Chapter 22

Estimating Volume Requirements for Runoff Storage Facilities: Old Simplicity vs. New Complexity

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Stormwater management analysis practices have evolved significantly over the past three decades and, at present, computer simulation is the technique most commonly used by the practising engineer to perform a variety of analyses ranging in scope from preliminary concept plans to detailed design. Typically accompanying the arrival of numerous and sophisticated simulation models into engineering practice is a general loss of knowledge of and appreciation for some relatively simple techniques which were advanced prior to the current era of stormwater management modeling.

An example of such a technique is presented in this chapter which estimates the size of a runoff storage facility such as a detention pond based on only two catchment characteristics (namely, depression storage and the runoff coefficient), allowable release rates and intensity-duration-frequency (IDF) curves. *[Assumption is made herein that probability of the storm equals probability of resulting flood - Ed. note]* The technology, originally published in the 1940's, converts IDF curves into curves of cumulative rainfall volume as a function of rainfall duration. Graphical or numerical techniques can be used for the solution of critical rainfall durations which yield the storage volume required to avoid spillage for the storm with a return period that corresponds to the IDF curve. The technique is, therefore, based upon event hydrology. It has since been generally recognized that the long term performance of drainage system elements such as storage devices cannot be designed or analyzed adequately using single design

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storm events based upon IDF relationships. Several analysis technologies have been developed to overcome this limitation including continuous simulation, analytical probabilistic techniques and stochastic simulation techniques, all of which utilize long term rainfall records or meteorological statistics derived therefrom.

This chapter investigates the adequacy of employing an older, simpler analysis method for arriving at preliminary estimates of volume requirements for runoff storage facilities by comparing results obtained using this method with results generated from continuous simulation and analytical probabilistic approaches. This simplified technique is formulated and solved utilizing exponentially decreasing and Chicago-type design storms. The results of this exercise indicate that this simple technique can be used with reasonable confidence for preliminary estimates. This means that less computational effort is required of the engineer producing concept plans for urban land development. The comparison of results also provides additional insight into the performance of the computationally efficient analytical probabilistic models relative to their more sophisticated and complicated counterpart, namely continuous simulation. It is noted, however, that the detailed design of urban drainage systems does deserve utilization of simulation techniques.

22.1 Simplified Method for Sizing Runoff Storage Basins

Originally published in 1940 by John A. Rousculp - Engineer in Charge of Sewer Design in the City of Columbus, Ohio - this simple technique for estimating the sizing of runoff detention facilities converts rainfall IDF curves into relationships between the cumulative volume of rainfall and the rainfall duration. Recent work noting the use of this technique include the Ontario Ministry of Transport (MTO) Drainage Management Technical Guidelines (Adams, 1989) and the Water Environment Federation (WEF) Manual of Practice FD-20 (WEF/ASCE, 1992).

All works to date, however, have implicitly assumed an exponentially decreasing rainfall hyetograph. This is perhaps due to the fact that the method was promulgated well in advance of many commonly used synthetic design storm patterns, such as the Chicago-type design storm (Keifer & Chu, 1957). Since the commonly used Chicago-type storm is often considered to more closely resemble most real storm patterns as opposed to the exponentially decreasing storm, Rousculp's method is modified herein to generate curves of cumulative rainfall volume with respect to rainfall duration for the Chicago-type storm.

22.1.1 Exponentially Decaying Storm (after Adams, 1989)

The IDF curve implies a rainfall volume at any given duration which is computed as the product of the intensity and the said duration. Therefore, from an IDF curve a plot of cumulative rainfall volume with respect to rainfall duration can be developed (see Figures 22.1 and 22.2). The curve represented in Figure 22.2 is essentially the mass curve of an exponentially decreasing rainfall hyetograph. The general expression for an IDF curve is:

$$i = a(b + t)^{-c} \quad (22.1)$$

where:

- i = rainfall intensity (mm/h),
- t = rainfall duration (min), and
- a, b and c = empirical constants derived from a moving window statistical analysis of rainfall records.

The mass curve is therefore given by:

$$v = \frac{i \cdot t}{60} = \frac{a \cdot t(b + t)^{-c}}{60} \quad (22.2)$$

where:

- v = cumulative rainfall volume (mm).

