

SELECTED APPROACHES TO URBAN WATERSHED RESPONSE MODELING

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INTRODUCTION

In recent years, the modeling of urban watershed response to hydrologic input has experienced significant development. Modeling detail for analytic purposes ranges from city block and street analyses to lumped tributary area analyses. The diverse needs for hydrologic information in both urban and rural areas have spawned a plethora of mathematical hydrologic models, which were usually designed initially for single purposes and which later, after several programming changes, became more general. Some models, however, were intentionally developed along general principles with universal application as the final goal.

This paper outlines several water quantity and quality modeling systems that in our judgment are well documented, sufficiently verified (in some cases only regionally), and easily calibrated. The objective of our review is to provide an introduction to the various models now being used to evaluate urban watershed response in runoff and water quality. This discussion is not all-inclusive; there certainly exist other models which would meet the criteria mentioned above, but which, in our opinion, have not been extensively applied to the solution of general hydrologic problems.

The water quantity and quality modeling systems described here include the U.S. Environmental Protection Agency Storm Water Management Model (SWMM), the U.S. Army Hydrologic Engineering Center Urban Storm Water Runoff Model (STORM), the Illinois Urban Drainage Area Simulation Model (QUAL-ILLUDAS), and the Espey and Winslow model (QNTQAL).

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STORMWATER QUALITY MODELS

The scope of modeling capabilities of the four models in this category ranges from detailed analyses to approximate or "first cut" solutions. The water quality methodologies of these models are constantly being revised and updated as new data are acquired and new analyses are conducted. Consequently several versions of each model may be available.

The Storm Water Management Model (SWMM)

The U.S. Environmental Protection Agency (1971) Storm Water Management Model (SWMM) evaluates existing and future phenomena associated with runoff from specific areas. Through simulation, responses of a system to existing and proposed development plans can be introduced, and recommendations aimed at minimizing the consequences of development may be formulated.

The SWMM, a comprehensive mathematical hydrologic-economic model, was developed under sponsorship of the EPA. The model generates hydrographs and pollutographs (time-varying quality concentrations) for real storms, and may be used to evaluate the effect of storage on reducing flow rates and pollutant loadings. Input data for the model consist of basic physical parameters that define the watershed runoff characteristics. These are the soil infiltration rates, interception storage, land slopes, channel cross-sections and slopes, amount of impervious area, and land use. The model uses these parameters and a standardized rainfall pattern to generate and route flows and water quality constituents through the watershed. Although the model was initially developed to simulate storm flows in closed sewer systems, the model capabilities have been expanded to reflect natural drainage phenomena.

The Executive Block controls all activity within the model because all input/output functions for the other blocks are programmed into the Executive Block. The Runoff Block computes the quantity and quality of runoff for a given storm and stores the results in the form of hydrographs and pollutographs at inlets to the main sewer system. The Transport Block sets up initial flow and infiltration conditions and then performs flow quantity and quality routing to produce combined flow hydrographs and pollutographs for the total drainage basin and at selected intermediate points. The quantity and quality of flow is stored and treated by predefined criteria in the Storage Block. The dispersion effects of the discharge in the receiving body of water are computed in the Receiving Water Block.

In general, only one or two computational blocks as well as the Executive Block are used in a run, but all blocks may be run together. The use of independent computation blocks allows examination of intermediate results.

TABLE 1
MODELING REQUIREMENTS OF SWMM
(Environmental Protection Agency, 1971)

