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Initial design of urban drainage systems for extreme rainfall events using intensity–duration–area (IDA) curves and Chicago design storms (CDS)¹

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Abstract Due to more frequent extreme rainfall incidents in recent years, many large cities are considering construction of new drainage systems to cope with rainfall in the order of 100-year events. In such cases, T -year point rainfall events should be supplemented with areal reduction factors (ARF) to avoid overdesign. To facilitate an initial design, a procedure based on using Chicago Design Storms (CDS) in combination with intensity–duration–area (IDA) curves was developed

¹ This is an invited contribution by the Volker Medallist of the 2017 International Hydrological Prize, Dan Rosbjerg.

to produce CDS-ARF input rainfall. By means of the time of concentration, a specific instantaneous unit hydrograph (IUH) was obtained for each subcatchment. Combination of CDS-ARF rains and the subcatchment IUHs using convolution integrals was used to produce inflow hydrographs to the drainage system. A sequential design procedure that successively includes subcatchments for the entire drainage system in the downstream direction is implemented and exemplified ensuring a consistent initial design.

Keywords extreme rainfall; area reduction factors; CDS storms; sequential drainage design; urban catchments

Introduction

Design against urban flooding dates back to the mid-18th century (Mulvaney 1851), when the rational method came into use. The maximum flow at the outlet of catchment is assumed equal to a constant rain intensity of duration equal to the time of concentration multiplied by the catchment area and a runoff coefficient. Although this is still in use for the design of simple systems, more advanced models have gradually been developed. The time–area method can handle progressive area contributions in a catchment, producing a complete hydrograph by convolution instead of just the maximum flow (Watkins 1963). In application of the rational method, Schaacke *et al.* (1967) found that the frequency of the occurrence of the peak runoff rate was approximately the same as the frequency of the rainfall intensity used in the design. For an assessment of the use of the rational method in Canada, see Madramootoo (1990).

The unit hydrograph introduced by Sherman (1932) also builds on linear convolution of the excess rainfall. Later, Dooge (1959) developed a general unit hydrograph theory. Although developed primarily for small rural catchments, the SCS (Soil Conservation Service) method (SCS 1956) has also been adapted to urban contexts (SCS 1986). It accounts for the storage in the soil of part of the precipitation depending

on the antecedent wetness. The Storm Water Management Model (SWMM; Metcalf *et al.* 1971) is the first computer-based urban hydrology model, which gradually developed into increasingly more sophisticated versions. A recent application was presented by Jiang *et al.* (2015). The most advanced model of today, but also the most complex, is perhaps the MIKE URBAN model² of DHI that combines pipe flow and distributed surface runoff.

For the design of an urban drainage system, it is often assumed that the T -year runoff will correspond to a T -year rainfall (with T being the return period), thus implicitly assuming linearity in the rainfall–runoff process. An efficient way to search for the T -year runoff is to load the catchment with the Chicago Design Storm (CDS) developed by Keifer and Chu (1957), which is a synthetic storm that includes a T -year rain intensity for all possible durations of uniform rainfall events. Huff (1967) analysed the time variability of rainstorms and classified them into four types with maximum intensity in different quartiles. The SCS method has been supplemented by standardized rainfall intensities to maximize the peak runoff at a given storm depth. A flexible method embedded in the HEC-HMS (Hydraulic Engineering Center – Hydrologic Modeling System) platform was developed by the US Army Corps of Engineers (USACE 2000). Ellouze *et al.* (2009) presented dimensionless synthetic triangular hyetographs based on statistical analysis of precipitation data.

Empirical area reduction factors (ARFs) have been developed for many areas around the world, e.g. NERC (1975). Theoretically, ARFs have been related to the spatial correlation of rainfall, for example by Rodrigues-Iturbe and Mejia (1974) and later by Bras and Rodriguez-Iturbe (1993), who applied the correlation length, i.e. the

² <https://www.mikepoweredbydhi.com/products/mike-urban> [Accessed 29 March 2019].

integral of the spatial correlation function of rainfall in an expression for the ARF. Areal reduction factors were addressed by Asquith and Famiglietti (2000), who focussed on the annual maximum storm. De Michele *et al.* (2001) developed general ARFs based on the scaling properties of rain in time and space.

