# URBAN HYDROLOGY--STATE OF THE ART[1]

by

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## INTRODUCTION

Fast removal of storm water, a luxury in the early nineteenth century, is essential to modern living. Urban drainage systems have grown from primitive ditches and stepping stones to today's complex networks of curbs, gutters and miles of underground conduits. Along with the increasing complexity of these systems has come the need for a more thorough understanding of basic hydrologic processes. Simple rules-of-thumb and crude empirical formulas are inadequate. The approximation of maximum rates of flow to be expected with some relative frequency is no longer sufficient for modern design. Management of urban waters on a day-to-day basis requires continuous time histories. Accordingly, we must represent all key hydrologic processes and unite them in composite models which can determine outputs at points of interest in time and space. In addition, demands by society for better environmental control require that quality be superimposed on estimates of quantity so management of the total water resource can be effected.

## SOME HISTORY

Methods used for estimating quantities of storm water runoff from urban drainage areas may be classified as: the rule-of-thumb approach; the macroscopic approach; the microscopic approach; and continuous simulation.

### The Rule-of-Thumb Approach

An early statement about urban rainfall-runoff was precipitated by the storm of June 20, 1857 on the Savoy Street sewer in London. One inch of rain fell in 75 minutes producing a maximum flow of 0.34 cubic feet per second per acre. Based upon information then available, the distinguished engineers Bidder, Hawksley and Bazalgette concluded that 0.25 inches of rainfall would contribute about 0.125 inches to the sewer, and 0.40 inches would yield approximately 0.25 inches to the sewer. At this time, a general English rule-of-thumb was that about 50 percent of rainfall would appear as runoff from urban surfaces. These early guidelines were forerunners of modern urban hydrologic models.

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[1] Presented at the Joint Annual Meeting of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, Tucson, Arizona, May 4, 1973.

## Macroscopic Approach

Following the early rules-of-thumb, empirical formulae became the principal mechanism for determining amounts of urban runoff. Most second-generation approaches were macroscopic. They are characterized by : (1) consideration of the entire drainage area as a single unit; (2) estimation of flow at only the most downstream point; and (3) the assumption that rainfall is uniformly distributed over the drainage area. The foremost example of this approach is the Rational Method. It was introduced by Emil Kuichling in 1889 and was based on four years of rainfall data using non-recording raingages and one year of runoff data estimated from pairs of white-washed sticks. Five open ditches were used for flow determination.

The Rational Method is described by the statement $Q = ciA$, where $Q$ equals peak runoff rate in cfs, $c$ is a runoff coefficient (the ratio of an instantaneous peak runoff rate and a rainfall rate averaged over a time of concentration), and $A$ is the drainage area in acres. The Rational Method has been used for over half a century with little change in its original form. It is the standard method of urban storm drainage design today. Persistence in the use of this formula can be attributed to its simplicity. The present analytical effort in urban hydrology should bring about some change in design concepts, but new techniques should not sacrifice the practicing profession's desire for easy-to-apply procedures. In fact, sophisticated models might serve a useful purpose in evaluating parameters for simpler procedures which can be applied to routine problems.

A second example of the macroscopic approach is the unit hydrograph method developed by Leroy K. Sherman in 1932. The unit hydrograph is the hydrograph of one inch of runoff from a drainage area produced by a uniform rainfall lasting one unit of time. Once determined, the unit graph can be used to construct the hydrograph for a storm of any magnitude and duration. Until recent times, the unit hydrograph concept was applied mainly to river basins, but it is now being adapted to urban networks as well. The concept of the instantaneous unit hydrograph has been a major factor in this expansion to use in urban hydrology. The instantaneous unit hydrograph operates on an effective precipitation applied in zero time. This is unreal but the assumption makes the hydrograph independent of duration of effective precipitation and eliminates one variable from hydrograph analysis. A number of models using an instantaneous unit hydrograph or an approximation of it have been reported in the literature.2, 11, 13/ One of the pioneers was J.E. Nash.8/

## Microscopic Approach

The microscopic approach is characterized by an attempt to quantify all pertinent physical phenomena from the input (rainfall) to the output (runoff).4, 6, 9/ This usually involves the following steps: (1) determine a design storm; (2) deduct losses from the design storm to arrive at an excess rainfall rate; (3) determine the flow to the gutter by overland flow equations; (4) route the gutter flow; (5) route the flow in pipes; and (6) determine the outflow hydrograph. The result obtained is affected by the accuracy of determination of losses and hydraulic phenomena and the validity of simplifying assumptions. If errors are small and non-cumulative, the prediction of runoff is valid.