- Item 1. *Define the Study Area*
Land use, topography, population distribution, census tract data, aerial photos, area boundaries.
- Item 2. *Define the System*
Plans of the collection system to define branching, sizes, and slopes. Types and general locations of inlet structures.
- Item 3. *Define System Specialties*
Flow diversions, regulators, storage basins.
- Item 4. *Define System Maintenance*
Street sweeping (description and frequency), catchbasin cleaning, trouble spots (flooding).
- Item 5. *Define the Receiving Waters*
General description (estuary, river, or lake). Measured data (flow, tides, topography, water quality).
- Item 6. *Define the Base Flow (DWF)*
Measured directly or through sewerage facility operating data. Hourly variation and weekday vs. weekend. DWF characteristics (composited BOD and SS results). Industrial flows (locations, average quantities, quality).
- Item 7. *Define the Storm Flow*
Daily rainfall totals over an extended period (6 months or longer) encompassing the events studied. Continuous rainfall hyetographs, continuous runoff hydrographs, and combined flow quality measurements (BOD and SS) for the events studied. Discrete or composited samples as available (describe fully when and how taken).
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The data required to model an urban watershed are listed in table 1. Line printer tabulations of specified hydrographs and pollutographs are produced by the program.

Recently expanded SWMM capabilities include subroutines to determine base flows and the relative costs of alternative drainage systems, and to evaluate the effects of porous pavement parking lots on the hydrologic response of an urbanizing watershed. By using site characteristic data, base-flows resulting from the interflow portion of the hydrologic cycle may be computed. Groundwater flow may be used as a constant, linearly varying, or logarithmic function. Groundwater flows are added to the surface runoff

and a total hydrograph is produced. The cost subroutine accounts for time-varying costs by use of the Engineering News-Record Cost Index. Porous pavements are modeled as two hydraulically connected control volumes for which the inflow and outflow conditions are controlled by the equation for continuity or conservation of mass. Inflow to the porous pavement area is determined as the sum of direct rainfall onto the pavement and the overland flow hydrograph. The outflow is the sum of vertical seepage losses, horizontal seepage losses, surface runoff when the porous pavement storage capacity is exceeded, and evaporation losses.

Initially, the pollutant loading rates used in the SWMM were a function of curb length and street cleaning frequency only, because the dust and dirt loading per foot curb was a fixed value established by a study done in Chicago by the American Public Works Association (1969). An optional mode in the SWMM allows all loading rates to be added by the user. A maximum of twenty land uses can be studied, and loading rates can be specified as a function of any convenient parameter that the user selects. The

TABLE 2
QUANTITY ANALYSIS

Runoff Quantity (Coefficient Method)

$$r = C(P-f)$$

Where:

$$\begin{aligned} r &= \text{Runoff in inches per hour} \\ P &= \text{Hourly precip or precip + melt} \\ f &= \text{Land surface depression storage} \\ C &= \text{Composite runoff coefficient} \\ &= C_p + (C_i - C_p) L \\ &\quad \sum_{i=1} X_i F_i \end{aligned}$$

Where:

$$\begin{aligned} C_p &= \text{Runoff coefficient for pervious surfaces} \\ C_i &= \text{Runoff coefficient for impervious surfaces} \\ X_i &= \text{Area in land use } i \text{ as a fraction of total watershed area} \\ F_i &= \text{Fraction of land use } i \text{ that is impervious} \\ L &= \text{Total number of urban land uses} \end{aligned}$$

$$f = f_o + N_d k, f \leq D$$

Where:

$$\begin{aligned} f &= \text{Available depression storage (inches) at beginning of rainfall} \\ f_o &= \text{Available depression storage after previous rainfall} \\ N_d &= \text{Number of dry days since previous rainfall} \\ k &= \text{Recovery factor (inches/day) representing recovery (evapotranspiration)} \\ D &= \text{Maximum available depression storage} \end{aligned}$$

pollutant washoff rate, which is a function of storm intensity and duration, can also be calibrated. This approach allows the SWMM to be used in all areas for which the pollutant loading rates are site specific.

It has been determined that for specific watersheds, total pollutant loading in units of pounds per acre is a function of total inches of runoff, and also that a unique relationship exists between cumulative runoff and pounds of pollutants (Diniz and Espey, 1976). The pollutant loading relationship is used to determine a total pollutant mass relationship, which can provide a flow-dependent mass transport rate to be used in the SWMM to develop a pollutograph.

