Design and management of stormwater detention basins: review and challenges

DESIGN AND MANAGEMENT OF STORMWATER DETENTION BASINS: REVIEW AND CHALLENGES

Mariacrocetta Sambito[1], Angelo Avino[2], Ana Maria Rotaru[3], Eleonora Dallan[4], Paola Mazzoglio[5], Dario Treppiedi[6], Marco Lompi[7], Panagiotis Asaridis[3], Anita Raimondi[3]

(1) University of Enna "Kore" (2) University of Naples Federico II (3) Politecnico di Milano; (4) University of Padova; (5) Politecnico di Torino (6) University of Palermo (7) University of Florence

KEY POINTS

- *The modelling of a stormwater detention basin should integrate the historical series of observed data with real-time measurements and future climatic scenarios.*
- *Traditional methods and criteria should be updated to overcome the limitations of simplifying assumptions, which are often not representative of the processes but have a significant impact on results.*
- *It is important to consider in the management rules of the detention basin the impacts on the downstream catchment and the damages, considering different scenarios.*

1. INTRODUCTION

In recent decades, the effects of climate change have produced a progressive worsening of the control of meteoric flows and an increase in flood events. Urban areas, characterized by the rise of soil sealing and the strong interconnection between the drainage infrastructure and the hydrographic network, are the most vulnerable. Stormwater detention basins are often introduced in the upstream catchment and used as effective tools for runoff management. Traditional criteria for their design and management are based on simplifying assumptions, which are not always sufficient to model the complexity of the process. The manuscript proposes a critical review of the state of the art on the topic and suggests new methodologies and approaches to overcome the limits of those currently used in practice. It gives a complete multidisciplinary overview of the challenges in the hydrologic and hydraulic fields, with a focus on a probabilistic approach for detention basin design and management, future climatic scenarios, impacts, and damage assessment.

2. LITERATURE REVIEW

Stormwater detention basins are often introduced in the upstream catchment to reduce the flood risk in urban areas, limiting and delaying peak flows. However, the design and management of a detention basin are extremely challenging due to the high number of factors involved in the decision-making process. The basic equations regulating the storage process (the balance equation, the discharge law, and the storage function) can be integrated in close form only for simplified conditions (i.e., constant outflow rate, regular geometry, etc.). Often, for their design and verification, simplified methods such as the just rainfall method, kinematics, and reservoir models are used. They can be useful for preliminary analysis but present some important limits due to the simplified hypotheses on the hydrology and the catchment they are based on. They assume a constant rainfall intensity and outflow rate and neglect the possibility that the storage capacity can be partially filled by previous rainfall events. On the other hand, continuous simulation requires the long-term availability of recorded data and often involves high computational effort.

The analytical-probabilistic approach represents an alternative to traditional methods for both the design and management of stormwater detention tanks. Since the flood attenuation process is influenced by several hydrologic and hydraulic factors (such as flood wave shape, duration, and geometric parameters of the detention basin), an analytical-probabilistic framework able to interpret the functional relationships among the considered variables is needed. Once the output variable of interest is analytically defined, the approach derives its probability distribution function from the probability distribution functions of the input variables, relating the design parameters to a return period (*Hassini & Guo, 2020*). The model can include the possibility of pre-filling from previous rainfalls, multiple management rules for the storage volume (*Raimondi & Becciu, 2015*), and different discharge laws (*Manfreda et al., 2022*). It can be applied to different time and spatial scales, climatic regimes, and control scenarios.

3. CHALLENGES

Further developments of the analytical-probabilistic approach will focus on:

- the optimization of the design and management of storage capacity by means of multi-objective functions for achieving more than one target (i.e., runoff control, sediment removal, stormwater management),
- its integration with a descriptive-predictive model based on artificial intelligence for the prediction of the trend of the main variables involved in the process.

