Chapter 7

Comprehensive Urban Runoff Quantity/Quality Management Modelling

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This study introduces an analysis methodology for the preliminary planning of urban runoff quantity and quality control systems. The methodology consists of five basic steps: rainfall analysis, evaluation of existing runoff conditions, prediction of runoff control system performance, determination of the least-cost combinations of control measures, and sensitivity analysis. An application is demonstrated by employing the methodology on the Barrington catchment in East York, Toronto.

7.1 Introduction

Traditionally, drainage systems have been designed primarily to

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control the quantity of urban runoff. As the deterioration of receiving water quality due to combined and/or storm sewer overflows is frequently observed in many urban centers, drainage systems are being designed or rehabilitated to provide control over both the quantity and quality of urban runoff.

Urban runoff control can be planned for both quantity and quality objectives. As a result, there is an acute need for a planning methodology which takes into consideration the performance and cost of quantity and quality control measures.

The following sections present an optimization methodology for the preliminary planning of urban runoff quantity and quality management systems. Both upstream control measures such as storage and infiltration facilities, and downstream control measures such as storage and treatment facilities can be analyzed by the proposed methodology.

7.2 Literature Review

Lager et al. (1976) developed a stormwater management planning model to evaluate the performance of storage-treatment facilities for controlling stormwater runoff. Although this model provides an extensive analysis of stormwater control, it can only be used to determine the performance of the various combinations of downstream storage and treatment alternatives. Moreover, the continuous simulation of the storage and treatment performance required is time-consuming for preliminary planning purposes.

Sullivan et al. (1978) incorporated cost and performance analyses in the assessment of the magnitude and significance of pollution loadings from urban runoff of Ontario cities. The STORM model (HEC, 1974) was employed for the development of performance isoquants (combinations of downstream storage and treatment measures that achieve the same degree of pollution control) while the least-cost combination of downstream storage-treatment measures that can achieve a certain level of pollution control was determined using the constrained cost minimization approach.

To overcome the burden of continuous simulation of control system performance, Flatt and Howard (1978) derived analytical probabilistic models for the prediction of control system performance. The analytical models were compared with the simulation model STORM and it was found that the predicted performance was close to that obtained by the STORM model. The tradeoff between storage and treatment was analyzed by employing the production theory of microeconomics.

Nix et al. (1983) and Nix and Heaney (1988) employed the production theory of microeconomics to determine the least-cost combinations of storage-release strategies. The control system performance was simulated by the SWMM model (Huber et al., 1982) and the design performance isoquant was developed from the simulation results. The least-cost mix of storage-release strategies was determined using the constrained cost minimization approach.

The approaches of Sullivan et al., Flatt and Howard, and Nix et al. and Nix and Heaney are an improvement over that of Lager because they consider control system cost explicitly in the analysis for urban runoff planning. However, the analytical probabilistic models proposed by Flatt and Howard can be improved and the least-cost analysis of Nix et al. can be extended to include upstream control measures in addition to downstream storage-treatment measures.

7.3 Urban Runoff Quantity/Quality Control Methodology Overview

Layouts of a typical combined and storm sewer system are illustrated in Figure 7.1. Rainfall fills the depression storage of a catchment and part of the remaining rainfall becomes runoff which is finally collected at a potential downstream storage site. If the storage capacity and treatment rate available is less than the runoff volume, the excess runoff volume overflows uncontrolled to the receiving water. The proposed planning methodology is

Figure 7.1: Typical layout of combined and storm sewer systems.

developed to analyze this simplified rainfall-runoff-overflow process.

An overview of the planning procedure is illustrated in Figure 7.2. Quantity analysis follows the left path of the flowchart while quality analysis follows the right path of the flowchart. Integrated quantity and quality analysis follows both the left and right paths of the flowcharts.

