OVERVIEW OF URBAN RUNOFF MODELS

by M. B. McPherson,* F.ASCE

Introduction

It has been estimated that approximately one-sixth of the "Urbanized Areas" of the United States fall within natural 100-year flood plains,[1] whereas well over half of such areas are drained by systems of underground conduits. Further, national investment for storm drainage conduit facilities appears to be more than four times as great as that for flood plain protection works benefiting urban areas.

There is widespread interest in multi-purpose drainage facilities that exploit opportunities for water-based recreation, provide more effective protection of buildings from flooding, and allow for the use and re-use of storm water for water supply. In addition, the 1972 Amendments to the Federal Water Pollution Control Act have led to considerable interest in reducing the entry of pollutants into receiving waters from combined sewer overflows and storm sewer discharges. Over the last few years urban runoff model development and usage has greatly intensified. Because of this and of the tendency to use tailor-made or custom-adapted models for urban streamflow discharge-quality, discussion of models for simulation of underground conduit system performance will predominate in the overview that follows.

Why Simulation?[2]

All but a small fraction of storm and combined sewers around the world have been sized by means of wholly empirical methods. Given a lack of evidence of superior methods, these overly simplistic procedures proved adequate when the primary purpose of storm sewers was to drain the land and express the accelerated convergence of surface runoff to receiving waters. Out of sight, out of mind. Once restrainment or containment of flows and their pollutant burdens become added primary objectives, traditional procedures of analysis are no longer adequate because of added system complexities.

Why not use observed discharge variations as a guide? There are several compelling reasons precluding this possibility: (1), very few urban catchments, particularly sewered ones, have been gaged; (2), a statistical approach requires a

*: Urban Water Management Consultant, Marblehead, Massachusetts.

period of record spanning at least ten years, substantial physical changes commonly take place on most urban catchments over this long a time, and the mixed statistical series that results is not interpretable; (3), while such a statistical series would characterize the existing situation, there would be substantial uncertainty over its extension to differing future situations; and (4), the clinching reason, in the usual case where no field measurements have been made, is that it would be necessary to postpone planning and analysis until new long-term field records were accumulated, an unacceptable option under contemporary imperatives. An even less acceptable alternative would be to rely solely on empirical tools and determine prototype system performance after system changes had been instituted, a procedure that would indicate the overall errors implicit in the tools used, but would be very expensive experimentation. Thus, in order to anticipate future system performance under changed conditions, because these changes can very rarely be simulated by manipulating prototype systems, recourse must be made to performance simulation by calculation or analogy using tools of analysis such as mathematical models.

Categories of Model Applications

Mathematical models used for the simulation of urban rainfall-runoff or rainfall-runoff-quality can be divided into three different application categories: planning, analysis/design and operations. Some particular models have been employed in both planning and analysis/design, and a few models have been applied in analysis/design and operations applications, making it difficult to allocate them to a single category. Additionally, the reader is cautioned that on no account should the models to be mentioned be regarded as typical tools. Rather, common practice still favors rudimentary techniques, although the use of new tools of analysis seems to be growing rather rapidly around the world.

Planning applications are at a macro-scale, such as for comprehensive metropolitan or municipal plans. Model requirements for planning are less rigorous and require and permit less detail than for analysis/design because investigation of a range of broad alternatives is at issue. What are sought for planning tools are general parameters or indicators for large-scale evaluation of various alternative schemes. Hence, the degree of model detail required in jurisdictional planning is generally less than in analysis/design.

Analysis/design applications generally require more sophisticated, more detailed tools, for the analysis of individual catchments and subcatchments where the simulation of detailed performance of discrete elements within a subcatchment must be achieved.

Operations applications are likely to be more use-specific because of wide diversities in management practices, operating problems and individual service-system configurations.

Taxonomy of Urban Runoff Models

The structural characteristics of urban runoff models can be segregated into two broad categories, "lumped" and "distributed". In a lumped model, rainfall is transformed into the runoff at a given point without any hydraulic routing through the tributary area. An example is the conventional unit hydrograph, a tool in widespread use in river basin hydrological analysis and applied occasionally to urban drainage. A distributed model is characterized by a capability for the hydraulic routing of flows in addition to the hydrologic transformation of rainfall into runoff, such as through all or part of the underground conduit system within the tributary area being modeled. Because many more catchment details are accounted for, distributed models are considerably more complex than lumped models.

