplain management and non-stationary design practices. These findings reinforce the importance of integrating hydrodynamic uncertainty and climate variability into catchment design. For this reason, this section is meant to give some practical methodological aspects that need to be considered in determining future design discharges with hydrological modelling under climate projections.

Downscaled climate projections are essential for impact assessment studies, as rainfall projections to force hydrological models must have adequate spatial and temporal scales, especially for small and medium catchment areas (Tofiq *et al.* 2014). An ensemble of climate projections is preferred to a single climate model to remove potential biases in the outputs of regional climate models (RCMs) or global climate models (GCMs) (Pechlivanidis *et al.* 2017).

The impact of climate change on floods can be determined at different temporal scales, i.e. using event-based or continuous hydrological models. In this latter case, projections of the climate model are directly the input of the hydrological models without a rainfall frequency analysis, and bias correction is particularly important (Hall *et al.* 2014). The frequency analysis, in this case, is applied to the output of the hydrological model. In applying the bias correction methods, it is usually assumed that the model biases of the past climate will remain the same in the future (Teutschbein and Seibert 2013). There are several bias correction methods (Teutschbein and Seibert 2012, 2013), and identifying the best ones to improve the fitting of flood frequency curves in the control period to observations is essential (Soriano *et al.* 2019, Michalek *et al.* 2024). Chen *et al.* (2013) noted that the selection of the bias correction method can significantly affect the flood simulations. Therefore, continuous hydrological models are recommended in cases of small biases, as correcting large biases can introduce artefacts into the analysis (Teutschbein and Seibert 2013).

Event-based hydrological models are more common as they imply the use of the 'delta-changed' approach. In this case, the projection is not the input of the hydrological model; instead, the climate change signal of the model is extracted by comparing future scenarios and control periods and superimposed on observations, as described in the previous section. This simple method allows the evaluation of changes in flood quantiles at the catchment scale (Lompi *et al.* 2021), which can help in assessing changes in future flood losses for different return periods (Soriano *et al.* 2023).

Uncertainties in climate projections and limitations in modelling techniques pose challenges in predicting future flood scenarios with absolute certainty. Moreover, since the analysis can be done with different climate models, downscaling techniques, or bias correction methods, results can vary greatly depending on the selected methodology (Kundzewicz *et al.* 2017). The integration of climate scenarios into stormwater infrastructure design is crucial to ensure resilience against future extreme rainfall. This need is evident in recent studies assessing hydrological infrastructure under projected climate conditions. Nunes Carvalho *et al.* (2020) analysed the performance of rainwater harvesting systems under six Global Climate Models (GCMs) and two Representative Concentration Pathways (RCP 4.5 and RCP 8.5) in Brazil, showing that peak runoff could increase by up to 61% under future rainfall extremes. Their results indicated that while cisterns could mitigate some runoff, large-scale implementation would be necessary, illustrating the limitations of decentralized solutions if climate change is not fully accounted for. Similarly, Abduljaleel *et al.* (2023) used regional climate models to project future rainfall and, by incorporating these projections, were able to compare the effectiveness of different detention basin designs in mitigating climate-induced increases in runoff and pollutant loads. These examples highlight the importance of incorporating multiple climate projections into stormwater infrastructure planning, as failing to do so could lead to under-designed systems that become ineffective under future rainfall extremes. However, standardized methodologies for adapting detention basin design to non-stationary rainfall conditions remain limited, emphasizing the need for further research in this area.

5. Hydraulic models

Understanding and modelling flood events is essential for the design of stormwater retention basins (Mishra *et al.* 2024), which are key tools for mitigating hydrological risk and managing runoff. The main flood models fall into three categories: empirical methods, hydrodynamic models, and simplified conceptual models. Empirical methods are based on historical data and observations (Amadio *et al.* 2016), providing useful support for calibrating more advanced models. Although they are not directly applicable to design, they can integrate fundamental information to validate simulations and understand past hydrological behaviour. Hydrodynamic models are a fundamental tool for basin design (Förster *et al.* 2005), allowing for the simulation of flood dynamics and the evaluation of peak flows and response times. 1D models analyse the hydrological behaviour along the main course of a river, while 2D models provide a more detailed representation of the spread of water and the duration of floods, making them particularly suitable for basin design in complex contexts. An example of the combined application of 1D and quasi-2D models is represented by the study conducted on the River Thames, which uses the TINFLOOD model to simulate floodplain inundation (Kuiry *et al.* 2011). 3D models, although providing a very detailed representation, are rarely used in basin design due to their high computational cost and complexity of implementation. Their use is more common in scientific studies or in cases of special interest (Chabokpour 2025). Regarding simplified conceptual models, they are valuable tools for the preliminary design phases, providing rapid estimates of the required retention volume and the extent of inundation (Malla and Arya 2024). Although they have limitations in managing complex scenarios, they are particularly useful for an initial design evaluation.