The above quantity control planning process starts with input rainfall analysis in which the statistical properties of rainfall event characteristics are quantified. Measures of the existing runoff conditions such as the average annual or extreme-event runoff volume are then determined using the statistical models of the methodology. These statistical models are closed-form analytical transformations of the probability density functions (pdf's) of rainfall characteristics to the pdf's of runoff characteristics. If there are existing control measures, the control performance of those measures can be assessed using the derived analytical probabilistic models.

The quality control planning process also starts with rainfall analysis which is then followed by the runoff pollution load analyses. Quality analysis of runoff pollution load is based on a constant concentration approach in which pollution load is determined as the product of an average event concentration and event rainfall volume. The next step is to determine the pollution control performance of existing control measures using the derived analytical probabilistic models.

If existing control measures cannot achieve the required level of quantity and/or quality control, additional control measures must be provided. The least-cost analysis enables the planner to evaluate different combinations of upstream and downstream control measures and to determine the most cost-effective combinations of control measures that can achieve the required level of control.

The final step is to conduct sensitivity analyses of the model parameters where the impact of uncertainty in parameter estimation on runoff control analysis is assessed. From these analyses, upper and lower bounds of the least-cost mix of control

Figure 7.2: Urban runoff control planning methodology.

measures can be determined. Details of the methodology are discussed in the following sections.

7.4 Input Rainfall Analysis

Since a probabilistic approach is used to predict runoff and control system performance, the statistical properties of input rainfall events are required. Rainfall volume is recorded continuously at rainfall gauging stations across Canada. These series of continuous rainfall pulses can be separated into individual rainfall events with respect to an interevent time definition (IETD). The IETD is defined as the minimum elapsed time with no rainfall that distinguishes one independent rainfall event from another. Rainfall pulses separated by a time larger than the IETD are considered to be separate events. Typical IETD's for urban catchments range from 1 to 6 hours.

After a continuous rainfall series is separated into events, event rainfall characteristics such as rainfall volume (v), duration (t), average intensity (i), interevent time (b), and number of events per year can be computed. Statistics of these characteristics such as the mean, standard deviation, etc. are then determined.

The probabilistic models developed for the methodology are based on statistically independent rainfall characteristics (i.e., v , t , b) which can be described by exponential probability density function (pdf's) as follows:

1. Event rainfall volume, v (mm)

$$f(v) = z \exp(-zv) \quad ; \quad z = 1/E(v) \quad (7.1)$$

2. Event duration, t (hr)

$$f(t) = l \exp(-lt) \quad ; \quad l = 1/E(t) \quad (7.2)$$

3. Event average intensity, i (mm/hr)

$$f(i) = w \exp(-wi) \quad ; \quad w = 1/E(i) \quad (7.3)$$

4. Interevent time, b (hr)

$$f(b) = k \exp(-kb) \quad ; \quad k = 1/E(b) \quad (7.4)$$

in which $f(v)$, $f(t)$, $f(i)$, $f(b)$ are the pdf's of v , t , i , b ; $E(v)$, $E(t)$, $E(i)$, and $E(b)$ are the mean value of v , t , i , b ; and z , l , w , k are the pdf parameters.

It has been found by Adams et al. (1986) and others that the exponential distribution is suitable for describing the rainfall characteristics of many cities across Canada.

7.5 Analysis of Runoff Quantity/Quality

The rainfall-runoff process is modelled by a simple runoff coefficient method in which initial rainfall is stored in depression storage and a portion of subsequent rainfall becomes runoff from the catchment. The transformation of rainfall events to runoff events is given by:

$$V_r = 0 \quad v \leq S_d \quad (7.5)$$

$$V_r = PHI (v - S_d) \quad v > S_d \quad (7.6)$$

in which V_r is the runoff event volume, v is the rainfall event volume, S_d is the depression storage, and PHI is the runoff coefficient. With the pdf of rainfall event volume (Equation 7.1), the pdf of runoff event volume can be derived analytically using derived probability distribution theory (Benjamin and Connell, 1970). The expected value of runoff event volume and the average annual volume of runoff volume can then be determined (Adams and Bontje, 1983).