The slope of a line in volume-duration (V-t) space is a flow rate, hence, the steeper the curve of cumulative rainfall volume, the greater the rate of runoff. For purposes of the preliminary design of runoff storage facilities, it may be assumed that the controlled outlet rate (Ω) from the storage facility is relatively constant and, therefore, plots as a straight line in V-t space. Losses due to infiltration are represented by a constant runoff coefficient (ϕ). Such losses can be considered in one of two ways: (i) the cumulative rainfall volume may be directly multiplied by ϕ to yield a plot of cumulative runoff volume as a function of storm duration or (ii) the outlet rate (among other quantities including the storage volume, S_A , and the depression storage, S_d) may be divided by ϕ on a plot of cumulative rainfall volume as a function of duration. Both techniques yield identical results; the latter approach is adopted herein.

Required storage volumes are determined by establishing a *critical* storm duration, t^* . This critical duration corresponds to the maximum storage volume requirement and is determined by plotting the *adjusted* outlet rate (Ω/ϕ) through the origin and locating the duration at which the vertical departure between the adjusted outlet rate and the cumulative rainfall curve of interest (e.g. 50-yr) is maximized. This occurs when the slope of the cumulative rainfall curve is equal to the adjusted outlet rate (Ω/ϕ) as indicated on Figure 22.2. The critical duration can be determined according to the following expression:

Figure 22.1 IDF curves. **Figure 22.2** Curves of cumulative rainfall volume.

$$\frac{dv}{dt} = \frac{a(b+t^*)^{-c-1}[b-t^*(c-1)]}{60} = \frac{\Omega}{\phi} \quad (22.3)$$

By inspection of Equation 22.3, the critical duration, t^* , cannot be solved analytically and therefore graphical or numerical solution techniques are required.

Assuming linear hydrology, the volume of runoff (v_r) can be related to the rainfall volume (v) according to the following expression:

$$v_r = \phi(v - S_d) \quad (22.4)$$

Equation 22.4 can be rearranged to give:

$$v = \frac{v_r}{\phi} + S_d \quad (22.5)$$

For a runoff event to completely fill a storage facility without inducing a spill, the volume of the runoff event must exactly equal the volume of the storage facility itself plus the volume of runoff processed through the outlet which is determined by the product of the outlet rate (Ω) and the storm duration (t):

$$v_r = S_A + \Omega t \quad (22.6)$$

Substituting Equation 22.6 into 22.5 and isolating S_A yields an expression for the required size of the storage facility:

$$S_A = \phi(v^* - S_d) - \Omega t^* \quad (22.7)$$

where v^* is the cumulative volume of rainfall at the critical duration, t^* , determined using Equation 22.2. The result given by Equation 22.7 is shown graphically in Figure 22.3.

22.1.2 Chicago-Type Storm

A Chicago-type design storm hyetograph is considered to resemble real storm patterns better than the exponentially decreasing storm discussed in the previous section. Figure 22.4 shows the generalized Chicago-type storm.

Figure 22.3 Estimating storage volume requirements.

Figure 22.4 Chicago-type design storm (Keifer & Chu, 1957).

Based on the expression for the IDF curve given by Equation 22.1, the rainfall intensity before the peak (i_A) is given by (modified from MTO, 1989):

$$i_A = \frac{a \left[(1-c) \left(\frac{r T_d - t}{r} \right) + b \right]}{\left[\frac{r T_d - t}{r} + b \right]^{1+c}}, \quad 0 \leq t \leq r T_d \quad (22.8)$$

where:

T_d = storm duration, and
 r = ratio of the time of peak intensity to the storm duration.

The rainfall intensity after the peak (i_B) is given by (modified from MTO, 1989):

$$i_B = \frac{a \left[(1-c) \left(\frac{t_B}{1-r} \right) + b \right]}{\left[\frac{t - r T_d}{1-r} + b \right]^{1+c}}, \quad r T_d \leq t \leq T_d \quad (22.9)$$

where:

t_B = the time after the peak rainfall intensity.