Tholin's Hydrograph Method (Chicago, 1957) is a good example of the microscopic approach.14/ The procedure is to: (1) develop a design storm pattern from local intensity duration-frequency curves and an average chronological storm pattern; (2) compute overland flow using selected infiltration capacity curves, estimated depth of rainfall retained in surface depressions, and Izzard's overland flow equations; (3) route overland flow through gutters using the storage equation to obtain the runoff into catchbasins; (4) route sewer supply hydrographs from roofs and street inlets along a typical headwater sewer lateral to produce a lateral outflow hydrograph; and (5) route the lateral outflow hydrograph by a time offset method along sub-mains and the main sewer to a point of discharge. Tholin provides charts to facilitate computation.14/

Until recently, most microscopic procedures delt solely with individual storm events. With the advent of modern computers, the trend has been more toward continuous simulation of hydrologic processes.3, 12/

## SIMULATION

Crawford and Linsley state that simulation is an indirect approach to the study of the behavior or response of a system. Systems may be simulated by physical models, analog models or digital models. Digital simulation is a more recent method used to analyze large and complex systems. It has the advantage of high speed and does not require extensive hardware often needed for physical or analog models. The digital program itself becomes the model, and its parameters can be changed to allow for experimentation or to represent any particular condition of interest. Simulation of the hydrologic system through use of models has many virtues. The model can be much more easily operated and observed than the real system. Another important advantage is that it is possible to compress real time scales on the order of years to time scales on the order of minutes. As a result, long periods of time can be successfully studied.

Digital simulation expresses physical systems in mathematical terms which involve various parameters. These mathematical models are improved and verified by simulating the systems reaction to known inputs and outputs, continuing until the model is considered to be a reliable representation of the prototype. The procedure is analogous to that of verifying a physical model. Once this has been accomplished, the model can be used for a variety of purposes including project planning and operation. Seasonal effects, impact of land management practices, and many other situations of practical interest can be modeled.

### Simulation Using Equations of Gradually Varied Unsteady Flow

Equations for gradually varied unsteady flow in open channels have been used to describe relationships between rainfall and area, depth, velocity and rate of flow of surface runoff since about 1960.10,15/ Conservation of mass and momentum of surface runoff at any point in space and time are accounted for. Because the equations are complex, numerical methods are resorted to for solutions.

The first descriptive equation is a continuity equation written as:10/

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

This equation is derived by considering the water entering and leaving an infinitesimal section of channel (Figure 1). The term $\partial A/\partial t$ accounts for the change in storage with time in the infinitesimal section; the term $\partial Q/\partial x$ accounts for the difference between the outflow and the inflow to the infinitesimal section; and the term $q$ is the lateral inflow in cfs/ft along the channel.

The second equation (the momentum equation) refers to the dynamic behavior of the flow. It is written as:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial H}{\partial x} + g(S_f - S_o) + \frac{Vq}{A} = 0$$

and derived by considering all of the forces acting on a fluid element. Neglecting the first and last terms, the remaining terms are commonly used to compute backwater profiles for steady flow in reservoirs and stream channels. The first term, $\partial V/\partial t$, accounts for the local acceleration of the fluid. The convective terms, $V\frac{\partial V}{\partial x}$ and $g\frac{\partial H}{\partial x}$, relate to changes in kinetic and potential energy respectively. The terms $gS_f$ and $gS_o$ account for friction along the channel and the component of gravitational force in the direction of flow, respectively. The last term, $qV/A$, accounts for momentum that must be imparted to the lateral inflow by the water flowing in the channel.