The Urban Storm Water Model (STORM)

The STORM model (Abbott, 1976) provides the same model flexibility and internal editing of computational results as the SWMM. The Executive Module controls all functions in the individual computational modules (Runoff, Route and Combine, Stream Quality, and Post Processor). The model uses simple yet classical methods for determining the runoff components. Initially programmed for the Rational method, a recent option allows for the use of the Soil Conservation Service curve number technique as shown in table 2 (opposite) and figure 1 (p. 34).

The Illinois Urban Drainage Area Simulator (QUAL-ILLUDAS)

The dominant feature of the QUAL-ILLUDAS is that it accommodates runoff from the paved areas of the basin that are directly connected to the storm drainage system, from contributing grassed areas, and from supplemental paved areas that are not directly connected. The principal elements of the computational procedure are as follows: equal time increments of rainfall are applied to a small sub-basin of the total urban basin (see figure 2); next a computation is made of the travel time required for each increment of runoff to reach the inlets at the downstream end of the sub-basin. In this way a surface hydrograph is provided for each sub-basin. These surface hydrographs from each sub-basin are accumulated in order, downstream through the basin. The accumulation of inflow hydrographs is routed through each section of pipe to accommodate the temporary storage within each pipe section. The result is a computed outflow hydrograph from each section of the pipe, and this is ultimately provided at the outlet of the total basin.

The QUAL-ILLUDAS is applied by first dividing the basin to be studied into sub-basins. A sub-basin is normally a part of the basin contributing to a single inlet or set of inlets into one storm drain pipe. Two physical factors must be evaluated for each sub-basin. First, the paved area directly connected to the storm drainage system, the supplemental paved area, and the grassed area must be determined; second, the travel time must be cal-