Another characteristic of urban runoff models deals with the time scale of their representation. Some models can accommodate only one individual rainfall event at a time and hence are commonly termed "event models". Other models that can handle a long series of events, ranging from a season to a decade or more, are commonly called "continuous models". Most urban runoff models were developed within about the last thirteen years. Event models are usually tied to synthetic hyetographs. As the limitations in the use of synthetic hyetographs became more evident, continuous versions of event models were developed to the point where continuous simulation options are now available for nearly all of the former event models that had received user acceptance.

A few years ago, urban runoff models could be additionally segregated by whether or not they could accommodate water quality parameters. The recent trend has been to add such a capability where it did not exist before, and thus this distinction is rapidly fading.

The most widely used models are in the public domain. Versions of nearly all formerly proprietary models have very recently been placed or are in process of being placed in the public domain. Conversion has been predominantly by the U.S. Environmental Protection Agency and the Hydrologic Engineering Center of the Corps of Engineers.

In sum, the recent trend has been to expand the repertoire of the formerly less complete models to include: their applicability to both analysis/design and planning; continuous simulation; and water quality characterization. Distributed features are being added to formerly lumped models, and lumped features are being added to otherwise distributed models, in an effort to extend them all to a combined analysis/design and planning capability. The result of all this is a homogenization of capabilities in a group of models all of which are in the public domain. It is particularly important to realize that practically all urban runoff models are being continually upgraded and improved. As a result, it is not possible to keep up with every new development, and the remarks about specific models in this paper are applicable only contemporaneously.

Components of Urban Runoff Models

Discussion of selected available models will start with total system simulation models and then take up the less complete cases. The principal functional components of the most comprehensive, distributed models are depicted in Figure 1.[3] Because pollutants are physically dissolved within and suspended by the flow of water, the runoff behaves as a pollutant carrier. Thus, pollutant routing (the two lower steps in the column to the right) is performed as an adjunct to hydraulic routing of flow (the two lower steps in the column to the left). "Surface Runoff" refers to the above-ground flow of water from the time rainfall lands until it enters the underground conduit system; and the underground conduit system is termed "Sewerage Transport" in Figure 1. Routing in "Receiving Water" can accept the outflow from one or more sources of contributary combined or separate storm sewers.

Three models deserve mention because they have all the capabilities indicated in Figure 1. All three of these models, in one variant or another, are programmed for routing flows using fundamental hydrodynamic equations of motion (after Barré de Saint-Venant). Late in 1975 it was reported that publicly available documentation