The design and management of stormwater detention basins should be focused not only on the update of the probabilistic approach, as discussed in the previous paragraph, but also on its integration with the following main features: (a) future climatic scenarios; (b) detailed hydraulic modelling of the upstream and downstream catchments; (c) damage assessment of the potential affected areas.

3.1 Future climatic scenarios

3.1.1 Stationary conditions

One of the input variables that must be carefully evaluated is the design rainfall. In Italy, that is the area that will be investigated in this work, the official methodology that is considered for design purposes is the VAPI (VAlutazione delle PIene) method (http://www.idrologia.polito.it/gndci/Vapi.htm), developed using time series acquired up to the '80s (*Claps et al., 2022*). This method is based on a hierarchical approach in selecting homogeneous regions, where higher-order parameters are considered uniform in areas larger than the homogeneous regions of mid and low-order parameters. During this project, Italy was divided into several "compartments" and for each compartment, a detailed analysis was performed. The results of this national-scale work are described in a series of publications referred to each compartment (the full list of reports is available at http://www.idrologia.polito.it/gndci/Vapi.htm).

In more recent years, several research works have been conducted to update these estimates on a regional scale (*Caporali et al., 2008; Forestieri et al., 2018; Libertino et al., 2018; Deidda et al., 2021*). Some of this work became operational, while others have not yet been officially adopted. In some regions, however, updating is currently in progress. One of the rainfall frequency analysis methodologies currently adopted for updating the design rainfall is the patched kriging (*Libertino at al., 2018*), which consists of a sequential (i.e. year-by-year) application of a kriging to the annual rainfall maxima of an assigned duration. This procedure produces a rainfall data cube, with an extent that coincide with the areas of interest and number of layers equal to the number of years. By sampling in each pixel, a complete historical series can be obtained. These series can then be used to calculate the L-moments and, consequently, the design rainfall.

3.1.2 Temporal trend and non-stationary methods

In recent decades, temporal trends in extreme precipitation have been observed in Italy, which can be locally increasing and statistically significant (*Libertino et al., 2019; Mazzoglio et al., 2022.; Dallan et al., 2022; Avino et al., 2024*). In the context of climate change, recent literature generally agrees on the increase in extreme precipitation due to rising temperatures, especially at sub-daily durations. It is therefore of fundamental importance to be able to estimate future changes in extreme precipitation to adapt hydraulic and hydrogeological risk management. In recent years, the so-called "convection-permitting" (CPM) climate models have demonstrated to more realistically represent short and intense precipitation than lower-resolution regional climate models.

An initial study has already been undertaken regarding the use of an ensemble of 9 different CPM models, available for the most severe emission scenario (RCP 8.5), and three time periods (1996-2005, historical; 2041-2050, near future; 2090-2099, far future). We focus on a study area centered on the Great Alpine Region, and part of northern and central Italy. Using a recent methodology for the statistical analysis of extremes (Simplified Metastatistical Extreme Value), precipitation return levels have been estimated at various sub-daily durations and different return periods up to 100 years. Their future change is calculated as the relative difference between the future and historical periods. The initial results show a positive change in extreme precipitation intensities in the area for all durations from 1 to 24 hours. The increase appears stronger and more significant in some predominantly mountainous areas, at shorter durations (1 and 3 hours) in the eastern Alps and at longer durations in the Apennines in northern Tuscany. This information is relevant for future hydraulic and hydrogeological risk management.

Since CMP projections have recently become available (*Raffa et al., 2023*) for the entire Italy, the impact of climate change on extreme rainfall can be assessed with a high spatiotemporal resolution also for the Southern part of the country. The dataset has a 1h temporal resolution over a ~2.2 km^2 grid in two future scenarios (RCP 4.5 and RCP 8.5) from 2006 to 2070 and the historical period (1981-2005). Therefore, a continuous timeseries of 90 years of rainfall (1981-2070) is available for a non-stationary extreme frequency analysis. A non-stationary SMEV is used to obtain changes in extreme precipitation for different return periods and durations. The preliminary results show a general increase in the short durations, and changes with different directions for the long durations. The changes are more statistically significant in the RCP 8.5.