Traditional methods for designing detention basins, such as the Rational Method and the NRCS Curve Number Method, provide simplified hydrologic assessments that are useful for preliminary design. These empirical approaches estimate peak flows and require storage volumes based on static equations, making them effective for small to moderately sized watersheds with uniform land use. However, they do not account for dynamic stormwater processes, including temporal variations in rainfall intensity, spatial heterogeneity of the watershed, or real-time floodwave progression. As a result, these methods may oversimplify hydrologic responses, particularly in complex urban or large-scale watersheds where flow routing, infiltration variability, and storage-discharge relationships play a critical role in flood mitigation.

Hydrodynamic modelling has emerged as a more effective approach, offering greater precision in evaluating flood hazards and optimizing detention basin performance. These models enable engineers to refine detention basin designs through scenario-based analysis and cost–benefit evaluations. Unlike traditional methods, these models simulate unsteady flow conditions, generate detailed flood hazard maps, and assess impacts of basin modifications. Their ability to account for soil permeability, structural interactions, and changing floodplain conditions makes them indispensable in modern flood management. By generating flood hazard maps, these models provide critical data on flood depths, velocities, and extents, which can be used to estimate potential economic losses to infrastructure, property, and communities. Scenario-based analysis enables engineers to evaluate how different storm events, land-use changes, and climate conditions influence flood risks, helping optimize basin designs to achieve maximum protection at the lowest cost.

Several studies highlight the advantages of hydrodynamic modelling. Ferreira and Cabral (2025) developed an optimization model for detention basin placement, using PCSWMM and HEC-RAS 2D to identify flood-prone areas. Their findings showed that optimized basins could significantly reduce flood extents while minimizing construction costs. Liu *et al.* (2015) applied a coupled 1D–2D model to the Jiakouwa flood detention basin in China, demonstrating how high-accuracy flood predictions and hazard maps improve flood risk assessment. Gomes *et al.* (2023) explored the optimization of an existing detention pond in Brasília, Brazil, finding that hydrodynamic models could enhance flood control without requiring new infrastructure. Additionally, Shen *et al.* (2020) demonstrated how integrating high-resolution LiDAR-derived DEM data with 2D hydraulic modelling can significantly improve floodplain flow simulations. Their study on the Gongshuangcha detention basin in China highlighted the importance of fine-scale topographic data in capturing localized flooding dynamics, refining flood hazard maps, and reducing false inundation areas in modelling outputs.

By leveraging flood hazard mapping, hydrodynamic modelling enables damage estimation for a more robust decision-making process, ensuring that detention basins are not only hydrologically effective but also economically justified.

6. Damage assessment

The estimation of flood damages represents the final step of an integrated framework for designing stormwater detention basins. Flood damage assessment is a crucial component of flood risk management, as it plays a key role in evaluating the effectiveness of mitigation and adaptation measures. By quantifying expected damages, it enables decision-makers to assess the benefits of their actions in terms of reducing impacts on human health, the environment, the economy and cultural heritage (Ruangpan *et al.* 2024). In particular, comparing the expected damages during extreme events with and without a stormwater detention basin, considering floodwater releases downstream, is essential for making risk-informed decisions to protect vulnerable urban areas (Arrighi *et al.* 2018). This approach allows for the comparison of multiple detention basin configurations and the evaluation of their effectiveness in reducing flood damages relative to construction and maintenance costs.

Damage models are the standard tools for estimating the impacts associated with a specific flood event on communities, describing the relationship between hazard, exposure, and vulnerability parameters and the damage itself. In addition to quantitative damage models, conceptual frameworks such as the DPSIR (Driving – Forces – Pressures – State – Impacts – Responses) approach have been successfully applied to analyse the causes and responses to floods in the context of sustainable development (Hashemi *et al.* 2014). This framework connects the physical, environmental, and socioeconomic dimensions of floods, enabling decision makers to identify key drivers, evaluate policy responses, and support integrated flood management strategies. Integrating such systemic approaches with hydrodynamic and damage models can improve understanding of the feedback mechanisms between human activities, land use, and flood vulnerability, thus supporting sustainable flood risk mitigation. Significant recent efforts have already been made to include damage modelling in the design of stormwater detention basins (Sahoo & Pekkat 2018, Yang *et al.* 2018, Hosseinzadeh *et al.* 2023, Masi *et al.* 2024). For example, Hosseinzadeh *et al.* (2023) present a framework for optimizing detention pond placement and design to mitigate urban flooding, integrating hydraulic simulations with multi-objective optimization to support decision-making, considering the reduction of direct damages to residential buildings; Sahoo and Pekkat (2018) follow a systematic approach to assess flood risk and evaluate the effectiveness of detention ponds by developing flood hazard maps and estimating the impacts on population and roads before and after the implementation of measures to compare their role; Yang *et al.* (2018) examine the flood risk transfer effect caused by detention basin development in the surrounding areas by assessing flood damage using damage curves for various land uses and an industry-related model for indirect losses.