The runoff quality models are derived on the basis of rainfall events. The runoff event pollution load (L_r) is the product of runoff event volume (V_r) and event flow-weighted mean concentration (C) given by:

$$L_r = V_r * C \quad (7.7)$$

thus:

$$E[L_r] = E[C] * E[V_r] + \text{COV}[V_r, C] \quad (7.8)$$

in which $E[C]$ is the expected value of C ; $E[V_r]$ is the expected value of V_r ; and $\text{COV}[V_r, C]$ is the covariance of V_r and C . If V_r and C are independent, their covariance is zero. According to the U.S. Nationwide Urban Runoff Program (U.S. EPA, 1983), C was found to be generally uncorrelated with V_r for a number of urban sites. Further analyses by Wallace (1980) also indicate that the correlation between pollutant concentration and runoff volume is weak. Therefore, the expected event runoff load ($E[L_r]$) is given by:

$$E[L_r] \approx E[C] * E[V_r] \quad (7.9)$$

and the average annual runoff pollution load (ALr) can be estimated by:

$$ALr = NR * E[Lr] \quad (7.10)$$

in which NR is the average annual number of rainfall events.

The constant concentration approach described above requires the determination of the expected value of event concentration, $E[C]$. If no runoff quality data are available for a catchment, $E[C]$ may be selected from the literature (e.g., U.S. EPA, 1983). However, it is important that the expected event concentration be selected on the basis of land use, location, hydrology and drainage system characteristics. If field data on runoff quality are available, $E[C]$ may be found from deterministic simulation (e.g., STORM) or statistical models (e.g., Driver and Tasker, 1988).

7.6 Control System Performance

The effectiveness of a runoff control system is usually measured by its long term average performance and its extreme event performance (e.g., average annual overflow volume or 5 year overflow volume). Two different approaches have been proposed for specifying runoff control system performance. The first approach is based on input control which requires the capture of a certain volume of rainfall or runoff. The second approach requires that the output from a runoff control system be limited to a certain fraction of the input. Input control performance such as the control of the 2 year rainfall volume or a half an inch of runoff volume cannot really represent the effectiveness of a runoff control system since different watershed and drainage systems react differently to the same input rainfall and runoff. As a result, it is the output control performance measures such as the average annual percent of runoff volume controlled (Cr) that are useful for describing the performance of a runoff control facility. The proposed methodology emphasizes the output control

performance in the analysis of runoff control systems.

Long-term quantity and quality control performance of a runoff control measure can be specified by: i) quantity performance measures such as the average annual percent of runoff volume controlled (C_r) and the average annual number of overflows (N_s); and ii) quality performance measures such as the average annual percent of runoff pollution load controlled (C_p) and average annual number of overflows (N_s). Both C_r and C_p can be used, for example, to represent the situation in which only a certain fraction of runoff control can provide the required benefit. On the other hand, N_s can be used, for example, to represent the situation in which every overflow event, no matter how large the overflow volume, causes damage and damage reduction is measured by the number of overflows abated.

Extreme event performance of a runoff control measure is important for quantity problems such as flooding and quality problems such as bacterial contamination because the time scale of the effect is usually short. Extreme event quantity and quality performance of control measures can be specified by: i) quantity performance measures such as the N -year event overflow volume (P_n); and ii) quality performance measures such as the N -year event pollution mass load (L_n). For instance, P_n may be used to measure the acceptable volume of overflow which the receiving water can accommodate while L_n may be used to measure the maximum allowable event pollution load in the receiving water.

The output performance of urban runoff control systems has been estimated by three different approaches: design storm event analysis, continuous simulation, and statistical models. Each approach has its own advantages and disadvantages.

Most drainage engineers are familiar with the design storm event analysis which is easy to apply and understand. However, there are numerous drawbacks of applying the design storm concept in designing urban runoff control systems (Adams and Howard, 1986).