The curve of cumulative rainfall (mass curve) can then be derived as follows:

$$v = \int_0^t \frac{i_A(t)}{60} dt = \int_0^t \left\{ \frac{a \left[(1-c) \left(\frac{r T_d - t}{r} \right) + b \right]}{60 \left[\frac{r T_d - t}{r} + b \right]^{1+c}} \right\} dt, \quad 0 \leq t \leq r T_d \quad (22.10a)$$

$$\begin{aligned} v &= \int_0^{r T_d} \frac{i_A(t)}{60} dt + \int_{r T_d}^{T_d} \frac{i_B(t)}{60} dt \\ &= \int_0^{r T_d} \frac{i_A(t)}{60} dt + \int_{r T_d}^{T_d} \left\{ \frac{a \left[(1-c) \left(\frac{t_B}{1-r} \right) + b \right]}{60 \left[\frac{t - r T_d}{1-r} + b \right]^{1+c}} \right\} dt, \quad r T_d \leq t \leq T_d \quad (22.10b) \end{aligned}$$

Performing the integrations yields:

$$v = \begin{cases} \frac{a}{60} \left[\frac{t - r T_d}{\left(b + T_d - \frac{t}{r}\right)^c} + \frac{r T_d}{(b + T_d)^c} \right], & 0 \leq t \leq r T_d \\ \frac{1}{60} \left\{ \frac{a r T_d}{(b + T_d)^c} + a(t - r T_d) \left[\frac{r - 1}{b(r - 1) + r T_d - t} \right]^c \right\}, & r T_d \leq t \leq T_d \end{cases} \quad (22.11)$$

It is important to note that the user must specify two additional parameters for the Chicago-type storm: the total storm duration (T_d) and the ratio of the time at which the peak intensity occurs to the total storm duration (r). Typical values of r range from 0.3 to 0.4; for the work presented here, a value of $r = 0.38$ was adopted based upon recommendations made by the Ontario Ministry of Transportation (MTO, 1989). The solution procedure is very similar to that presented in the previous section; however, since a total storm duration must be specified, it is possible that the *critical* storm duration or rainfall volume lies beyond the duration specified. This solution procedure is discussed in further detail below.

A typical mass curve for a Chicago-type design storm hyetograph is presented in Figure 22.5. Recalling that the slope of a line in V-t space is a rate

Figure 22.5 Curve of cumulative rainfall volume (mass curve) for a Chicago-type design storm.

of flow, it follows that storage is not utilized until the influent flow rate (being the slope of the mass curve at a given point in time) is greater than the release rate of the storage facility (Ω/ϕ). Therefore, one must determine the time, t_1 , and the corresponding rainfall volume, v_1 , at which storage is first utilized. Similar to the previous section, a straight line (denoting a constant release rate) with slope Ω/ϕ is drawn from the point (t_1, v_1) and not through the origin as in the previous section. The critical duration, t_2 , is located where the departure between the curve of cumulative rainfall and the curve representing the outlet rate (Ω/ϕ) is maximized; the cumulative rainfall volume at this point is denoted v_2 . Notice that both points (t_1, v_1) and (t_2, v_2) are located where the slope of the curve of cumulative rainfall is equal to the slope of the curve representing the release rate. t_1 and t_2 can be found using the following expressions:

$$\frac{dv}{dt} = \frac{a[b(r+c-1)(t_1 - rT_d)]}{60(b(r+c-1) + rT_d - t_1)} \left(b + T_d - \frac{t_1}{r} \right)^{-c} = \frac{\Omega}{\phi}, \quad 0 \leq t \leq rT_d \quad (22.12a)$$

$$\frac{dv}{dt} = \frac{a[b(r-1) + (c-1)(t_2 - rT_d)]}{60[b(r-1) + rT_d - t_2]} \left[\frac{r-1}{b(r-1) + rT_d - t_2} \right]^c = \frac{\Omega}{\phi}, \quad rT_d \leq t \leq T_d \quad (22.12b)$$

It is noted that the values of t_1 and t_2 in Equations 22.12 cannot be solved analytically and therefore graphical or numerical solution procedures are required.