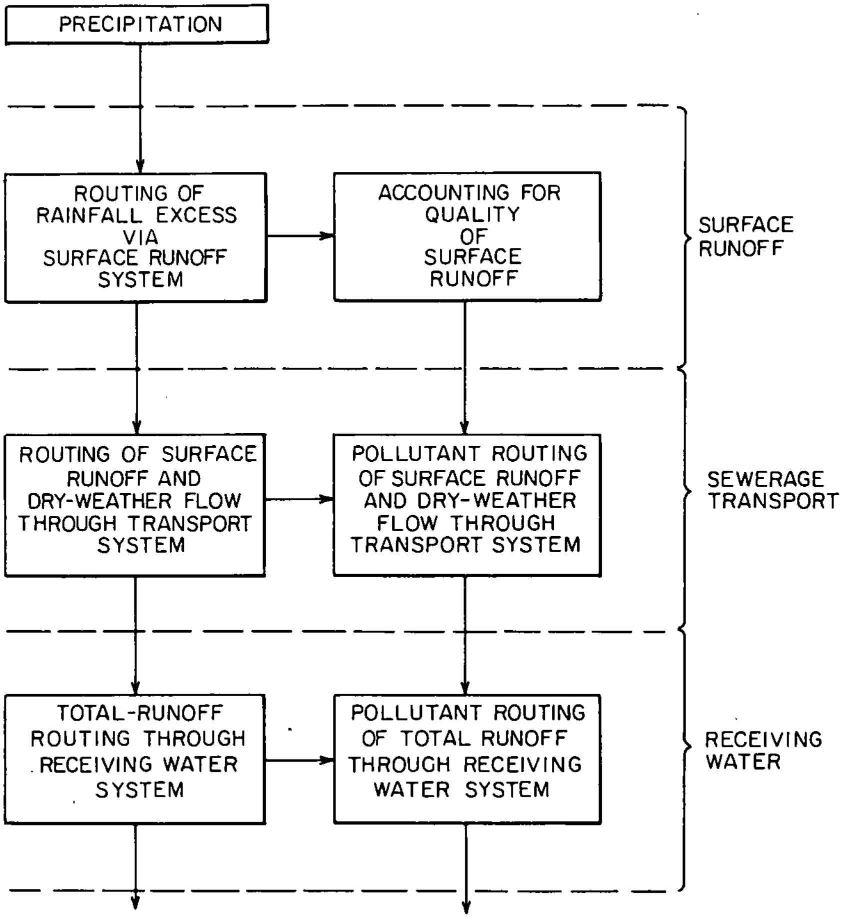

FIGURE 1 - COMPONENTS OF URBAN RUNOFF MODELS[3]

existed on the testing of variants of the Stormwater Management Model (SWMM) using data from 28 catchments (with water quality included for 18) in the U.S.,[4,5] its country of origin; and SWMM has also been tested and applied elsewhere. The QQS model has been tested and applied in the Federal Republic of Germany,[3] its country of origin, and elsewhere.[6] The CAREDAS Program (perhaps better known as the SOGREAH model) has been tested and applied in France,[7] its country of origin, and elsewhere. All three models have been used in both planning and design applications. Features of SWMM and QQS will be described later.

Some of the Models

The last few years have seen an explosion in the applications of urban runoff models, much of which was in conjunction with or as a result of the areawide planning for water pollution abatement mangement that has taken place in most metropolitan areas. Any discussion of urban runoff models is necessarily discretionary and somewhat subjective. To be cited here are only those models that are being used the most. The only exceptions will be formerly proprietary models that have recently passed into the public domain or for which a version is in process of being so transferred.

In a 1975 U.S. national report on urban hydrological modeling and catchment research,(4,5) 64 urban catchments were identified from which data had been used to test some 16 urban runoff models. Citations were restricted to cases that were publicly documented. Since 1975, the number of such catchments may well have doubled, mostly as a result of PL 92-500 (Federal Water Pollution Control Act of 1972) Section 208 planning and jurisdictional master planning activities, but it will be some time before the new ones can be collectively documented because a number are components of on-going planning. In a continuing project for the EPA,(8) urban catchment rainfall, runoff and quality data are being placed on magnetic tapes in a common format and are being entered in the EPA STORET data retrieval system.

SWMM. Subroutines for the EPA Storm Water Management Model are represented symbolically in Figure 2.(9) SWMM, the most widely used system analysis model in North America, is continually upgraded.(10) A user's manual,(11) its substantial updates and the computer program, are available to the public. The latest additions are to be included in a revised user's manual late in 1980. The earlier versions were restricted to a kinematic wave approach for stormwater transport, but a solution to the St. Venant equations is included as an option in the latest version of the model under the acronym EXTRAN. Another new feature is a detailed analysis option for detention storage and treatment.(12a) A conversational version of the Runoff block in SWMM is being used in a course on modeling in Ontario.(12c) Twice per year U.S. and Canadian users meet to review experiences with all types of models.(13) The SWMM Users' Group has become an informal U.S.-Canadian cooperative venture, and participation is open to all interested persons. While SWMM was originally an event model, continuous simulation capability has since been added. A user's experience