The most important term in the dynamic equation is the friction term $S_f$. Since its magnitude is usually larger than any of the other terms except $S_o$, the method of evaluating $S_f$ is important. A uniform flow formula is generally used to determine $S_f$. Where flows are laminar, the Darcy-Weisbach formula is suitable.

$$S_f = \frac{f}{H}\frac{V^2}{2g}$$

Manning's equation is used for turbulent flows.

$$S_f = \left(\frac{nV}{1.486\ r^{2/3}}\right)^2$$

It is generally assumed that the value of $S_f$ occurring for gradually varied unsteady flow anywhere in a drainage basin is the same as the value of $S_f$ at the same velocity and hydraulic radius for uniform steady flow at that point. The error introduced by this assumption is probably less than the error involved in selecting proper values for the coefficients in the foregoing equations for $S_f$.10/

Assumptions used in deriving the equations of flow normally include: (1) Accelerations normal to the direction of flow have been neglected. (2) Velocities normal to the direction of flow have been neglected. (3) Velocities are assumed uniform throughout a section normal to the direction of flow. This assumption is more restrictive than necessary since coefficients can be introduced into the dynamic equation to account for a variable velocity profile. (4) Frictional resistance is assumed to be the same as for steady uniform flow at the same velocity and depth of flow. The importance of these assumptions has been thoroughly studied.3, 10, 15/

The equations of flow written in finite form become

$$\frac{\Delta A}{\Delta t} + \frac{\Delta Q}{\Delta x} = q$$

$$\frac{\Delta V}{\Delta t} + \frac{\Delta V}{\Delta x} + g \frac{\Delta H}{\Delta x} + g(S_f - S_o) + \frac{qV}{A} = 0$$

To be computationally useful, the solution of the finite difference equations should approach the solution of the partial differential equations as $\Delta x \to 0$ and $\Delta t \to 0$. The strategy followed is to divide the channel into a number of intervals of length, $\Delta x$, and then solve the difference equations for $A(x,t + \Delta t)$ and $V(x,t + \Delta t)$ at successive intervals of time. Examples of the application of such equations to modeling urban runoff are well documented.10,15/

## Stanford Watershed Model

This model, or modifications of it, has had more applications in recent years than other deterministic ones because of its versatility. Basically, the model simulates snow pack and soil profile processes and calculates continuous soil moisture, evapotranspiration, groundwater accretion and inflow to stream channels. It assembles and routes channel inflows through the channel network and reservoirs. The model includes all major hydrologic processes and considers the surfacewater-groundwater linkage. The model must be calibrated to each watershed from existing records of rainfall and streamflow. Input parameters required are rainfall, potential evapotranspiration and physical descriptors of the watershed and hydrologic properties. If snow melt is involved, additional input parameters are required.

Three zones of moisture regulate soil moisture profiles and groundwater conditions. The rapid response encountered in smaller watersheds is accounted for in an upper zone, while upper and lower zones control such factors as overland flow, infiltration and groundwater storage. A lower zone is responsible for long-term infiltration and groundwater storage which later becomes base flow. Computed stream flow includes components of overland flow, groundwater flow and interflow. The model has been successfully applied to urban drainage systems.3/

The Stanford Model routes moisture entering the watershed through various storage categories until it becomes stream flow, evaportanspiration or subsurface outflow. The path followed by incoming moisture is determined by antecedent moisture storage, assigned parameter values, entry rate and season. A system of empirical and theoretical equations describes specific hydrologic processes and estimates rates and volumes of moisture movement through the various storages. Major storage categories are surface (upper zone including interception and depression), soil moisture (lower zone), groundwater, interflow, overland flow (divided between impervious surfaces and soil surfaces) and channel. Moisture movement between storages occurs through infiltration, deep percolation, overland flow and channel flow processes. The model routes channel inflow from the point it enters a tributary channel to the location where a hydrograph is required. A subroutine is available for handling snow.

To apply the model to flows from a given watershed, a trial and error process is used to assign values to watershed parameters. The synthesized and recorded flows are compared by inspecting pairs of synthesized and recorded numerical values and hydrographs. Parameters are then reviewed and adjusted if necessary to bring synthesized flows closer to recorded flows. Another run is made and the cycle repeated until a satisfactory verification results.

## Quantity-Quality Models

The problem of urban water quality has been neglected.1,15/ Few useful data are available and most of these are not adequate for continuous simulation. Variations in urban runoff quality result from changes in season and geographical area. Practices such as lawn watering also affect the ultimate destination of lawn fertilizers and other chemicals.16, 17, 18/

While a better understanding of the complex nature of physical, chemical and biological processes which affect urban water quality is needed for structuring urban water quality models, progress is being made. Initial efforts have been few and spotty but some examples exist.