Continuous simulation has significant advantages over the design storm approach because the entire recorded rainfall history is employed for the prediction of system performance.

Additionally, it allows detailed modelling of urban runoff processes such as the buildup and washoff of pollutants. On the other hand, continuous simulation is time-consuming for preliminary planning purposes.

Statistical models, such as the analytical probabilistic models employed in the proposed methodology, have the advantage of predicting the system performance from statistics of complete rainfall records rather than from the complete records themselves. Thus, system performance of various combinations of control measures can be investigated efficiently by the statistical models. However, statistical models lack flexibility in the detailed modelling of the control system performance because simplifying assumptions have to be made for the derivation of the relationship between input rainfall characteristics and system output performance characteristics. If statistical models predict system performance in close agreement with that obtained from calibrated continuous simulation models, they would be very useful for preliminary planning of urban runoff control systems. The proposed methodology employs analytical probabilistic models to analyze output performance of runoff control systems for this reason.

Following the pioneering work of Howard (1976), a series of developments on analytical probabilistic models was undertaken at the University of Toronto. Adams and Bontje (1983) developed a software package of analytical probabilistic models called Statistical Urban Drainage Simulator (SUDS) for the prediction of quantity performance. Details of the derivation can be found in Adams and Bontje (1983) and Adams and Zukovs (1987). Li (1991) derived analytical probabilistic models for runoff quality transformations through a storage-treatment system. The concept of the quantity and quality models is discussed in the following paragraphs. The reader is recommended to consult the aforementioned literature for details on the modelling procedure.

The layouts of the urban runoff control systems under consideration are presented graphically in Figure 7.1. The quantity control models, coded in SUDS, (Adams and Bontje, 1983) consider runoff from a catchment which is collected at a

potential downstream storage site of capacity S and released at a controlled outflow rate OMEGA . Runoff which exceeds the storage capacity and controlled release rate is spilled to the receiving water. The overflow volume is determined by the amount of runoff and the storage contents within the storage reservoir.

Volume balance relationships of rainfall-runoff-overflow are developed among the rainfall characteristics v , b , t and the catchment and drainage system characteristics PHI , S_d , S , OMEGA . These relationships are then transformed onto the joint probability space of v , b , t . The probability of overflow per rainfall event and the expected magnitude of overflow per rainfall event can then be derived. The control system performance measures such as C_r , N_s , and P_n are then derived in terms of rainfall, catchment, and drainage system characteristics (z , l , k , S_d , PHI , S , OMEGA). The depression storage S_d is used to model upstream storage and the runoff coefficient PHI is used to model upstream runoff reduction such as an infiltration facility. The storage capacity S is used to model the downstream storage reservoir volume and the controlled outflow rate OMEGA is used to model the outflow release rate from storage.

The approach used by Adams and Bontje (1983) is also used to model the transformation of runoff quality through a downstream storage-treatment system (Figure 7.1). If the runoff event volume is less than the combined capacity of available storage volume and constant controlled outflow rate to a treatment facility, no overflow occurs at the storage reservoir and the only source of pollution comes from the treated effluent. For larger runoff event volumes, part of the runoff is overflowed from the reservoir into the receiving water in addition to the treated effluent. For storm sewer systems, outfall treatment units may utilize physical or physical-chemical treatment operations of moderate efficiency. As a result, the treated effluent becomes an important long term source of pollution in addition to overflow from storage.

These quality models (Li, 1991), which have been coded in a software package called Extended SUDS, account for the

pollution contribution from treated effluent and storage overflow. Mass balance relationships have been developed among the rainfall characteristics v , b , t , the catchment and drainage system characteristics PHI , Sd , S , OMEGA , and the treatment efficiency of storage and treatment facilities N for both overflow and non-overflow conditions. These relationships are then transformed onto the joint probability space of v , b , t . The probability of exceeding a certain amount of pollution load per rainfall event and the expected magnitude of pollution load per rainfall event can then be determined. The control system performance measures such as Cp and Ln are then derived in terms of rainfall, catchment, and drainage system characteristics, as well as treatment efficiency (z , l , k , Sd , PHI , S , OMEGA , N). Upstream and downstream control systems are modelled by Sd , PHI , S , OMEGA in a manner similar to that in SUDS.