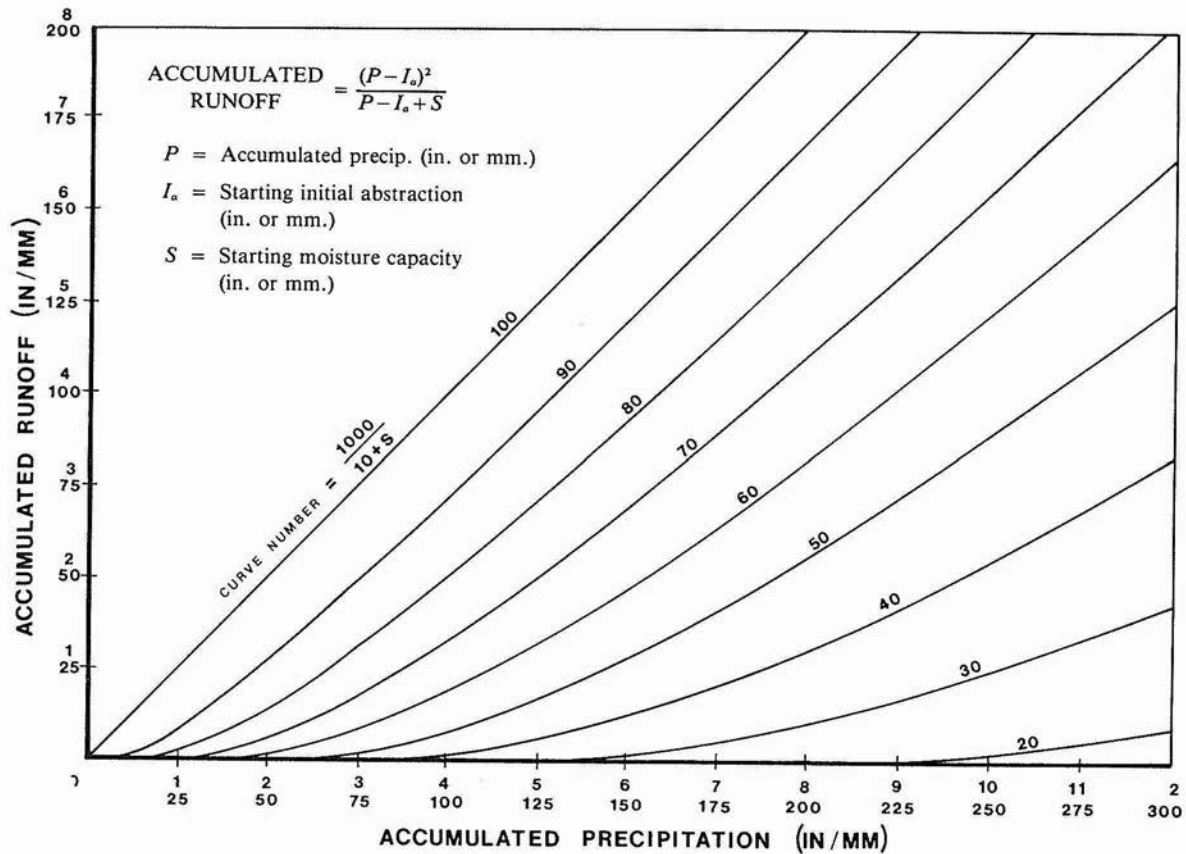


FIG. 1. SCS RUNOFF PROCEDURE

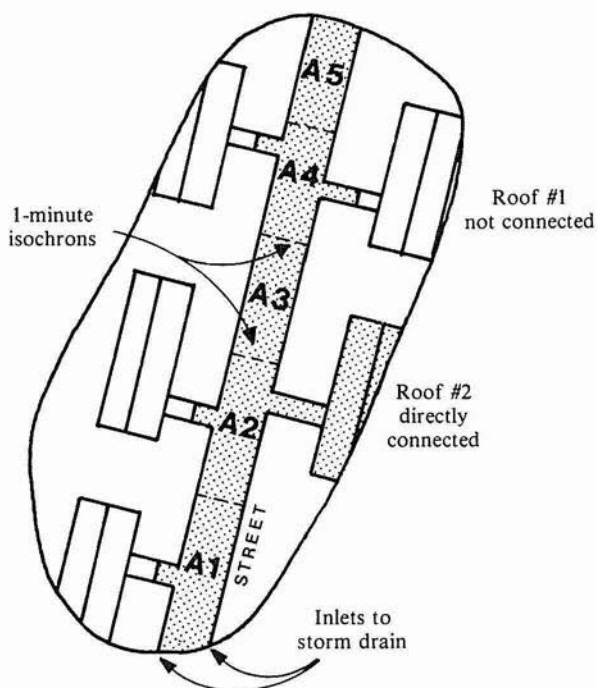


FIG. 2. SUB-BASIN MAP (DIRECTLY CONNECTED PAVED AREA SHADED)

culated for flows on paved and grassed areas and in gutters. Travel time is determined by application of Manning's equation for a specified length, slope, and runoff rate of 1 cfs./acre.

A simple storage routing technique is used to pass the hydrograph from one input point to the next. In order to use this technique, a deterministic relationship must exist between discharge and storage for the reach or channel or pipe between the input points. Such a relationship is developed by first using Manning's equation to compute a stage-discharge curve for the cross section in question. Since the length and geometry of the reach are known, the required discharge-storage relationship may be computed by assuming uniform flow in the particular reach. Errors incurred by this assumption are minimized by keeping the time increment and reach length as short as practical (Stall and Terstriep, 1972).