A design hyetograph was developed by Grimaldi and Serinaldi (2006), using 3-copula analysis. Hereby, both peak and total depth for use in design can be estimated, but use of advanced copula theory is necessary in the application. Multivariate return periods for synthetic design hydrograph estimation were addressed by Gräler *et al.* (2013). Eventually, this method may develop into a useful framework for practitioners to address multivariate frequency analysis. Synthetic design hydrographs were recently developed by Brunner *et al.* (2017) addressing both peak discharge and flood volume. Gauged information is necessary, but if so, design values for specific flood types become available. For intended use in ungauged catchments, Petroselli and Grimaldi (2018) presented a method for hydrograph estimation in small, primarily rural dominated watersheds using the SCS curve number approach, CDS and instantaneous unit hydrographs (IUHs). The same model was combined with flood frequency analysis by Mlynski *et al.* (2018) for selected catchments in southern Poland.

In this work, we develop a method that is intended for the preliminary design of urban drainage systems and, therefore, simple techniques are applied. Nevertheless, valuable information, as background for more advanced design efforts, will be obtained. Often crucial decisions are made before more advanced methods can be introduced, thus leaving room for simple, but also reasonably realistic methods. Following Rosbjerg and Madsen (2005), the use of models should reflect the purpose of the modelling. This calls for appropriate modelling, where the purpose of the modelling dictates the level of sophistication.

In the following, CDS will be combined with ARFs and applied in combination with a triangular IUH to calculate inflows to a main urban drainage structure, here assumed to be a drainage tunnel. A drainage canal could be used as well. The triangular IUH is flexible and can be adjusted to actual conditions. The method prescribes a sequential use on subcatchments, first one by one and subsequently by gradually incorporating subcatchments in the downstream direction, thus ensuring a consistent T -year design independent on the occurrence of concentrated or more widespread rainfalls. By superposing inflows to the drainage structure from small subcatchments in the downstream direction, and disregarding the transport time in the tunnel/canal, a first simple, but consistent, assessment of the necessary dimensions of the tunnel/canal can be obtained. The application addresses extreme rainfall events in the order of 100-year return periods, where surface runoff is dominating pipe flow and infiltration in a metropolitan area. Drainage structures of this order for large cities are being considered in many cities around the world. However, sufficient data availability in such cases may be lacking, and therefore the method must build on synthetic rainfall series.

Methodology

Application of the developed methodology is partly based on a case study from Denmark. For estimation of the ARF, we use spatial correlations of extreme rainfall events that have been analysed in Denmark in connection with the development of regionally distributed intensity–duration–frequency (IDF) curves (Madsen et al. 2002, 2017). The obtained correlation lengths as a function of rainfall duration are shown in Fig. 1.

[Fig. 1 near here]

Using six extreme rainstorm events in the Copenhagen area, Høybye and Paludan (2016) estimated the relationship:

$$\text{ARF} = c_0 \exp \left[-c_1 \left(\frac{A}{l^2} \right)^n \right] \quad (1)$$

where A is the area; l is the rainfall duration-dependent spatial correlation length; and c_0 , c_1 and n are calibration coefficients. The ARF curves are shown in Fig. 2.

[Fig. 2 near here]

Combining an IDF curve for a given return period (the ID curve) with the ARF curves leads to intensity–duration–area (IDA) curves, where the intensity for a given return period is dependent on the rainfall duration and rainfall area, as shown in Fig. 3.

[Fig. 3 near here]

The CDS introduced by Keifer and Chu (1957) is characterized by the fact that a single storm embeds T -year storms of all durations, in practice from 1 min up to a chosen maximum length (usual several hours).