## EPA Storm Water Management Model

The EPA Storm Water Management Model was developed by Metcalf and Eddy, Inc., the University of Florida and Water Resources Engineers, Inc.7/ The objective was to produce a combined sewer system model which would simulate the quantity and quality of storm water flows from urbanized areas. The program consists of a control segment and five computational blocks: (1) Executive; (2) Runoff; (3) Transport; (4) Storage; and (5) Receiving Water.

The Executive block is the control for computational blocks with all access and transfers between the other blocks routed through its subroutine MAIN. The Runoff block accepts rainfall data and a description of the drainage system as inputs and provides both hydrographs and time-dependent pollutional graphs (pollutographs). The Transport block routes flows which are corrected for both dry weather flow and infiltration through the distribution system. It is also capable of producing hydrographs and pollutographs at specified points. In the Storage segment, flows from the Transport block are received and the effect of any treatment provided is considered. Effects of the discharge on a receiving stream are determined in the Receiving Water block. Segments may be run separately to facilitate adjustments.

The drainage area is divided into subcatchments, gutters and pipes. Subcatchments are divided into three parts: pervious, impervious with surface detention, and impervious without surface detention. Subcatchments are defined by area, width, slope and ground cover, while gutters and pipes are described by slope, length and Manning's roughness coefficient. This information and rainfall data in the form of hyetographs are read into the Runoff block. A step-by-step computation of runoff volume is then initiated. The mathematical procedure is as follows:

(1) The water depth on the subcatchment is found from the hyetograph as follows:

$$D_1 = D_t + R_r \Delta t$$

Where $D_1$ = Water depth after rainfall

$D_t$ = Water depth at time t

$R_t$ = Intentisty of rain, time interval $\Delta t$

(2) Horton's exponential function is used to account for infiltration. This is:

$$I_t = f_o + (f_i - f_o)\, e^{-at}$$

where $I_t$ = Infiltration

$f_o, f_i$ and $a$ = Hortin's coefficients

(3) Infiltration is subtracted from water depth according to the following equation:

$$D_2 = D_1 - I_t\, \Delta t$$

where $D_2$ = Depth after infiltration

$I_t$ = Infiltration rate at time t

(4) The water depth $D_2$ is compared with a specified detention value $D_d$ and, if found greater, the outflow for the catchment is found by using a form of Manning's equation.

$$V = 1.49/n\, (D_2 - D_d)^{2/3}\, s^{1/2}$$

where V = Velocity

n = Manning's coefficient

$D_d$ = Detention requirement

$$Q_w = VW\,(D_2 - D_d)$$

where s = Ground slope

W = Width of area

$Q_w$ = Outflow

(5) Water depths on the subcatchments are computed by the continuity equation:

$$D_{t + \Delta t} = D_2 - (Q_w/A)\Delta t$$

where A = Surface area of subcatchment

(6) The preceding steps are continued for all subcatchments.

(7) Gutter inflow is found by adding the outflow of the subcatchments tributary to it and the flow from all upstream gutters.

$$Q_{in} = \Sigma Q_{w,o} + \Sigma Q_{g,i}$$

where $\Sigma Q_{w,i}$ = Sum of flow from subcatchments

$\Sigma Q_{g,i}$ = Sum of flow from upstream gutters

(8) Depth of flow in gutters is calculated as follows:

$$Y_1 = Y_t + (Q_{in}/A_s)\Delta t$$

where $Y_1$, $Y_t$ = Water depths in gutter
$A_s$ = Mean water surface area between $Y_1$ and $Y_t$

(9) Outflow from the gutters is computed from Manning's Equation:

$$V = 1.49/n\ (R)^{2/3}\ (S_i)^{1/2}$$

where R = Hydraulic radius
$S_i$ = Invert slope

$$Q_g = VA_c$$

where $A_c$ = Cross-sectional area at $Y_1$

(10) Water depth in gutters is found using the continuity equation:

$$Y_t + \Delta t = Y_1 + (Q_{in} - Q_g)\ \Delta t/A_s$$

where all symbols are as defined previously.

(11) Gutter computations are carried out for all gutters in the system and summed to yield runoff.