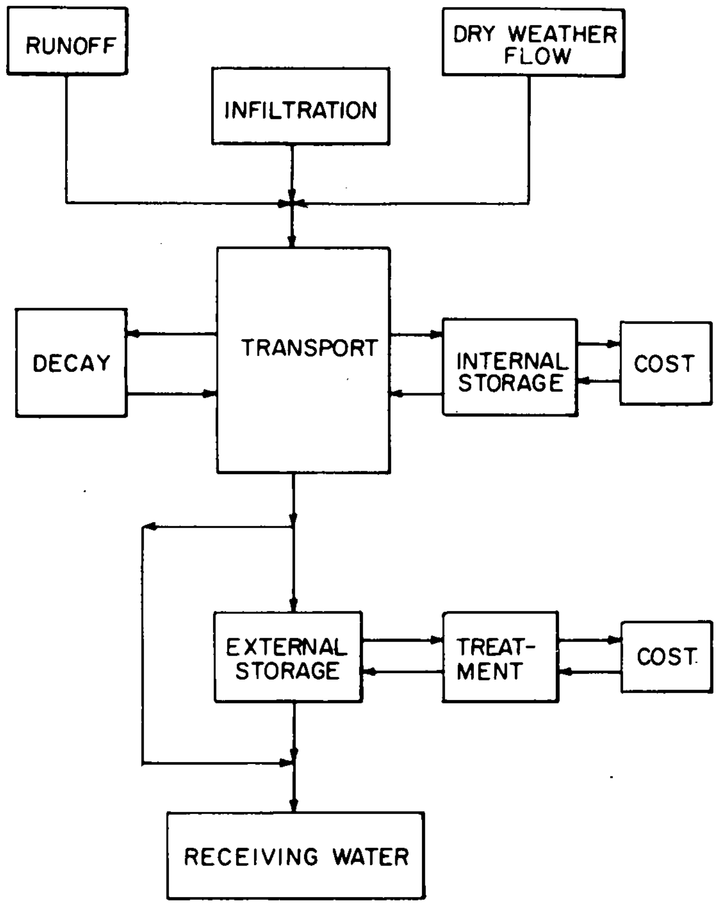

FIGURE 2 - SUBROUTINES OF STORMWATER MANAGEMENT MODEL[9]

with continuous simulation has been reported.[14]

<u>QQS</u>. Figure 3[3] is an overall flow chart for the Quantity-Quality-Simulation Model. Its North American applications have been in Rochester, N.Y., Toronto, Ontario, and Vancouver, B.C.[6] The QQS Model uses a solution to the St. Venant equations for stormwater transport and is a continuous model that can be run for single events. Developed in the Federal Republic of Germany, the model is available to the public from EPA.[6]