Following the same logic as that given in the previous section (i.e. Equations 22.4 to 22.7), the required size of the storage facility can be estimated as follows:

$$S_A = \phi[(v_2 - v_1) - S_d] - \Omega(t_2 - t_1) \quad (22.13)$$

There are some guidelines which must be respected when solving for the required storage capacity using the Chicago-type storm methodology presented in this section. These criteria have been established empirically through numerical testing and are stated as follows:

- The required storage volume is not dependent upon the total storm duration chosen (T_d) provided that t_1 and t_2 are not located at the boundaries of the duration range ($t_1 = 0$ and $t_2 = T_d$, respectively).
- If $t_1 = 0$ and/or $t_2 = T_d$, then another (longer) duration (T_d) must be selected for analysis to estimate the storage requirements

22.1.3 Comparison of Results

It is important to note that the results obtained from both storm patterns, the Chicago-type design storm and the exponentially decreasing storm, are *identical*. This is due to the fact that although the Chicago-type storm assembles the rainfall intensities derived from IDF curves in a different pattern, the hyetograph ordinates resulting in runoff rates greater than the release rate are distributed continuously. This is illustrated graphically in Figure 22.6. This result is also attributable to the linear hydrology employed. It is noted that, in reality, the Chicago-type rainfall distribution would be expected to yield a greater runoff volume than the exponentially decreasing storm since, by the time the high rainfall intensities occur in the former case, the soils would be closer to saturation and, therefore, would have less infiltration capacity.

Figure 22.6 Rainfall volumes from different storm types.

Since both storm types produce identical results, engineering judgment indicates that the simpler of these techniques (i.e. the exponentially decreasing storm hyetograph) could be used in practice for the preliminary estimation of detention storage capacities.

22.1.4 Applicability and Limitations of Method

It is important that the users of such techniques understand and appreciate the theoretical basis upon which they are founded. Moreover, it is (at least) equally important that the limitations of the approach are thoroughly understood. To arrive at such a simple method to estimate runoff storage requirements, many simplifying assumptions have been made. For each of these assumptions, in turn, realism may be sacrificed. In this section, the fundamental assumptions and limitations of the above methodology are explored.

The use of a design storm derived from an IDF curve can be criticized in at least two fundamental ways. Firstly, IDF curves were originally intended to assist in the estimation of peak runoff flow rates and not the generation of runoff hydrographs or runoff volumes. Secondly, the use of a design storm does not account for antecedent soil moisture conditions nor for the possibility of runoff from a previous event being detained in the storage facility (i.e. the storage facility is assumed to be empty when the event occurs). It is currently well known that interevent times play a crucial role in sizing storage facilities. This can only be accomplished using a continuous analysis technique. Shortcomings of the IDF-based design storm approach are well known (e.g. Adams & Howard, 1986).

The approach assumes that the outflow rate (Ω) from the storage facility is constant which is rarely the case in reality, especially for gravity-drained facilities such as stormwater detention ponds, where outlet rates are dependent upon the depth of ponding. It is also assumed that the runoff coefficient (ϕ) is constant for a given catchment and independent of storm duration. In reality, the proportion of rainfall which becomes runoff increases with storm duration as soils approach saturation. In addition, the routing of runoff through drainage system conveyances (pipes, channels etc.) is neglected by this approach which affords a degree of conservatism in the results. In cases where the above assumptions are untenable or too restrictive, a continuous analysis is necessary.

Finally, it has been noted that this technology should be used for small runoff storage facilities and conservative estimates of the runoff coefficient, ϕ (Watson, 1981).

The following sections give comparisons between this simplified technique and more modern technologies including event simulation and continuous analysis using analytical probabilistic models and continuous simulation.

22.2 Simplified Approach vs Event Simulation

Since the simplified method can be implemented with relative ease and efficiency, it may be very useful as an alternative to more complex and laborious methods for estimating runoff storage requirements at the preliminary planning stage. It is therefore useful to investigate how the results obtained from such a method compare to the more sophisticated and complex modeling techniques. This section compares results obtained from the simplified method with OTTHYMO (Wisner et al., 1989), a hydrologic model commonly used in Ontario.

22.2.1 Modeling Methodology

For purposes of comparison, a hypothetical 10 ha catchment with 40% imperviousness was used to run the OTTHYMO model for two different storm

events: an exponentially decreasing storm and a Chicago-type storm. Additional parameters used in the OTTHYMO model include the percentage of the catchment which is directly connected to the sewer system (assumed 40%), the average slope of the catchment (assumed 1%) and a model for losses (Horton's relation assumed). A 4 hr total duration Chicago-storm was simulated with a time-to-peak ratio (r) of 0.38. The DESIGN STANDHYD command was used to generate runoff and the COMPUTE VOLUME command was subsequently used to estimate the size of detention facility required given a constant release rate. Output from the model also includes an estimation of the runoff coefficient for the rainfall event under analysis computed as the ratio of the volume of runoff to the rainfall volume. The runoff coefficients computed by OTTHYMO were then used in the simplified method to estimate storage requirements.