Input to the runoff quality model consists of flow hydrographs develoepd in the quantity model. Output takes the form of pollutographs for each pollutant modeled. Pollutographs and hydrographs are introduced into the Transport block where they are summed and modified by addition of dry weather flow and infiltration to produce final outfall characteristics. At present, due to lack of sufficient data, only a few water quality parameters can be modeled.

It is assumed that the amount of pollutant which can be removed during a rainfall is dependent on storm duration and initial quantity of pollutant. This can be modeled by a first-order differential equation of the form:

$$-dp/dt = dP$$

or

$$P_o - P = P_o(1-e_{-kt})$$

where $P_o$ = Pollutant originally on ground, lbs.
P = Pollutant after time t, lbs.
k = A constant

The value of k is assumed to be directly proportional to the rate of runoff. Therefore, k = br, where b is a constant and r is the runoff intensity. Based upon available data, a value of 4.6 is assigned b. For each time step, the runoff rate is determined from the hydrograph and a value of P, which becomes the new value of $P_o$ for the next step, is calculated.

## Cincinnnati Urban Runoff Model

The Cincinnati Urban Runoff Model (CURM) was developed by the Division of Water Resources, Department of Civil Engineering, University of Cincinnati.5/ The program consists of three sections:

(1) MAIN-infiltration and depression storage and two subroutines; (2) GUTFL-gutter flow; and (3) PIROU-pipe routing. It is similar to the EPA model and divides the drainage basin into subcatchments whose flows are routed overland into gutters and sewer pipes. Rainfall is read in as a hyetograph. Infiltration and depression storage are summed and subtracted from rainfall to give overland flow. This is routed through the gutter system to storm water inlets and the pipe network. Starting at the upstream inlet, flows are calculated in successive segments of the sewer system, including discharges from inlets, to produce the total outflow.

The drainage area is divided into small subcatchments with closely matched characteristics. Rainfall data are introduced and infiltration is computed for each subcatchment. Principal elements of the modeling process follow.

(1) It is assumed that runoff begins when the rainfall rate equals infiltration rate and the mass of precipitation balances infiltration. The equations representing these conditions are:

$$t = \frac{-1}{k} \ln((i(I) + x/DT(i(I+i)-i(I))-f_c)/f_o-f_c)$$

and

$$\frac{f_c}{60} t + \frac{f_o-f_c}{60k} (1-e^{-Kt}) = mi(I)+(i(I) + \frac{x}{2DT} (i(I+1) -i(I)))\frac{x}{60}$$

where $mi(I)$ = Mass precipitated until time t, in.
$i(I)$ = Ordinates of rainfall intensity curve
$K$ = Decay rate of infiltration (units/min.)
$f_o$ = Initial infiltration capacity, in./hr.
$f_c$ = Ultimate infiltration capacity
$DT$ = Time increment of rainfall intensity curve
$t$ = Time to intersection of rainfall curve and infiltration curve
$x$ = Increment of DT

The infiltration curve is computed from the equations and t, I and x are stored.

(2) Surface retention is related to depression storage by an equation derived by Linsley, Kohler and Paulhus:

$$s = (i-f)\; e\, \frac{-P-F}{S_d}$$

where $S_d$ = Total depression storage, inches
$P$ = Accumulated rainfall in storage, inches
$F$ = Accumulated infiltration, inches
$i$ = Rainfall intensity, inches/hour
$f$ = Infiltration, inches/hour
$s$ = Surface retention, inches/hour

Infiltration and surface retention are subtracted from rainfall intensity to yield runoff.

(3) The hydrograph of overland flow is derived by solving

$$\frac{r_1 + r_2}{2} - \frac{q_1}{2} + 60\ D_1/t = \frac{510.35}{nl}\ s^{1/2}\ D_2^{5/3}\ (1+.6(D_1/D_{2e})^3)5/3 + 60D_2/t$$

where $D_e = (.0097n^{0.6}r^{0.6}L^{0.6})/s^{0.3}$

$D_{1,2}$ = Depresseion storage at beginning and end of time interval t, inches/unit area

$r_1,r_2$ = Overland flow supply at beginning and end of time interval, t, cfs/min.

n = Manning's coefficient

L = Length of overland flow

s = Slope, ft/ft

q = Discharge, in./hr./unit area

(4) For the initial time increment, values of $q_1 = 0$ and $D_1 = 0$ are substituted, $D_2$ is calculated, and $q_2$ is found from:

$$q = 1020.7/nL\ (s^{1/2})D^{5/3}(1 + .6(D/D_e)^3)^{5/3}$$

where the symbols are as previously defined.