Both the SUDS and Extended SUDS models have been compared with the continuous STORM model (HEC, 1974). Kauffman (1987) found that the analytical model SUDS compared reasonably well with STORM simulation results for catchments with an average of less than 120 runoff events per year. Li (1991) compared SUDS and Extended SUDS with STORM using the data from Barrington catchment in East York, Ontario and found that Cr , Ns , Cp , Pn predicted by SUDS and Extended SUDS were in good agreement with those simulated by STORM. Figure 7.3 illustrates the comparison between the analytical models and STORM for the Barrington catchment. However, Ln predicted by SUDS and STORM was found not in good agreement and the discrepancy might be attributed to the different approach in modelling runoff pollutant generation.

Since the analytical probabilistic models are generally able to predict control system performance in close agreement with the simulation model STORM, they have been suggested for use in the preliminary analysis of existing runoff control systems and the preliminary planning of runoff control system design and rehabilitation.

Figure 7.3: Comparison of Cr isoquants (S and OMEGA mixes) from STORM and SUDS.

7.7 Least-cost Analysis

If the existing runoff condition or the existing runoff control system performance is undesirable or unable to achieve the required level of runoff control, additional runoff control measures must be provided. Preliminary planning of runoff control systems requires the determination of the most promising combinations of control measures that can achieve the required level of control so as to focus the design level analysis on those combinations of control measures. To determine the most promising combinations of control measures, cost-effectiveness relationships for different combinations of control measures should be established. By comparing those relationships, the most

promising combinations can be identified.

Cost-effectiveness relationships of different combinations of control measures can be established by determining the least-cost mixes of control measures that achieve different levels of quantity and/or quality control. A constrained cost minimization technique is employed to determine the least-cost mix of control measures that can achieve a certain level of control. The formulation of the least-cost analysis is as follows:

$$\text{minimize } CT = fc [X_i, \dots, X_n] \quad ; \quad i=1, \dots, n \quad (7.11)$$

$$\text{subject to } Y_k[X_i, \dots, X_n] \leq Y_{ko} \quad ; \quad k=1, \dots, m \quad (7.12)$$

in which CT is the total cost of providing the required control measures; $fc[X_i, \dots, X_n]$ is the total cost of providing n types of control measures (e.g., S, OMEGA); n is the total number of feasible control measures; $Y_k[X_i, \dots, X_n]$ is the control performance measure k as a function of control measures X_i to X_n ; Y_{ko} is the required control performance measure k; X_i is the control measure i; m is the total number of required control performance measures (e.g., Cr and Ns).

A graphical illustration of the optimization procedure is shown in Figure 7.4. The performance isoquants (isoquants 1 and 2) represent the combinations of control measures which achieve the same level of performance while the isocost curves (c1, c2, c3) indicate the combinations of control measures with the same total cost.

The top figure depicts the situation in which the required performance isoquants intersect. The tangency point A is the least-cost mix of control measures 1 and 2 for isoquant 1 while tangency point B is the least-cost mix of control measures for isoquant 2. The intersection point C between the isoquants is the control measures mix which achieves both isoquants exactly. However, the least-cost mix of control measures which can achieve both isoquants is point B because this combination of control measures can achieve the control of isoquant 2 and a

Figure 7.4: Illustration of the determination of least-cost mix of control measures for integrated quantity and quality control.

greater control than isoquant 1.