Rainfall characteristics in the form of IDF curves were derived from the Toronto Pearson International Airport Meteorological Station #6158733. The corresponding parameters for IDF curves (Equation 22.1) are given in Table 22.1.

Table 22.1 IDF curve parameters.

Parameter	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
a	706.6	896.5	1018	1190	1288	1411
b	5.9	5.6	5.3	5.3	5.0	5.0
c	0.804	0.789	0.781	0.777	0.771	0.769

22.2.2 Comparison of Results

Figures 22.7 and 22.8 illustrate results from OTTHYMO and the simplified approach for determining storage requirements for specified return periods. Figure 22.7 compares the modeling results assuming an exponentially decreasing storm for the OTTHYMO runs. As illustrated in Figure 22.7, the two approaches agree reasonably well with each other, especially for higher return frequency events (i.e. 2 yr to 25 yr events). It should be noted that, for the sake of efficient presentation, not all results are illustrated herein. These results suggest that, for an exponentially decreasing storm, the simplified method may be employed with reasonable confidence in the preliminary design of stormwater management facilities. The use of an exponentially decreasing storm, however, may not represent actual storm conditions and, therefore, a Chicago-type design storm may be more appropriate for comparison.

Figure 22.8 illustrates the comparison of results for the two modeling techniques using a Chicago-type design storm in the OTTHYMO simulation runs. It is evident from Figure 22.8 that the models agree reasonably well for the rainfall

Figure 22.7 Comparison of OTTHYMO and simplified method for exponentially decreasing storm.

events characterized by higher frequencies of occurrence; however, there appears to be significant divergence for the more rare events. This is due to the shape of the rainfall hyetograph for a Chicago-type storm which exhibits low intensities initially, contributing to the degree of soil saturation but not to storage. Therefore, by the time the higher rainfall intensities occur, less rainfall can be absorbed or infiltrated and, hence, more runoff is generated. The simplified method assumes linear hydrology and cannot take this effect into account. In general, for the lower frequency events (i.e. the 25, 50 and 100 yr events) the simplified method underestimates the required storage capacity by 20-25% on average.

Figure 22.8 Comparison of OTTHYMO and simplified method for Chicago-Type design storm.

22.3 Simplified Approach vs Continuous Analysis Technology

Both the simplified method for estimating runoff storage requirements and the simulations using OTTHYMO consider only specific, single rainfall events. The shortcomings of event hydrology for determining long-term performance characteristics of drainage systems are well known (e.g. Adams and Howard, 1986). Single rainfall events do not consider the full spectrum of meteorological conditions to which a drainage system can be subjected to in its lifetime. It is therefore generally accepted that continuous analysis of drainage systems is required to provide an adequate representation of a drainage systems' long-term performance.

There exists three types of technologies available for the continuous analysis of drainage systems: continuous simulation using long-term (decades) historical rainfall records; stochastic simulation techniques which generate long-term time series of rainfall hyetographs using rainfall statistics derived from historical rainfall records for use in subsequent continuous simulation; and analytical probabilistic models which transform probability distributions of rainfall characteristics into probability distributions of system performance using rainfall statistics derived from historical rainfall records. The modeling results obtained previously using OTTHYMO and the simplified technique are compared herein to results using SWMM (Huber & Dickinson, 1988) and analytical probabilistic models (Adams and Bontje, 1984).

22.3.1 Continuous Simulation Modeling

The RAIN, RUNOFF and STORAGE/TREATMENT blocks of SWMM were used to generate the results presented herein for a 10 ha catchment with 40% imperviousness, a value of 0.013 for Manning's n for impervious areas, a value of 0.25 for Manning's n over pervious areas, a catchment width of 400 m and an average catchment slope of 1%. Horton infiltration was used to model hydrologic losses. Input to the RAIN block consisted of 33 yr of historical rainfall data from Toronto Pearson International Airport Meteorological Station #6158733 (the same rainfall station from which the IDF parameters were derived). It should be noted that the IDF parameters were generated from rainfall data collected from 1950 to 1986 (37 yrs) while the rainfall record used covers the time period ranging from 1960 to 1992. This slight difference in time frame is not anticipated to significantly affect the results.