The determined values of $D_2$ and $q_2$ become new values of $D_1$ and $q_1$. The overland flow hydrograph is derived by repeating this cycle.

(5) Gutter flow is computed using the continuity equation:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t}\ T = q_2$$

where T is the width of the water surface.

The term $\frac{\partial y}{\partial t}$ T is neglected because change in depth of gutter flow is very small with respect to time. After integration, the equation becomes:

$$Q = q_L(L) + Q_o$$

where $Q_o$ = Upstream gutter contributions

L = Length of gutter, feet

$q_L$ = Overland flow from hydrograph

Q = Flow from gutter system

Inlet flows are routed through the pipe network by delaying the hydrographs by the flow time required to reach the next inlet and summing values at a terminal point in the network. Manning's equation is used to find the velocity of flow in the sewer and the corresponding time delay. Provision is made for sewers of varying cross section. The model has been found to closely simulate gaged flows.5/

Calculation of pollutant concentrations in runoff is based on the assumption that the rate of pollutant removal depends on the amount of pollutant initially in the drainage area and the rainfall intensity. The equation used is:

$$\frac{dP}{dt} = KqP$$

$$\text{or} \qquad \frac{-dP}{P} = Kq\,dt$$

After integration, this becomes

$$P = P_o e^{-KV_t}$$

where $P$ = amount of pollutant remaining on the ground at time t, lbs.
$P_o$ = Initial amount of pollutant
$K$ = Constant
$V_t$ = Volume of runoff up to time t, $ft^3$

During a storm, the amount of pollutant washed into the sewer system in a time interval t, is:

$$P_1 - P_2 = P_o(e^{-KV_1} - e^{-KV_2})$$

The amount of solids washed into a storm sewer during a rainstorm is assumed proportional to the square of the runoff intensity. This equation is as follows:

$$r = \lambda q^2$$

where $r$ = Fraction of solids carried off
$\lambda$ = Proportionality factor
$q$ = Runoff intensity, inches/hour

The amount of solids brought into the system in a time interval may be expressed as:

$$P_1 - P_2 = P_o\ \lambda \bar{q}^2\ (e^{-KV_1} - e^{-KV_2})$$

where $\bar{q}$ = Mean runoff intensity
$V_1, V_2$ = Runoff volumes at time $t_1$, $t_2$, $ft^3$

Soluble pollutants are routed downstream at the same velocity as the flow, and are summed in the same manner as flows to determine final values. Provision is made for sediment transport.

## DATA NEEDS

A good deal is known about analyzing the hydrology of natural basins. Much of this knowledge should be transferrable to urban watersheds but more data are needed to prove this point. The present data base is inadequate. Mathematical modeling requires data for calibration. Rainfall-runoff-quality data are needed on a variety of urban watersheds exhibiting a range of climatic and watershed parameters.

Several fully instrumented urban watersheds should be developed to provide data of research quality. These data should be on a time and space grid at least as small as that required for finite differencing solutions to hydrologic problems.15/ Enough data should be obtained to provide for split-sample testing. Perhaps the most serious data deficiency is in the area of urban water quality. Fully instrumented research watersheds should include an extensive quality sampling program designed to provide insight into time and space variations in quality loadings for the major constituents considered important in urban runoff. Of special concern is the variability of quality loadings in response to environmental and climatic variations, seasonal effects and the effects of flushing by antecedent rainfall.

## SUMMARY

The state-of-the-art in modeling urban runoff quantity and quality has progressed from simple rules-of-thumb to complex simulation models incorporating all fundamental hydrologic processes. We are not totally aware of the mechanics of all of these processes and some empiricism remains. In fact, urban hydrologic modeling is still part art and part science, but as more data become available and we become better equipped to evaluate the tools being developed, a greater degree of sophistication and reliability will be the product. Perhaps the greatest underlying need is for more data characterizing the water cycle on urban areas. Information on both the quantity and quality of urban runoff is in critically short supply.