The lower figure indicates the situation in which the performance isoquants do not intersect. For this particular situation, one of the isoquants is dominant. As a result, the least-cost mix of control measures is point E. This two-dimensional analysis can be extended to multiple mixes of control measures such as S, OMEGA, Sd and PHI. A

microcomputer program has been written for this purpose to facilitate preliminary quantity and quality management planning of urban runoff control measures.

7.8 Sensitivity Analysis

The evaluation of engineering alternatives is subject to uncertainty both in model selection and in parameter estimation. The proposed planning methodology requires analytical models to predict control system performance and optimization models to determine the least-cost mixes of control measures. Sensitivity analysis should be conducted for each application of the methodology so that the impacts of the model assumptions and the parameter values on the analysis results can be evaluated.

Various assumptions have been made to derive the analytical probabilistic models. As a result, the sensitivity of the analytical models should be investigated in each application of the models. Input rainfall characteristics and treatment efficiency should also be varied to test the sensitivity of control performance. From these analyses, the upper and lower bounds of control system performance can be determined.

7.9 Application of Methodology

A catchment in the Barrington area of East York, Toronto is used to demonstrate the methodology. The study area is single family residential served by a storm sewer system. Its area is 17.4 ha and the estimated percent impervious is 60%. Rainfall data was collected by the East York Engineering Department. The statistics of the data were found to be comparable to the closest permanent rain gauge located at the Toronto Bloor Street. Quantity and quality data on the storm overflows were recorded by the Ministry of Environment (Mill, 1977; Kronis, 1982). The purpose of this study is to determine the most promising

combinations of control measures that can achieve long term quantity and quality control performance.

Forty-three years of continuous rainfall record at the Toronto Bloor Street gauging station were first analyzed to determine the probability density functions and statistics of rainfall characteristics such as event volume, duration, interevent time, and average intensity. It was found that exponential distributions could be used to describe these characteristics.

The analytical probabilistic model results from SUDS were then compared with the continuous simulation model STORM in terms of the performance isoquants of Cr, Cp, Ns. The performance isoquants predicted by SUDS were generally in good agreement with those simulated by STORM. Figure 7.3 presents the comparison of Cr isoquants between SUDS and STORM. Other comparisons of performance isoquants indicate similar results.

Four different types of control measures, namely upstream and downstream storage (Sd and S), runoff reduction facilities (PHI) such as infiltration facilities, and downstream treatment rate (OMEGA), are modelled by the proposed methodology. There are many combinations of these four types of control measures that can achieve the required performance. The combinations of upstream runoff reduction (PHI), downstream storage volume (S) and treatment rate (OMEGA) are examined in this study. Other combinations of control measures have been investigated with the proposed methodology for the Barrington catchment (Li, 1991).

The cost functions for the downstream detention basin (S) and microscreening facility (OMEGA) are taken from literature (Pavoni, 1977; Wiegand, 1986) while the cost function of upstream runoff reduction facilities (PHI) is assumed.

Quantity performance is modelled by Cr which ranges from 10% to 98%, while quality performance is modelled by Ns which ranges from 1 to 50 spills per year. The total and marginal costs of providing various combinations of Cr and Ns are indicated in Figure 7.5. It is noted that both the total and marginal costs increase rapidly when Cr is higher than about 70% and Ns is below about 5 spills per year. For instance, the total cost to

Figure 7.5: Total and marginal cost surfaces for integrated Cr and Ns control.

provide 98.5% runoff control and to limit spills to 1 per year is about \$3.40 per square meter of catchment while the marginal cost is about \$0.80 per square meter. The least-cost combination of S and OMEGA to provide this performance is 6.62 mm and 1.2 mm/hr, respectively.

Other least-cost combinations of control measures (e.g., S and PHI, OMEGA and PHI) are also determined and compared with those of S, OMEGA, and PHI. The most promising combination of control measures for achieving the Cr and Ns control requirement is the S and OMEGA combination (the downstream storage and treatment systems).