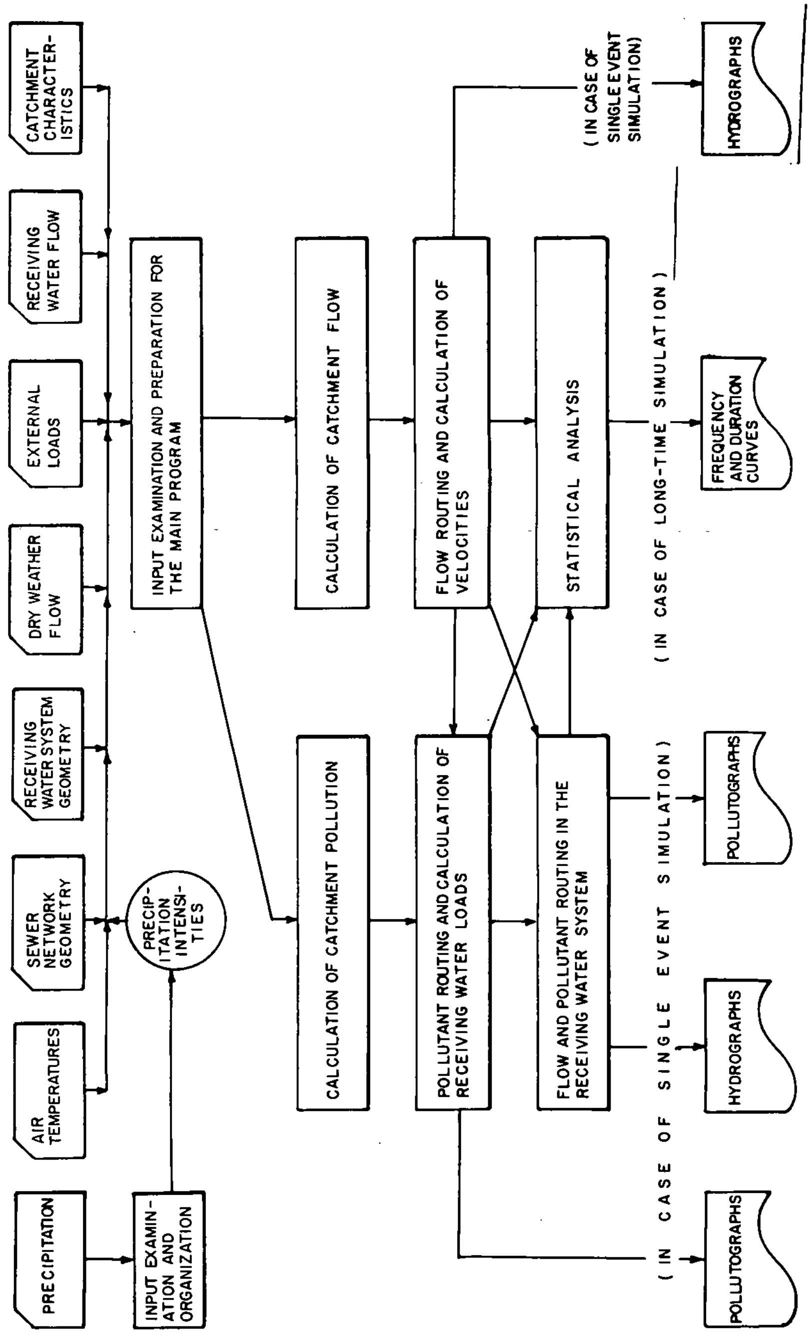

FIGURE 3 - OVERALL FLOW CHART FOR QQS MODEL [3]

Both SWMM and QQS were developed as urban land drainage models that included some receiving water simulation capability. The next model to be discussed was first developed as a streamflow simulator that was later refined to include detailed modeling of urban land drainage.

HSP. The earlier Hydrocomp Simulation Program, as outlined in Figure 4,(15) fundamentally simulated watershed hydrology and flow routing. The HSP was the commercial successor to the Stanford Watershed Model, first reported in 1960. An entirely new version using the same basic equations but in FORTRAN, (HSP-F), is available to the public from the EPA Environmental Research Laboratory, Athens, Georgia 30601. HSP is strictly a continuous simulation model.

EPA's Nonpoint Source Pollutant Loading Model(16,17) (NPS Model) incorporates the LANDS subprogram of the HSP. While the original testing of NPS was on urban watershed data, the methodology is said to be sufficiently flexible for other land use applications. NPS is a continuous model but has yet to be interfaced with a receiving water model. The reference report(16) is actually a user's manual.

MITCAT. The general structure of the proprietary MIT Catchment Model is shown in Figure 5.(18) A water quality handling capability has yet to be added formally. Its experimental use by the USGS and the Corps of Engineers will be mentioned subsequently.

ILLUDAS. Figure 6(19) is a flow chart for the Illinois Urban Drainage Area Simulator. It is an offshoot of the empirical British Road Research Laboratory (RRL) method,(20,21) and is the only widely used model that has determination of pipe sizes as a modeling objective. The water quality algorithms of SWMM have been adapted in a version known as QUAL-ILLUDAS, an event model.(22) The parent RRL method was reported in 1962, which made it one of the first distributed-type design models on the scene. ILLUDAS is predominantly a hydrologic model. Uses of various modifications of the RRL method for design have also been reported in Australia, Canada, the United Kingdom, Norway and India.

The USGS has modified the MITCAT and ILLUDAS models for continuous simulation, detention-storage accommodation and water quality simulation.(25) From its experiences with MITCAT, the USGS has evolved its own urban rainfall-runoff model.(26)

Through the use of greatly simplified hydrologic considerations, a computer

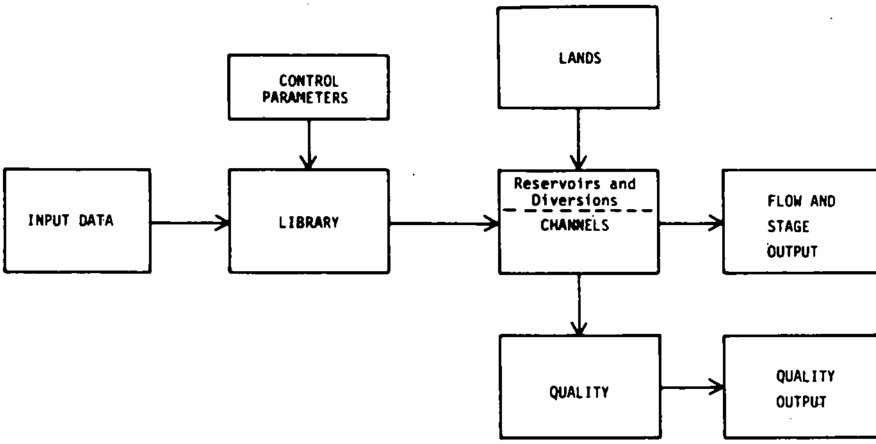

FIGURE 4 – THE HYDROCOMP SIMULATION PROGRAM SYSTEM[15]

program has been developed for the optimal deployment and sizing of separate storm sewers for altogether new developments.[23] A newer optimal layout model[24] incorporates STORM (cited later herein) and includes sizing of storage and treatment facilities for pollution abatement.