The output from the RAIN block was used as input to the RUNOFF block where the winter months (i.e. November-March) of each year were excluded from the simulation. Monthly evaporation data from the Canadian Climate Normals for Hamilton, Ontario derived from statistics reflecting the period from 1955 to 1980 were also used in the simulation.

Finally, the output from the RUNOFF block was used as input to the STORAGE/TREATMENT block for a variety of storage volumes and constant outflow rates. For each combination of storage volume and release rate, SWMM determines the number of spills that occur throughout the simulation period from which the average annual number of spills and average return period of spill can be determined. This data is then used to generate isoquants of spill return period. It is important to note that, since there exists only 33 yr of rainfall data in the data set used, the maximum theoretical return period one can observe is limited to 33 yr. Generally, the higher frequency (i.e. 1, 2, and 5 yr) isoquants contain higher degrees of statistical significance than the lower frequency (i.e. 10 and 25 yr) isoquants. As a result of this limitation, isoquants up to the 10 yr return frequency are used for comparative purposes.

22.3.2 Analytical Probabilistic Modeling

An alternative approach to continuous simulation modeling which requires substantially less computational effort is the analytical probabilistic modeling of urban drainage systems. Using derived probability distribution theory (Benjamin and Cornell, 1970), probability distributions of rainfall characteristics including rainfall volume, duration and interevent time are manipulated to produce expressions representing various drainage system performance parameters. These models are elegant and efficient and calculable by hand since the model expressions are generally in a mathematically closed form. Extensive research comparing results from these models with the more complex modeling technology of continuous simulation have shown that these models are very effective in urban drainage systems performance estimation, especially where detailed (hence expensive and time-consuming) analyses are unwarranted, such as at the preliminary planning and design stages.

Inputs to analytical probabilistic models include the catchment characteristics of depression storage (S_d) and runoff coefficient (ϕ) and statistics of rainfall characteristics. Using the same rainfall record as that used in the SWMM continuous simulation modeling described previously, statistics of rainfall duration, volume and interevent time have been derived assuming an interevent time definition (IETD) of 2 hrs. These statistics were then used to estimate parameters for the exponential probability distributions of rainfall characteristics used in the development of the analytical probabilistic models. The resulting parameter values are provided in Table 22.2.

Additional input parameters for estimating required storage volumes for specified spill return frequencies include the controlled release rate (Ω), the average annual number of spills (θ) and the return period (T_R).

The analytical probabilistic model expressions (Adams and Bontje, 1984) can take on two forms depending on the assumption of storage contents prior to the analysis period. The most conservative case assumes that storage is full prior to the analysis period; therefore, time is required to drain the pond before its full capacity is available. The least conservative case assumes that the storage

Table 22.2 Results of statistical analysis of rainfall record for IETD = 2h (Adams, 1996).

Characteristic	Mean	Parameter for Exponential Probability Distribution
Rainfall Volume, v	5.00 mm	$\zeta = 0.200 \text{ mm}^{-1}$
Rainfall Duration, t	3.55 h	$\lambda = 0.282 \text{ h}^{-1}$
Interevent Time, b	43.4 h	$\psi = 0.0230 \text{ h}^{-1}$
Average Annual Number of Events	104	

reservoir is initially empty and its full capacity is available immediately. In reality, the average reservoir condition prior to the analysis period will lie somewhere between these extremes. It is impossible, however, to analytically derive the steady-state probability of reservoir contents prior to the analysis period and, therefore, to maintain simplicity, both limiting conditions should be examined and careful judgment exercised.