3.2 Hydraulic modelling

Hydraulic modelling serves two key purposes: firstly, evaluating the behaviour of detention basins under various conditions, and secondly, facilitating the assessment of flood risk impact by comparing scenarios with and without the basin, along with different operational conditions.
It is possible to identify three main categories of models/methods (*Teng et al.*, 2017):

- empirical methods,
- hydrodynamic models (1D, 2D and 3D models),
- simplified conceptual models.

Regarding empirical methods, although they are considered accurate, they are mainly used to support decision-making processes and/or as input data for other types of methods.
Hydrodynamic models, on the other hand, are the most used because they combine a good level of precision and prediction of scenarios with a modest computational effort. In particular, one-dimensional models are used when a high level of precision in the results is not required, or the flow direction is predominantly 1D and therefore there is no interest in investigating other directions. Two-dimensional models, however, are the most used among hydrodynamic models, this is because they have a higher level of accuracy than the previous ones, but unlike 3D models they do not require a high computational effort. In fact, three-dimensional models, since they return a more accurate output in all three directions, are used to simulate areas that are not too large.
Finally, simplified conceptual models require less computational effort and are mainly used for wide floodplains and for probabilistic risk assessment.
For a detailed analysis of detention basin effects, 1D modelling proves straightforward and effective, allowing for a comprehensive assessment of hydrodynamic conditions along the flow path, particularly in evaluating the impact of basin size on outflow rates. On the other hand, 2D modelling enables the exploration and understanding of bidimensional effects, providing deeper insights into water dynamics within the basin.
In flood hazard and risk assessment, hydraulic modelling plays a critical role by determining flood extent, water depths, and velocities. This information is pivotal for hazard characterization, serving as the foundational step toward risk assessment and damage evaluation.

3.3 Damage assessment

Flood damage assessment constitutes a key aspect in any decision-making process on flood risk management. In fact, it is essential for evaluating the effectiveness of flood risk mitigation and control measures, such as the design and management of stormwater retention basins. The main reason is because it allows stakeholders to estimate the benefits associated with their decisions, expressed in terms of avoided impacts on human health, the environment, the economy, and cultural heritage (*Ruangpan et al., 2024*). In particular, the estimation of the expected damage, associated with the release of floodwater downstream of a stormwater retention basin in case of an extreme event, is fundamental for making decisions to protect the potential affected (urban) areas situated downstream (*Arrighi et al., 2018*).
Damage models are the standard tools for estimating the impacts associated with a specific flood event to the exposed elements, as they describe the relationship between hazard, exposure and vulnerability parameters and the damage itself. Flood modelling studies usually focus on the estimation of direct damage (i.e., damage caused due to the physical contact of floodwater with humans, properties or other) with the use depth-damage functions that relate inundation depth with specific flood damage to each exposed element. Damage models are commonly classified into different categories according to the required scale of analysis. Micro-scale

analysis is based on single elements exposed to flood risk (e.g., residential buildings, infrastructure assets), meso-scale analysis is based on spatial aggregations (e.g., land use units, administrative units) whereas macro-scale analysis is based on large-scale spatial units (e.g., regions, countries).

The choice of the spatial scale of analysis is strongly related to the specific context under investigation, and especially to the purpose of the study, the required reliability of the results, and the availability of the data. For example, in local studies, where the effectiveness evaluation of a single flood control measure is required, the micro-scale perspective is usually adopted. On the other hand, when larger areas must be assessed, meso-scale and macro-scale perspectives are often selected since they require less detailed information and effort. Generally, damage estimation constitutes the last part of a modelling chain that integrate models coming from multiple disciplines, as previously mentioned. A set of risk metrics can be finally defined to estimate the benefits associated with the design and management of the stormwater retention basin in the specific context under investigation.

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