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Research papers

The temporal variability of a rainfall synthetic hyetograph for the dimensioning of stormwater retention tanks in small urban catchments

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A B S T R A C T

The paper presents issues relating to the influence of time distribution of rainfall on the required storage capacity of stormwater reservoirs. The research was based on data derived from simulations of existing drainage systems. The necessary models of catchments and the drainage system were prepared using the hydrodynamic modelling software SWMM 5.0 (Storm Water Management Model). The research results obtained were used to determine the critical rainfall distribution in time which required reserving the highest capacity of stormwater reservoir. In addition, it can be confirmed based on the research that dimensioning of enclosed structures should rely on using the critical precipitation generated as the characteristics of a synthetically developed rainfall vary dynamically in time. In the final part of the paper, the results of the analyses are compared and followed with the ensuing conclusions. The results of the research will have impact on the development of methodologies for dimensioning retention facilities in drainage systems.

1. Introduction

The development of urban areas increases the surface of sealed catchment areas at the expense of biologically active areas (Zeleňá ková et al., 2014). This results in a shift of the water balance and an increase in the volume of stormwater discharged as surface runoff flows (Bornatici et al., 2004; Fletcher et al., 2013). Another consequence of this is the increased hydraulic load for drainage systems (Kim et al., 2015) and the need for their modernization or expansion. Du et al. (2012) also highlighted issues relating to the intensity of floods. Todeschini (2016), on the other hand, emphasized that increased sealing of surfaces could result in increased pollution of rainwater.

In most cases, a significant improvement can be achieved through the use of rainwater management systems in the catchment area, with sewerage systems being supplemented with retention tanks in the absence of such capabilities (Calabrò and Viviani, 2006). Their implementation is particularly significant especially in respect of controlling the negative effects of storm sewer discharges (Bertrand-Krajewski and Chebbo, 2002). Todeschini et al. (2012) indicated that the use of retention tanks is also beneficial in the context of limiting rainwater contamination.

The most important design parameter of these facilities is their required retention capacity (Hong, 2008) which to a large extent depends on the assumed characteristics of reliable precipitation. In the case of designing these facilities, actual runoff data and fixed or synthetic models, variable during rainfall, are applicable.

Artificial rainfall is used in the absence of having reliable data concerning actual rainfall. A range of runoff models and design rainfall curves, intensity duration frequency (*IDF*) and depth duration frequency (*DDF*) are widely available (Amec, 2008; Elsebaie, 2012; Yu et al., 2004).

Rainfall models enable a mathematical description of the phenomenon, namely rain, thus enabling the determination of the most important design parameters.

On the other hand, *IDF* curves of rainfall design are based on rainfall data from long-term periods of rainfall measurement. They enable the creation of a graphic representation depending on the intensity of rainfall or the amount of precipitation as a function of time at a given probability of occurrence (Schmitt et al., 2004). They are generated separately for different geographical areas and are still being modified in the process of obtaining current data on precipitation (Koutsoyiannis et al., 1998; Sivapalan and Blöschl, 1997).

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In both cases, when utilising rainfall models, the *IDF* and *DDF* curves, the following rainfall design parameters can be determined:

- the amount of precipitation *h* (alternatively intensity *I* or intensity of precipitation *q*),
- the time of precipitation *t*,
- the probability of precipitation *p*.

Zambrano et al. (2017) additionally emphasized the need to take into consideration spatial patterns of rainfall in the analysis. Liang and Melching (2015), on the other hand, considered the movement of the storm center as a significant feature of precipitation.

The rainfall models obtained by these methods are distinguished by a constant flow throughout the period of their duration. This represents a considerable simplification of the process of transforming rainfall into surface runoff, which can cause the underestimation or overestimation of facilities dedicated to sewage systems. In developing tools for hydrodynamic modelling (Pochwat, 2016), it would be reasonable to undertake analysis of the functioning of such facilities when loading catchments with rainfall with varying time distribution.

An example of such rainfall is the actual rainfall hyetographs obtained from meteorological stations using tipping bucket rain gauges or radar sensors (Bruni et al., 2015). The rainfall is distinguished by the basic design parameters of precipitation concerning both its total amount and duration, as well as information concerning the temporal variability of the amount of precipitation. Studies (Pochwat et al., 2013) show that the use of actual rainfall data is difficult and, in the case of a limited resource, it typically does not allow for an unambiguous determination of the design parameters of drainage facilities.