The isoquant expression for the most conservative case (denoted by the subscript 1) is given by (from Adams and Bontje, 1984)

$$S_{A_1} = -\frac{\Omega\phi}{\psi\phi + \zeta\Omega} \ln \left\{ \frac{\phi}{\zeta} \left[\frac{e^{\zeta S_d}}{\theta T_R} \left(1 + \frac{\zeta\Omega}{\phi\lambda} \right) \left(\frac{\psi}{\Omega} + \frac{\zeta}{\phi} \right) - \frac{\psi}{\Omega} \right] \right\} \quad (22.14)$$

The isoquant expression for the least conservative case (denoted by the subscript 2) is given by (from Adams and Bontje, 1984):

$$S_{A_2} = -\frac{\phi}{\zeta} \ln \left\{ \frac{e^{\zeta S_d}}{\theta T_R} \left(1 + \frac{\zeta\Omega}{\phi\lambda} \right) \right\} \quad (22.15)$$

where:

- ϕ = runoff coefficient (in mm)
- S = depression storage (in mm)
- Ω = constant release rate (in mm/h)
- θ = average annual number of rainfall events
- T_R = return period (yrs), and
- S_A = required storage volume (in mm), and
- ζ (mm⁻¹), λ (h⁻¹)
and ψ (h⁻¹) = the parameters for the exponential probability distributions of rainfall volume, duration and interevent time, respectively.

The functional form of these models makes them very amenable to sensitivity analyses and to the solution of optimization problems. The accuracy which may be sacrificed by simplifying assumptions is traded-off with their ease of implementation when so warranted. It should also be noted that these models are developed on a *per unit catchment area* basis and, hence, do not require the catchment area as an input parameter.

It is important to note that, since these models are derived using exponentially distributed probability densities of rainfall characteristics, they represent average conditions well. Extreme meteorologic and hydrologic conditions, however, may not be adequately represented by the single-parameter exponential distributions. In order to analyze very extreme conditions adequately using probabilistic techniques, statistics of such extreme conditions are required. The intended use of these models is for the long-term performance estimation of drainage systems for urban stormwater management planning purposes.

In the following section, results obtained from the continuous simulation and analytical probabilistic modeling of the hypothetical 10 ha catchment described earlier are compared with the results obtained from the simplified approach originally published by Rousculp (1940) and from OTTHYMO.

22.3.3 Comparison of Results

In order to usefully interpret the results of the model comparisons, it is instructive to define a practical design range within which runoff control facilities would commonly operate. For the purposes of this preliminary investigation, it is assumed that a stormwater detention facility designed to attenuate peak runoff flow rates would typically exhibit drawdown times within the range of 2 to 10 hrs. Assuming a constant release rate from storage, Ω , the drawdown time, t_d , can be determined using the following expression:

$$t_d = \frac{S_A}{\Omega} \quad (22.16)$$

Figure 22.9 shows the comparison of model results for the 2 yr and 10 yr return frequencies with the practical design range delineated. As can be seen from the figure, all modeling approaches agree fairly well for the more frequent events. This results means that, at least for the higher frequency recurrence intervals, the simpler the technology the better since no appreciable loss in accuracy is exhibited.

For the 10 yr event, Figure 22.9 indicates that the simplified method proposed by Rousculp in 1940 agrees quite well with the most complicated of technologies, namely continuous simulation. Additionally, the analytical probabilistic models also agree favourably with SWMM and the simplified technique. Results generated using OTTHYMO, however, consistently over-estimate volume requirements when compared to the other methods. This result illustrates that event modeling using synthetic design storm patterns may produce overly conservative designs.

22.4 Conclusions

As engineering practice advances and produces more comprehensive and sophisticated methods for analysis, it is quite likely that older (but useful) analysis technologies may become forgotten. It is important for new generations of modelers to understand the origins of current practices and appreciate the vast array of technologies available for the even wider array of applications. The tool to be used by the analyst should be commensurate with the type of analysis to be undertaken, otherwise the analysis may suffer from inefficiency.

Figure 22.9 Comparison of modeling results.

The method published by Rousculp in 1940 is shown herein to provide reasonable estimates (relative to newer, more sophisticated methods) of required storage volumes with very little effort. Such a method can be very useful to the engineer involved in the planning of urban developments where stormwater management is required. The technology is simple to understand and easy to apply. Currently available computer spreadsheet programs are able to perform a number of numerical tasks which can enhance the power of such a simple technique. Such a spreadsheet application is discussed in further detail below and is available from the authors.

It is cautioned, however, that the modeler/analyst must be fully aware of the applicability and limitations of any technology which he/she employs. The simplified method herein is indeed limited in its range of applicability and is

intended for preliminary estimates of storage volume requirements. The detailed design of stormwater management systems is best served by more comprehensive and sophisticated approaches.