7. Discussion and conclusions

This review highlights the urgent need to rethink the design, operation, and evaluation of stormwater detention basins within the context of increasingly non-stationary climatic and urban dynamics. Changes in rainfall patterns, the increasing intensity of extreme precipitation events observed across large regions of the world (and projected to intensify further in the coming decades), combined with the progressive loss of natural infiltration areas due to urbanization, are altering the hydrological balance of catchments, rendering many traditional design assumptions obsolete. In this scenario, detention basins continue to represent a cornerstone of flood risk mitigation strategies; however, their effectiveness largely depends on how well their design methods and operational frameworks can adapt to new boundary conditions. Indeed, in light of the increasingly complex challenges posed by climate change and urban development, stormwater basin design requires a shift from traditional, simplified approaches to more integrated and adaptive methodologies. While conventional design strategies (like the 'design storm' method) still hold value for initial feasibility studies and quick assessments, they are no longer sufficient to ensure the robustness and resilience of stormwater infrastructure under evolving hydrological and climatic conditions. Traditional methods are often built upon the assumption of stationarity (i.e. by considering that the statistical properties of extreme rainfall and resulting floods remain constant over time), constant runoff coefficients, and neglect of antecedent soil moisture or partial pre-filling conditions. Consequently, stormwater detention basins designed using historical rainfall statistics or outdated information of land cover may be drastically under-dimensioned for future conditions, leading to increased vulnerability to urban flooding due to under-designed systems that fail during extreme events. To bridge this gap, the integration of up-to-date rainfall frequency analyses, particularly those incorporating non-stationary behaviour, is essential. This entails not only leveraging recent observations but also incorporating climate model projections, including those derived from high-resolution convection-permitting models. These approaches can help practitioners estimate future design rainfall more accurately and align detention basin capacities with future hydrological extremes.

Hydrological modelling, particularly in climate change scenarios, enables rainfall projections to be translated into future flood estimates, providing more accurate design flows. The adoption of continuous or event-based modelling approaches, especially when supported by downscaled and bias-corrected climate data, improves our ability to understand the interaction between rainfall, land use and runoff generation under future conditions. However, uncertainties in climate models and methodological assumptions underscore the need for ensemble approaches and standardized procedures for practical applications. By incorporating information from an ensemble of climate models, stormwater basin designs can account for multiple possible projected futures, improving resilience against both extreme wet and dry conditions. By considering the uncertainty in climate predictions, the likelihood of specific outcomes could be assessed based on different model outputs and parameter uncertainties, providing a probabilistic understanding of these future conditions and enabling designs that remain effective under both typical and extreme scenarios.

Still, hydrological models alone cannot capture the full spectrum of flood risk. Hydraulic modelling plays a critical role in accurately capturing flood dynamics and informing the design of retention basins. Through hydrodynamic simulations, engineers can visualize flood extents, assess the true effectiveness of proposed basins, and refine their geometry and operation based on realistic flood scenarios. These models support scenario-based assessments and damage evaluations, both of which enable robust cost–benefit analyses and inform context-sensitive flood mitigation strategies. Traditional design procedures also rarely employ integrated hydrodynamic and damage modelling to quantify how much flood risk is actually reduced once a detention basin is in place. As a result, key metrics such as expected annual damage before and after implementation are seldom estimated, which prevents a rigorous evaluation of residual risk and makes it difficult to perform sound cost–benefit or risk-based optimization of detention schemes (Zhou *et al.* 2013, Molinari *et al.* 2021).

Together, these limitations highlight the need for design frameworks that extend beyond purely hydraulic criteria and integrate economic, environmental, social, modelling, and operational considerations to more accurately represent detention basin performance. Despite their proven benefits, hydrodynamic models are still underused in practice, often neglected in favour of simplified empirical approaches. Equally important, yet likewise overlooked or oversimplified, is the integration of damage assessment into the design process. Estimating expected flood damages provides a more comprehensive understanding of the benefits of stormwater retention basins, allowing decision-makers to balance investment costs against the potential reduction of flood-related losses. Although significant progress has been made in developing models capable of quantifying damages across multiple sectors, accurately capturing both direct and indirect impacts remains a challenge. Nevertheless, the combined use of damage models with hydrological and hydrodynamic simulations enables the creation of a fully integrated, risk-informed design framework, supporting the development of cost-effective solutions.

An emerging frontier is the application of artificial intelligence. Machine learning techniques can optimize basin operation strategies, and identify patterns in rainfall-runoff responses that conventional models may overlook. Despite these advances, a disconnection between research innovation and practical implementation still remains. While probabilistic and AI-based models show clear advantages in simulation studies, their application in real-world design is still limited by data availability, computational demand, and lack of standardized procedures.

In conclusion, while traditional methods still offer a useful framework for preliminary assessments, emerging approaches in modelling and design optimization, supported by real-time data, probabilistic methods, and artificial intelligence, present a major opportunity to improve the performance, reliability, and resilience of stormwater retention basins. Moving towards these integrated strategies is critical to address the challenges of flood risk management in a changing and uncertain future. Hybrid approaches that integrate grey and green infrastructure, such as combining detention basins with wetlands or permeable landscapes, could offer promising pathways towards multifunctional systems that deliver flood protection, water quality improvement, and ecological enhancement simultaneously.

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ORCID

Noemi Maglia http://orcid.org/0009-0004-5089-9373

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