The water quality computational scheme in the QUAL-ILLUDAS is identical to that used in the SWMM with the exception of the initial pollutant loading rates. Either user-supplied loading rates may be provided (as in SWMM) or pre-programmed national average loading rates may be specified. As with SWMM, the same option applies to the pollutant washoff

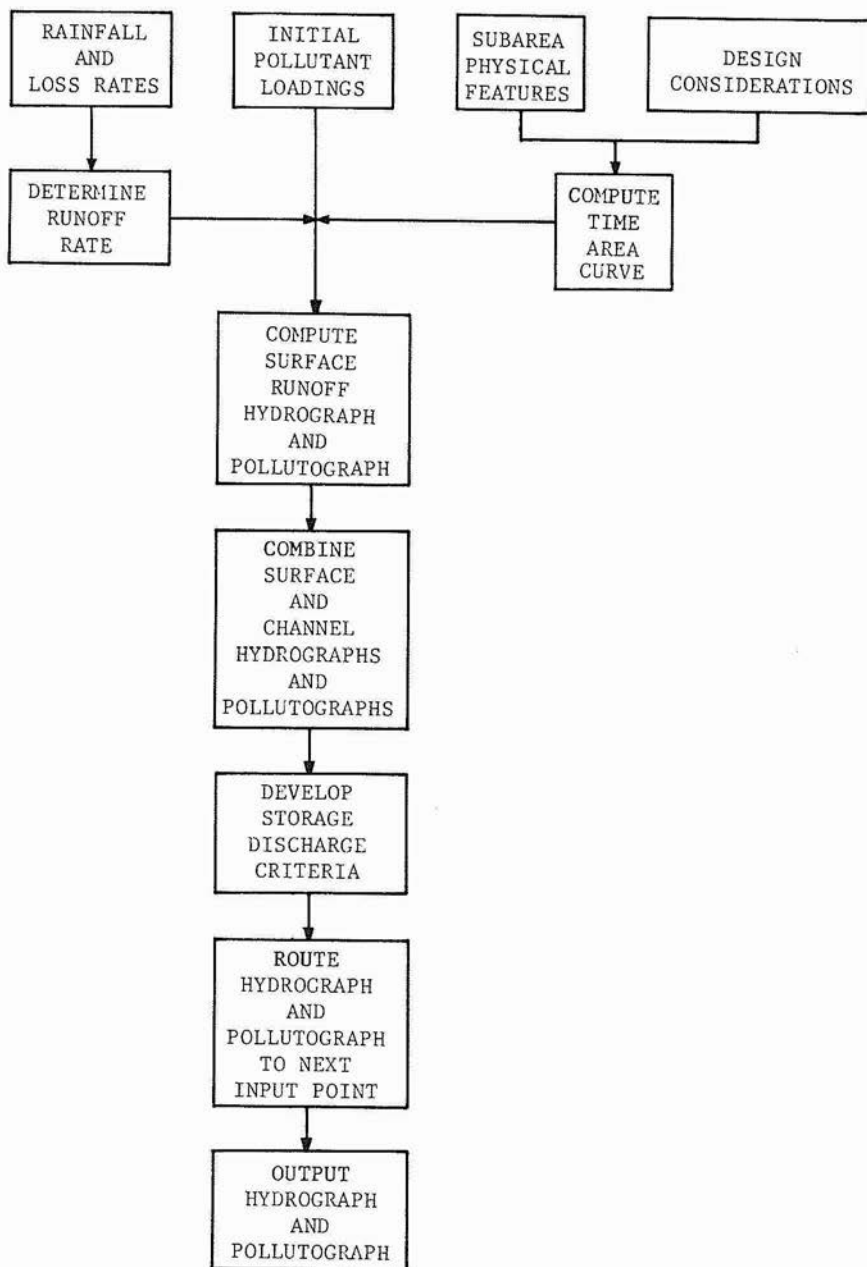


FIG. 3. GENERAL PROGRAMMING ROUTINE IN QUAL-ILLUDAS

exponent. The general programming routing for QUAL-ILLUDAS is shown in figure 3.

The Espey and Winslow Model (QNTQAL)

This runoff and water quality model uses empirically derived unit hydrograph, rainfall runoff rates, stream channel routing, critical rainfall events, and water quality equations to determine the hydrographs and pollutographs from a particular area for varying land-use projections. The model is composed of two interfaced computer programs, which together perform the desired computations as shown in figure 4.