22.5 Sample Spreadsheet Application

To illustrate the power of the simplified method for estimating runoff storage requirements, a spreadsheet application is illustrated in Figure 22.10. The spreadsheet requires the following input: IDF curve parameters for the recurrence intervals to be considered; the catchment hydrology consisting of depression storage and a runoff coefficient values; and the maximum allowable release rate from storage which, for many applications, may be the pre-development runoff rates. The spreadsheet uses Equation 22.3 to determine the critical storm duration, t^* . Since this value cannot be solved analytically, numerical techniques for solution are required. Many spreadsheets are equipped with algorithms that can perform the necessary computations with minimal time requirements. Once the critical duration is found, the required storage volume is determined using Equation 22.7. The process is repeated for all recurrence intervals specified, and the critical storage volume is determined. The entire computational process may be automated and completed in seconds.

Notation

a,b,c	empirical parameters for IDF curves
i	rainfall intensity (mm/h)
IDF	intensity-duration-frequency
r	ratio of time before the peak intensity to the total storm duration (Chicago-type)
S_A	(active) storage capacity (mm uniformly distributed over catchment area)
S_d	depression storage (mm uniformly distributed over catchment area)
t	rainfall duration (min)
t^*	critical storm duration (min)
t_A	duration of rainfall prior to peak intensity (min) (Chicago-type)
t_B	duration of rainfall after peak intensity (min) (Chicago-type)
T_d	total duration of Chicago-type design storm (min)
t_d	drawdown time of storage facility (h)
T_R	average return period (yr)
t_1	time at which storage facility begins to be filled (min) (Chicago-type)
t_2	critical storm duration (min) (Chicago-type)
v	rainfall volume (mm)
V-D	volume-duration
λ, ψ, ζ	parameters for exponential probability distributions of rainfall characteristics
ϕ	runoff coefficient
θ	average annual number of rainfall events
Ω	release rate (mm uniformly distributed over catchment area per hour)

POND SIZE.XLS

Preliminary Pond Sizing Procedure

Fabian Papa, March 1997

Valdor Engineering Inc., 216 Chrislea Road, Suite 501

Woodbridge, Ontario L4L 8S5 Tel: 905/264 0054 Fax: 905/264 0069

Project: **Old Simplicity vs. New Complexity**

Date: **Feb. 21, 1997**

Proj. #: **97-001**

Analysis By: **F. Papa**

Client: **1997 SWM Conference, Toronto**

Remarks: *Estimating Volume Requirements for Runoff Storage Facilities*

Papa, Adams & Thoman

Sample Spreadsheet Application

Catchment Characteristics:

Area = 10 ha

Depression Storage = 1 mm

IDF Curve Parameters { $i = a(b + t)^c$ } and Pre-Development Flow Rates

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	
a	706.6	896.5	1018	1190	1288	1411	
b	5.9	5.6	5.3	5.3	5	5	
c	0.804	0.789	0.781	0.777	0.771	0.769	
ϕ	0.37	0.4	0.43	0.46	0.49	0.53	
Q_{PRE}	0.24	0.48	0.66	0.9	1.14	1.38	m ³ /s
Q_{PRE}	0.144	0.288	0.396	0.540	0.684	0.828	mm/min

	t^*	Q/ϕ	dv/dt	Δ	v^* (mm)	Required Storage (m ³)
2-yr:	16.7225	0.389189	0.389189	9.2E-11	16.04253	316
5-yr:	11.97088	0.72	0.72	2.9E-09	18.6373	361
10-yr:	10.81506	0.92093	0.92093	1.99E-09	20.93039	429
25-yr:	9.98293	1.173913	1.173913	4.68E-09	23.79716	510
50-yr:	9.147243	1.395918	1.395918	1.12E-10	25.46167	573
100-yr:	9.002278	1.562264	1.562264	2.11E-12	27.81643	676

Stormwater Management Pond Size Required

676 m³

This is a preliminary sizing procedure only where only rough estimates are required. The user is strongly recommended to become familiar with the procedure's underlying theoretical basis as well as with its applicability and limitations.

Figure 22.10 Sample spreadsheet application.

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