If the intensity–duration curve corresponding to a given return period T is given by:

$$i(t_d; T) = \frac{a}{t_d^b + c} \quad (2)$$

then the CDS curves can be expressed as (Keifer and Chu 1957):

– before the peak:

$$i(t_d; T) = \frac{a \left(\left(1 - b \right) \left(\frac{t_b}{r} \right)^b + c \right)}{\left(\left(\frac{t_b}{r} \right)^b + c \right)^2} \quad (3)$$

and

– after the peak:

$$i(t_d; T) = \frac{a \left((1-b) \left(\frac{t_d}{1-r} \right)^b + c \right)}{\left(\left(\frac{t_d}{1-r} \right)^b + c \right)^2} \quad (4)$$

where a , b and c are the parameters in the intensity–duration curve corresponding to the return period T ; t_d is the rainfall duration; and r is the fraction of t_d before the peak.

Combining CDS and IDA curves for different return periods (Equations (3)–(4)) and the ARF (Equation (1)) leads to regional CDS-ARF rainfall events, as shown in Fig. 4.

[Fig. 4 near here]

By introducing CDS-ARF rainfall, the applicability of the CDS concept can be extended from small catchments to larger areas. Inputs that are more realistic can hereby be provided for a T -year design of urban drainage structures.

The CDS-ARF approach can also be applied for a range of T values in order to assess the cost of different degrees of adaptation measures. Such estimates are necessary in an economic optimization of adaptation efforts (e.g. Rosbjerg 2017) and call for a fast and relatively simple rainfall–runoff model.

In the following, CDS-ARF rainfall will be applied in combination with a triangular IUH (Fig. 5) to calculate inflows to a main urban drainage structure, here assumed to be a drainage tunnel. By superposing subsequent inflows to the drainage structure and disregarding the transport time in the tunnel, a first and simple assessment of the necessary dimensions of the tunnel can be obtained.

The linear system described in more detail in the next section of course sets limits for the precision. The advantage, however, is a fast and easy dimensioning, which can form the basis for more precise calculations later.

[Fig. 5 near here]

The triangular IUK is given by:

$$u(\tau) = \begin{cases} 0 & -\infty < \tau < 0 \\ \alpha\tau & 0 \leq \tau \leq \tau_1 \\ \beta - \gamma\tau & \tau_1 \leq \tau \leq \tau_1 + \tau_2 \\ 0 & \tau_1 + \tau_2 < \tau < \infty \end{cases} \quad (5)$$

where

$$\begin{aligned} \alpha &= \frac{2}{\tau_1(\tau_1 + \tau_2)} \\ \beta &= \frac{2}{\tau_2} \\ \gamma &= \frac{2}{\tau_2(\tau_1 + \tau_2)} \end{aligned} \quad (6)$$

and τ_2 is equal to $t_c - \tau_1$.

The parameter τ_1 is equal to the time to peak of the IUH, while τ_2 is the time from the peak to the end of the IUH. By adjusting τ_1 , the maximum point can be arbitrarily decided.

The CDS-ARF rainfall on a catchment is denoted $I(t)$, and the IUH is introduced above by $u(\tau)$. The inflow $Q(t)$ to the drainage tunnel can then be determined by convolution:

$$Q(t) = \int_0^t I(t - \tau)u(\tau) d\tau \quad (7)$$

In practice, the integral is substituted by summation using the time unit 1 min. Accordingly, the IUH is transformed into a unit hydrograph with time base 1 min. Based on an application example, different assumptions about the CDS-ARF rainfall and the catchment configuration are analysed. The application example also illustrates a

recommended procedure for subsequent inclusion of subcatchments in the downstream direction to ensure consistent design of the drainage structure.

Application example

To illustrate how the CDF-ARF rainfall can be used in a design context, a catchment embracing four subcatchments (SUB1, SUB2, SUB3 and SUB4) and a reservoir (RES) is considered, as shown in Fig. 6.

[Fig. 6 near here]

The arrows from the subcatchments visualize the inflow to a drainage tunnel, which is cut by a reservoir between subcatchments 3 and 4. The areas and concentration times can be seen in the figure.

In the following the effect of asymmetry of the CDS-ARF rain will be shown for SUB1. Then it is analysed how the CDS-ARF approach can be applied on two subsequent subcatchments (SUB1 and SUB2) followed by a comparison with a copula approach. A comparison with inflow calculated from an observed rain is performed and, finally, the effect of including a linear reservoir between SUB3 and SUB4 is analysed considering different reservoir time constants.