However, they can be used in conducting simulations and analyses of the functioning of already-designed structures of urban infrastructure, modelling runoff from catchment areas (Santra and Das, 2013) and in simulating the functioning of rainwater harvesting systems (Stec and Kordana, 2015).

In turn, the use of synthetic rainfall with variable time distribution is associated with the need to select specific features describing its shape. According to many researchers (Vaes, 1999; Vaes and Berlamont, 1999), the geometry of the drainage system is important when choosing a time variation of rainfall. In the case of more complex sewerage systems, the use of rainfall with fixed time patterns can cause more errors and, consequently, resulting in inconsistency with reality.

Synthetic rainfall with variable time distribution can, based on publications, be divided into rainfall with features similar to a triangle, composed of linear elements, as well as rainfall with features described with curved functions.

The most common examples of time-varying rainfall, described with linear functions, are those proposed by:

- Yen and Chow (1980); the rainfall obtained by this method has characteristics similar to a triangle and can be used for rainfall duration of not more than six hours,
- Watt et al. (1986); a description of the creation of rainfall was published in 1986 and it enables the preparation of precipitation consisting of both linear functions (precipitation with triangular characteristics) and of a curved function using *exponential* functions, while the rainfall pattern obtained by this method, using a rainfall of one-hour duration is composed of the increasing time function *tp* (time corresponding to the maximum intensity of the rainfall) and the decreasing function to time *td* (time corresponding to the end of the rainfall phenomenon).
- Examples of rainfall with curved characteristics is the rainfall reported by:
- Huff (1967); this temporal variability of rainfall shows a considerable degree of flexibility and mimics the actual rainfall (Bonta and Rao, 1988),
- Watt et al. (1986); the rainfall acquired by this method is described by the exp function which increases from time *tp* and the exp *decey* function finishing at time *td*,
- Keifer and Chu (1957) who set the maximum value of the intensity of rainfall and the duration of the rainfall before and after the occurrence of this value; this is the so-called Chicago method (Prodanovic and Simonovic, 2004),
- USACE (2000),
- SCS (1986),
- Euler who developed rainfall characteristics, type I, II, III, while Euler's rainfall model (type II) is the most favourable in the hydrodynamic rainfall modelling, according to (DWA-A 118, 2006),
- Thorndal (1971),
- Sifalda (1973), the characteristics of which has a shape similar to Euler's rainfall model (type II),
- Pilgrim and Cordery (1975) who suggest the creation of artificial rainfall, aimed developing a temporal pattern that did not impact on the probability of transformation between precipitation and flood.
- Vaes (1999) who proposes the use of rainfall in the form of composite storms consisting of a combination of many rainfall events; the characteristics of rainfall drawn up in accordance with this method are reflected by the quadratic function increasing from zero to half the duration of the event, to reach its maximum, and then via a parabolic function decreasing to zero. The characteristics of rainfall obtained from *IDF* curves and, according to (VMM, 1996), can be used for hydrodynamic modelling.

The last group of rainfall data includes synthetically-prepared variable rainfall characteristics obtained with the use of advanced rainfall generators, for example:

- the Licznar generator (Licznar, 2009),
- generators forming synthetic rainfalls based on a variable time scale (Piantadosi et al., 2009).

It should equally be noted that there are significant differences between the parameters of reliable rain for the dimensioning of cross sections of channels, designed for the maximum instantaneous flow rate of stormwater and the parameters of the reliable rainfall required for the determination of the retention capacity of tanks *Vu* (Pochwat et al., 2013; Słyś, 2009), which results from the different specificity of the operation of these facilities (Dziopak and Słyś, 2007; Starzec et al., 2015).

The critical precipitation for calibration, in respect of linear objects, is often a relatively short-lived rainfall which results in intensive flows through the drains. The prolongation of this time period with the probability of a similar amount of rainfall would reduce its intensity. Different principles are, however, applicable when designing enclosed structures such as reservoirs, whose primary task is to store excessive volume of stormwater. Hence the design of facilities requires the assumption of longer periods of downpour, relative to the expected level of stormwater flow through the reservoir. The hydrograph of stormwater inflow to the reservoir then assumes a more flattened shape than it is expected of linear facilities (Pochwat et al., 2013).

The possibility of occurrence of series of storm events is of equal concern. This was highlighted in studies by Varga et al. (2009), who pointed out that the occurrence of the first rain event may partially