Espey and Winslow (1972) developed equations to predict the shape of the 30-minute unit hydrograph for Houston area watersheds. To define the shape, the following five parameters were chosen:

- T_r , the time of rise, in minutes,
- Q , the peak discharge, in cfs.,
- T_b , the base time, in minutes,
- W_{50} , the time, in minutes, between the points on the hydrograph when the discharge is half the peak discharge, and
- W_{75} , the time, in minutes, between the points on the hydrograph when the discharge is three-fourths the peak discharge.

The definitions of these parameters are shown for a typical hydrograph in figure 5. These five parameters were developed for average 30-minute unit hydrographs for 33 urban watersheds, eleven of which are located in Houston. The equations shown in figure 5, which define each unit hydrograph parameter in terms of physiographic characteristics of the watershed or other unit hydrograph parameters, were then developed using multiple linear regression. The physiographic parameters used in the equations are also defined in figure 5. The parameter Φ is defined as the sum of Φ_1 , the channel improvement factor, and Φ_2 , the channel vegetation factor.

To predict the runoff hydrograph for a given storm using the unit hydrograph, a relationship between the amount of rainfall and the amount of runoff was determined by multiple regression analysis of 142 storms for 21 Houston area watersheds. The following equation was obtained to predict the runoff for a given rainfall and watershed condition:

$$\text{RUN} = 0.325 R^{1.23} M^{0.23} I^{0.067} S I^{0.12}$$

where RUN is the total runoff in inches,

R is the total rainfall in inches,

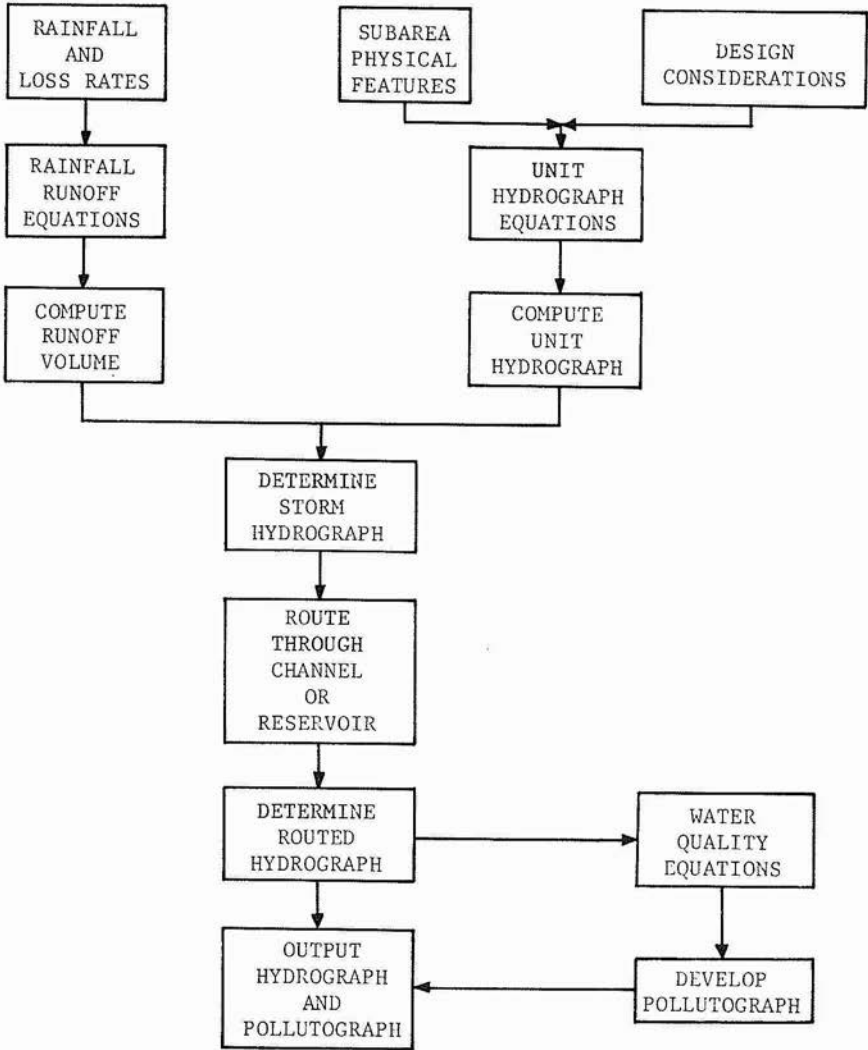


FIG. 4. GENERAL PROGRAMMING ROUTINE IN QNTQAL

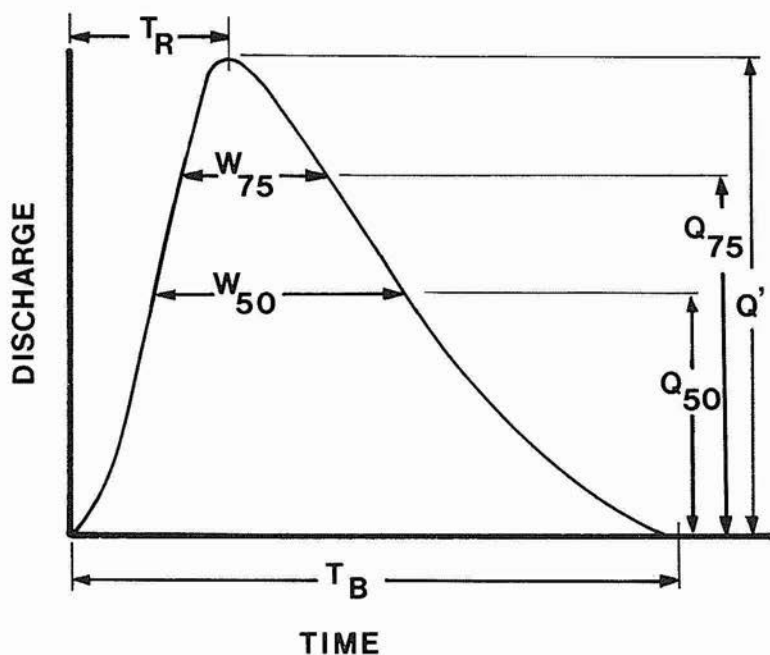


FIG. 5. UNIT HYDROGRAPH PARAMETERS

$$T_r = 16.4 \Phi L^{0.316} I^{-0.490} S^{-0.0488}$$

$$Q = 3.54 \times 10^4 A^{1.0} T_r^{-1.10}$$

$$T_b = 3.67 \times 10^5 A^{1.14} Q^{-1.15}$$

$$W_{50} = 4.14 \times 10^4 A^{1.03} Q^{-1.04}$$

$$W_{75} = 1.34 \times 10^4 A^{0.92} Q^{-0.94}$$

A is the drainage area of the watershed in square miles

L is the length of the main channel in feet

S is the slope of the main channel in feet/foot

I is the percentage of impervious cover for the drainage area

Φ is an urbanization factor defined below

Φ_1	CLASSIFICATION	Φ_2	CLASSIFICATION
0.6	Extensive channel improvement and storm sewer system, closed conduit channel system	0.0	No channel vegetation
		0.1	Light channel vegetation
		0.2	Moderate channel vegetation
0.8	Some channel improvement and storm sewers; mainly cleaning and enlargement of existing channel	0.3	Heavy channel vegetation
1.0	Natural channel conditions		

M is the soil moisture index,

I is the percentage of impervious cover, and

SI is the soil index, maximum permeability in inches per hour.

The primary source of data used to develop the water quality model was USGS records for five watersheds in the Houston area. These watersheds were selected for analysis because of the similarity of their development to that proposed for the study area and because there was no known industrial and municipal sewage discharge upstream of the stations.