Effect of asymmetry of CDS-ARF rain

The symmetrical 100-year CDS-ARF rainfall on SUB1 is compared with rainfall events with their peak located respectively one-quarter and three-quarters of the rainfall duration from the onset of the rain.

[Fig. 7 near here]

In Fig. 7 it is seen that the effect of an asymmetric CDS-ARF rainfall event is minor with respect to the maximum tunnel inflow. For a 100-year event, it is anticipated that pipe flow and infiltration are of minor importance in comparison to surface flow, indicating that the influence of the storm peak location will be minor too.

Extension to two subcatchments and comparison with a copula approach

A sequential design procedure that successively includes subcatchments can be used for design of the tunnel. As an example, the tunnel inflow from a 100-year CDS-ARF rain on the combined areas (2.73 km²) of SUB1 and SUB2 is shown in Fig. 8.

[Fig. 8 near here]

It could be argued that it would be better to apply a copula approach to assess the maximum tunnel inflow from the two catchments. This is investigated by assuming a Gumbel-Hougaard logistic copula (Raynal-Villasenor and Salas 1987). Corresponding return periods of T_1 and T_2 for the individual subcatchments are calculated and shown in Fig. 9 in the case of a combined $T_d = 100$ -year event. The association coefficient m is given by $m = (1 - r)^{1/2}$, where r is the correlation coefficient between extreme rain on the two subcatchments:

$$\frac{1}{T_1} + \frac{1}{T_2} - \frac{1}{T_d} - 1 + \exp \left\{ - \left[\left(-\ln \left(1 - \frac{1}{T_1} \right)^m + \left(-\ln \left(1 - \frac{1}{T_2} \right)^m \right)^{\frac{1}{m}} \right] \right\} = 0 \quad (8)$$

[Fig. 9 near here]

The corresponding return periods result in maximum tunnel inflows in the interval [30.3 m³/s; 32.7 m³/s]. It is seen that the deviation from applying a uniform CDS-ARF 100-year rain on the combined catchments is minor (maximum tunnel inflow

of 31.4 m³/s, cf. Fig. 8). It should be added that, in contrast to the copula approach, it is straightforward to include more subcatchments using the uniform CDS-ARF approach.

Comparison with observed rain

Using the Thiessen polygon method, the rain on SUB1 with 1-min resolution was calculated for the extreme rainstorm that hit Copenhagen on 2 July 2011. The resulting inflow hydrograph is shown in Fig. 10. It may be seen that the shape of the hydrograph from a real rainfall event is more irregular than the hydrograph originating from the CDS-ARF rainfall.

The maximum 1-min rainfall intensity of the storm is found to correspond to the maximum of a 150-year CDS-ARF rainfall event. By calculating moving average rain series using windows of, respectively, 30 min and 60 min and, again, comparing maximum values with the maximum values of the corresponding CDF-ARF rainfall, it is found that both maximum 30-min and maximum 60-min intensities should be considered as 1000-year events. Shorter time windows corresponded to considerably lower return periods.

[Fig. 10 near here]

In Fig. 10, the SUB1 tunnel inflow from a 1000-year CDS-ARF rainfall event, where all sub-durations correspond to 1000-year events, is shown for comparison. The maximum tunnel inflow is seen to be exactly equal to the maximum inflow originating from the observed rainfall.

Effect of a reservoir

By calculating maximum tunnel inflow from the combinations SUB1, SUB1+2, SUB2+3 and SUB1+2+3, taking into account the timing due to the differences in the concentration times, but not delays in the tunnel, it is found (as expected) that the maximum inflow comes from the combination SUB1+2+3. The reason for analysing all combinations is that the larger the area of the CDS-ARF rain, the smaller the rainfall intensity. The increase of the area, however, seems to be the dominant factor here.

Similarly, when including SUB4, looking at the maximum downstream tunnel flow and disregarding the reservoir, the combinations SUB4, SUB3+4, SUB2+3+4 and SUB1+2+3+4 should be screened. Again, it becomes clear that the combination SUB1+2+3+4 provides the largest downstream flow.