Unit Hydrograph. This relatively simple tool has been used in the hydrologic analysis of streamflows for quite some time. An excellent manual on urban unit hydrograph analysis is readily available.[27] The Corps of Engineers has developed a computer program user's manual for its Flood Hydrograph Package (HEC-1),[28] which develops unit hydrographs from field data and routes flows from one point to another. HEC-1 has been used extensively in urban projects by the Corps of Engineers and others. While HEC-1 is a single event simulator, a version known as HEC-1C has been developed for continuous simulation.[29]

The only interpretive tool for urban runoff that incorporates regionally specific parameters on a national scale has been developed by the Soil Conservation Service.[30] Its underlying hydrological element is a triangular unit hydrograph.

Synthetic unit hydrograph parameters derived from a number of field measurements in several States[2,31] offer a means for extrapolating findings from local field observations to local ungaged catchments in a given metropolitan area. A user can calculate synthetic unit hydrograph parameters directly from the equations given

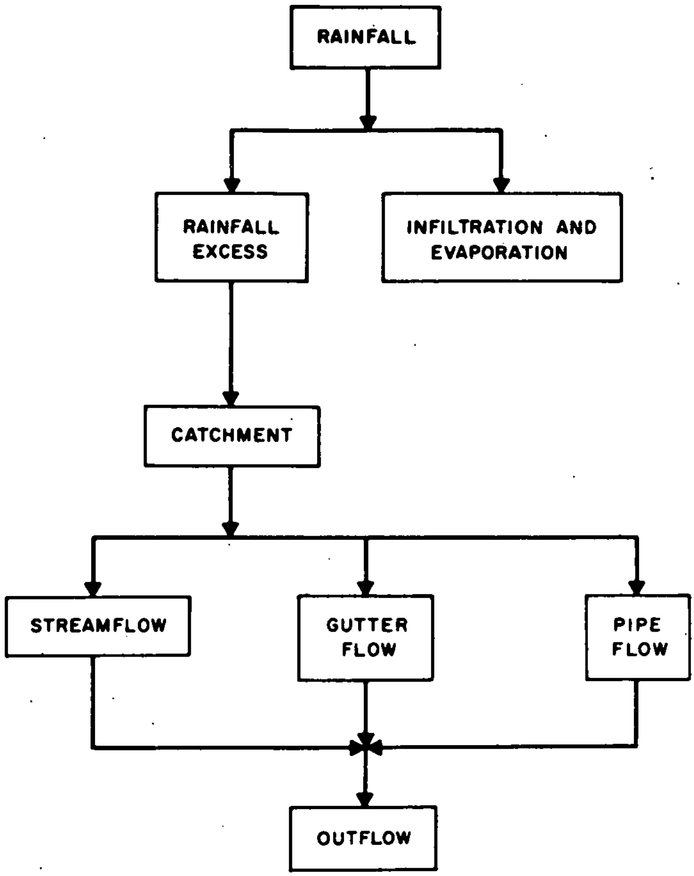

FIGURE 5 – GENERAL STRUCTURE OF MIT CATCHMENT MODEL (18)

with a pocket calculator of modest capability or simply use the nomographs provided.

Water quality considerations have not been included with any of the unit hydrograph formulations mentioned above. However, the QQS Model, noted earlier, employs unit hydrographs as the inputs to the routing module for underground conduit transport, and these inputs are accompanied with what might be termed "unit pollutographs" for water quality simulation.

STORM. The Storage, Treatment and Overflow Model was designed specifically for urban runoff and quality evaluation for total jurisdiction and metropolitan master