The sensitivities of performance measures Cr, Ns and Cp are investigated with respect to the rainfall parameters (z, l, k) and the treatment efficiency N of the downstream storage/treatment system. Each interevent time definition (IETD) results in a set of values for the rainfall characteristics. It is found that the performance measures are generally not sensitive to the variation of IETD. However, the performance measure Cp is sensitive to the variation of N as would be expected.

The sensitivities of the total and marginal costs of achieving Cr, Ns, and Cp are investigated with respect to the rainfall parameters (z, l, k) and the parameters of the cost functions for control measures. The total and marginal costs of the least-cost mix of control measures are found to be generally insensitive to the variation of IETD and sensitive to the variation of cost parameters of the downstream storage/treatment system. The uncertainty in cost parameters can cause up to 50% change in the total costs and 70% change in the marginal cost of achieving high levels of runoff quantity and quality control. These changes in cost are attributed to the changes in the design (i.e., magnitudes of S and OMEGA). Therefore, it is imperative to use accurate local cost data to conduct the runoff control planning.

7.10 Conclusions

As the deterioration of urban water quality continues and the need

to control runoff quantity problems such as flooding and erosion still prevails in many areas, an integrated approach to control both urban runoff quantity and quality problems becomes eminent. The techniques discussed above provide a comprehensive and systematic methodology for preliminary planning and screening of urban runoff quantity and quality control systems.

With the development of analytical probabilistic models such as SUDS and Extended SUDS, preliminary prediction of urban runoff control system performance can be efficient and reliable. Although the assumptions of the analytical models may not be perfectly satisfied in every application, the models may still be useful for preliminary evaluation of urban runoff control system alternatives.

Least-cost analysis of urban runoff control systems provide important information such as cost-effectiveness relationships and expansion paths for achieving various levels of runoff control. This information is useful for specification of the target design performance and subsequent design level analyses of control systems. Since the cost and performance of control systems are explicitly taken into consideration, the proposed runoff control planning methodology extends conventional engineering analysis which emphasizes an approximate performance analysis of runoff control with rather arbitrary design levels.

Future improvements to the methodology are encouraged to incorporate receiving water quality analysis in urban runoff control system planning. The probabilistic model of stream quality proposed by Di Toro (1984) offers some insight to modelling the impact of urban runoff on receiving water quality. The analytical probabilistic models SUDS and Extended SUDS should also be further verified with field data as well as other continuous simulation models.

7.11 References

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7.12 Nomenclature

ALr	: Average annual runoff pollution load,kg
b	: Interevent time, hr
ci	: Isocost cost function i, \$
C	: Event flow-weighted mean concentration, mg/L
Cr	: Average annual percent of runoff volume controlled, %
Cp	: Average annual percent of runoff pollution controlled, %

CT	: Total cost of control measures, \$
E(b)	: Mean value of b, hr
E(i)	: Mean value of i, mm/hr
E(t)	: Mean value of t, hr
E(v)	: Mean value of v, mm
fc	: Cost function of control measures, \$
i	: Event average intensity, mm/hr
IETD	: Interevent time definition, hr
k	: Reciprocal of mean of b, 1/hr
l	: Reciprocal of mean of t, 1/hr
Lr	: Event runoff pollution load, kg
Ln	: N-year event pollution load, kg
m	: Number of control performance measures
Ns	: Average annual number of spills
pdf	: probability density function
PHI	: Runoff coefficient, dimensionless
Pn	: N-year event overflow volume, mm
S	: Downstream storage capacity, mm
Sd	: Depression storage, mm
t	: Event rainfall duration, hr
v	: Event rainfall volume, mm
Vr	: Event runoff volume, mm
w	: Reciprocal of mean of i, hr/mm
Xi,	: Control measure type i
Xn,	: Control measure type n
Yk	: Control performance type k
Yko	: Required control performance type k
z	: Reciprocal of mean of v, 1/mm
OMEGA	: Downstream outflow control rate, mm/hr