The question is now how much this flow will be reduced due to the reservoir effect. This is analysed by assuming the reservoir to be linear and considering two different reservoir time constants, as shown in Fig. 11.

The outflow $Q_{\text{out}}(t)$ from the linear reservoir is given by:

$$Q_{\text{out}}(t + \Delta t) = Q_{\text{out}}(t) \exp\left(-\frac{\Delta t}{K}\right) + Q_{\text{in}}(t + \Delta t) \left[1 - \exp\left(-\frac{\Delta t}{K}\right)\right] \quad (9)$$

where $Q_{\text{in}}(t)$ is the inflow, K is the time constant of the linear reservoir, and Δt is the time step. Hereby, the total downstream flow can be calculated.

[Fig. 11 near here]

With a reservoir constant of $K = 60$ min, the maximum flow is reduced by 37.2%. A further reduction (53.0%) is obtained with a reservoir constant of $K = 300$ min.

Discussion

By first loading each subcatchment with a T -year rainfall event corresponding to the area of the subcatchment, it should be ensured that all the inflow structures to the tunnel correspond to the chosen T -year level. Then starting from the uppermost subcatchment and successively including more subcatchments in the downstream direction, while each time applying a T -year rainfall event corresponding to the actual sum of the subcatchment areas, tunnel dimensions that consistently correspond to the T -year level will be obtained. The applied approach is indeed simple. However, it addresses an important step in the design procedure. Design is different from application of detailed simulation models with ample data availability. The method has to be robust, and, in the first phase, relatively simplistic. Presentation of preliminary measures is an important step in a design process. The developed method has its strength in filling this gap and should only be used for this purpose. It is focussed on provision of a consistent design approach corresponding to a given return level, and it is important to be aware of this premise for the analysis. Despite new and highly advanced approaches, there is still room for relatively simplistic methods, particularly in the early steps of a design phase. It should, however, be added that the sequential design procedure is still applicable in a later design phase, where the simple rainfall–runoff model is substituted by a more detailed, distributed model.

Conclusions

The use of CDS-ARF rain combined with a triangular unit hydrograph provides a flexible and simple way to make an initial assessment of the inflow to urban drainage structures for extreme rainfall events. In the present case, the influence of asymmetry in the CDS rain is minor. In addition, it is found that when maintaining the overall return

period of rain on two subcatchments, there is no need for applying an uneven distribution of return periods of CDS-ARF rains on the subcatchments. Comparing the tunnel inflow from the 2 July 2011 rainstorm in Copenhagen, which embedded 30-min and 60-min 1000-year intensities with the inflow from a 1000-year CDS-ARF rain, resulted in the same maximum inflow rate. Finally, the effect of a reservoir to alleviate the downstream drainage flow was demonstrated. The simple and fast system for initial design of urban drainage of extreme rainfalls can be helpful in an optimization process and will constitute a basis for more refined design efforts in which the proposed sequential design procedure will still be applicable.

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Figure captions

Figure 1. Spatial correlation length as a function of rainfall duration.

Figure 2. ARF curves for extreme rainfall events of different durations.

Figure 3. IDA curves for different areas and a given return period.

Figure 4. Symmetrical CDS-ARF rainfall for different areas and a given return period corresponding to the IDA curves in Fig. 3.

Figure 5. Triangular IUH. The time to peak is τ_1 and the width is the time of concentration $t_c = \tau_1 + \tau_2$.

Figure 6. Sketch of the analysed catchment.

Figure 7. SUB1 inflow hydrograph to drainage tunnel from symmetric/asymmetric 100-year CDS-ARF rainfall.

Figure 8. Combined tunnel inflow from a 100-year CDS-ARF rain on SUB1 and SUB2.

Figure 9. Corresponding individual return periods of SUB1 and SUB2 for a combined 100-year event.

Figure 10. SUB1 tunnel inflow from, respectively, the 2 July 2011 storm in Copenhagen and a 1000-year CDS-ARF rain.

Figure 11. Downstream flow with reservoir constants of $K = 0$ min, $K = 120$ min and $K = 300$ min.

Fig. 1

Fig. 2

Fig. 3.

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8.

Fig. 9

Fig. 10

Fig. 11