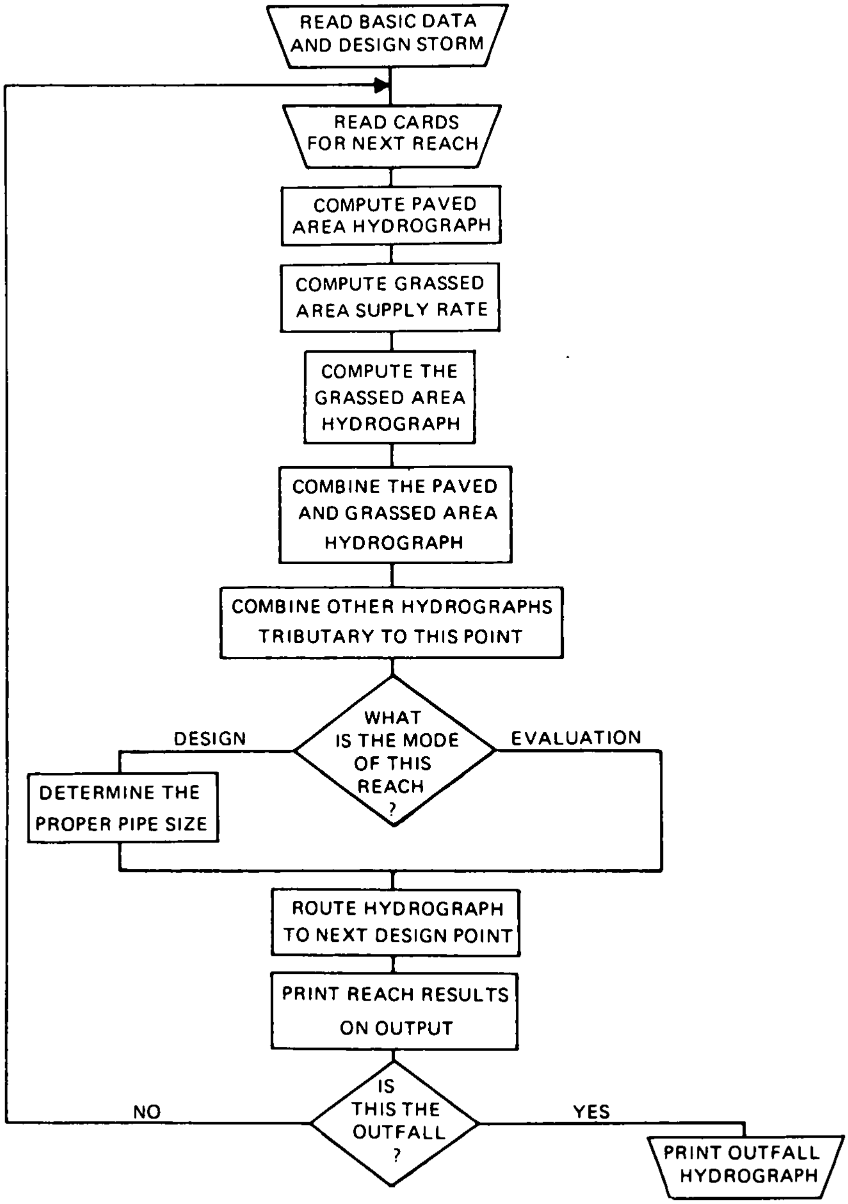

FIGURE 6 – FLOW CHART FOR ILLUDAS[19]

planning. It is eminently suited for that purpose and it currently enjoys, in one version or another, the most extensive use of any urban drainage simulation planning model. The computer program, model documentation,[32] user's manual[33] and guidelines[34] are available to the public. A simplified logic diagram for STORM is presented in Figure 7.[35] Note that this model focuses on structural means for flow and pollutant containment (storage and treatment). It is designed for use with many years of continuous hourly precipitation records (but can be used for individual storm events). Essentially, the model employs an accounting scheme that, for each storm event, allocates runoff volumes to storage and treatment, noting volumes exceeding storage or treatment capacities (overflows, in the case of combined sewer systems) as these capacities are exercised from one event to the next. Water quality is handled as a function of hourly runoff rates, with generated quantities of constituents allocated to storage, treatment and non-capture as for runoff volumes. Statistics are generated for each event and collectively for all events processed, including average annual values. STORM accommodates non-urban catchments and snowpack accumulation and snowmelt, and land surface erosion for urban and non-urban areas can be computed in addition to basic water quality parameters. Until recently, hydraulic simulation or flow routing was not incorporated in STORM. The latest Corps of Engineers' version includes a capability for routing to the outlet of each sub-basin through the use of triangular unit hydrographs based on the Soil Conservation Service procedure.[33] Capabilities of STORM and HEC-1 have been described in a symposium paper.[36]

A modification of STORM has been linked with the receiving water module of SWMM for continuous simulation of receiving water quality.[37,38] The Hydrologic Engineering Center has added a receiving water module to its STORM computer package.