TABLE 3
EQUATIONS OF BEST FIT FOR THE
THIRTEEN WATER QUALITY CONSTITUENTS*
(Espey & Winslow, 1972)

- 1) Suspended Solids, $\text{mg}/\ell = 21.55 + 4.36 \text{ LOG } (Q/A)$ for $Q/A \leq 0.75$
Suspended Solids, $\text{mg}/\ell = 37.83 + 134.7 \text{ LOG } (Q/A)$ for $Q/A > 0.75$
- 2) Dissolved Solids, $\text{mg}/\ell = 155.02 - 40.25 \text{ LOG } (Q/A)$
- 3) Ammonia, $\text{mg}/\ell = 0.465 - 0.078 \text{ LOG } (Q/A)$
- 4) Organic Nitrogen, $\text{mg}/\ell = 0.306 + 0.071 \text{ LOG } (Q/A)$
- 5) Nitrates, $\text{mg}/\ell = 0.188 + 0.148 \text{ LOG } (Q/A)$
- 6) Total Phosphorus, $\text{mg}/\ell = 0.0366 - 0.957 \text{ LOG } (Q/A)$ for $Q/A \leq 0.305$
Total Phosphorus, $\text{mg}/\ell = 0.508 - 0.042 \text{ LOG } (Q/A)$ for $Q/A > 0.305$
- 7) BOD, $\text{mg}/\ell = 4.11 - 0.282 \text{ LOG } (Q/A)$
- 8) COD, $\text{mg}/\ell = 34.43 + 10.12 \text{ LOG } (Q/A)$ for $Q/A \leq 5.6$
COD, $\text{mg}/\ell = 46.32 - 5.77 \text{ LOG } (Q/A)$ for $Q/A > 5.6$
- 9) Fecal Streptococci, 1000 counts/100 ml = $1010 (Q/A)^{3.24}$ for $Q/A \leq 0.22$
Fecal Streptococci, 1000 counts/100 ml = $15.35 (IQ/A)^{0.472}$ for $Q/A > 0.22$
- 10) Total Coliform, 1000 counts/100 ml = $17.4 (\text{Fecal Strep})^{1.463}$
- 11) Fecal Coliform, 1000 counts/100 ml = $0.152 (\text{Total Coliform})^{0.767}$
- 12) Total Insecticides, $\mu\text{g}/\ell = 0.269 + 0.11 \text{ LOG } (Q/A)$
- 13) Total Herbicides, $\mu\text{g}/\ell = 0.158 + 0.038 \text{ LOG } (Q/A)$

*All logarithms are base 10.

Q/A is flow/area.

For every percent increase in imperviousness over a base of 10% imperviousness, concentrations increase 1.35%.

For every unit increase in family per dwelling unit over a base of one family per dwelling unit, concentration increases 20.9 percent.

To use the data compiled from 62 samples from the five watersheds as a basis for predicting water quality, each of the water quality constituents was plotted against the logarithm of the unit discharge, which is defined as the flow rate at the time of the sample divided by the drainage area in square miles. Reasonable trends were established for all parameters except total coliform, fecal coliform, and fecal streptococci. For fecal streptococci the logarithm of the bacterial count instead of the count itself was plotted against the log of the unit discharge. The logs of the total and fecal coliforms were then plotted against the log of fecal streptococci count. Listed in table 3 (opposite) are the final equations obtained for all thirteen water quality parameters.

SUMMARY

The very brief descriptions of the models presented in this paper indicate the different types of modeling schemes available for the analysis of runoff and water quality problems. The level of accuracy in the modeling results is not necessarily proportional to the modeling detail, but rather to the competent selection of the input data variables. Therefore, it is imperative that the user be fully aware of the limitations of the model being used and the quality of data being supplied to the model. In many instances valid results can be obtained by judicious application of valid data to a simple model, rather than by the use of a highly complex model.

Of course, as more data become available, especially with regard to water quality, the modeling methodologies can be further tested and verified. Also new methodologies will emerge because of the present intensity of effort towards this goal in the academic and professional realms.

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