As part of a nationwide assessment of stormwater pollution control costs, a "desktop" procedure was developed, by streamlining the STORM model, that can be used to estimate the quantity and quality of urban runoff in combined sewer and storm sewer areas and unsewered portions of a jurisdiction. Combinations of storage and treatment for pollution abatement and their costs can be estimated taking advantage of generalized results from the nationwide assessment.[39]

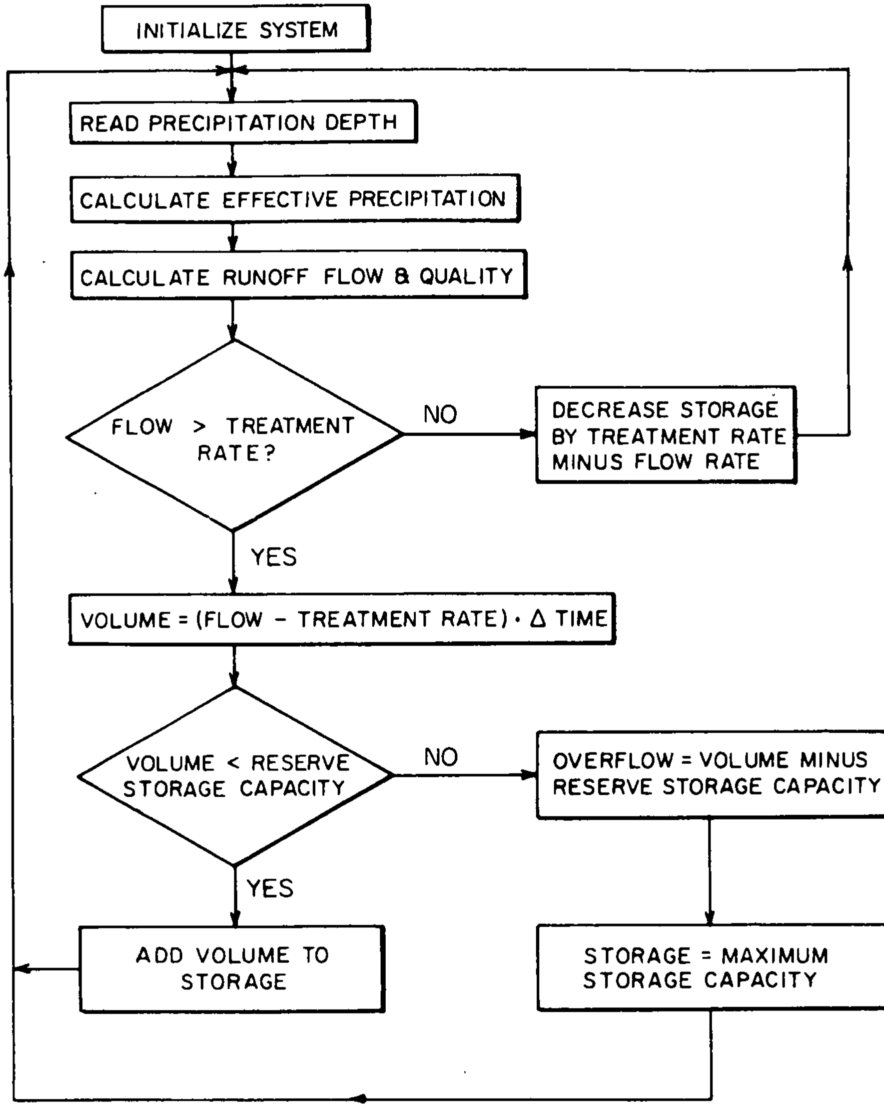

FIGURE 7 – "STORM" SIMPLIFIED LOGIC DIAGRAM[35]

Model Comparisons

From 1973 to 1976 there was a rash of projects comparing the merits of various models on the basis of a variety of criteria.[40-48] More recently, reliabilities of some of the simpler models (three versions of STORM and HEC-1 and HEC-1C) have been compared with those of some of the more complex models (SWMM, MITCAT and HSP) using data for a particular catchment.[29] Instances where tests had been published of the performance of various types of models against field data were reported in 1975.[4] Advances in modeling capability occur almost too rapidly to keep track, and in 1975 it could be said that mathematical model development for sewered system applications had already seemingly greatly outpaced the data base for model validation.[4]

Results of the various tests are mixed, mostly because there is no acceptable basis for multiple-objective comparison. Peak flow is the major consideration in sizing conduits, volume and hydrograph shape are critical for sizing storage, and concentrations and loadings of pollutant emissions are essential for evaluation of receiving water impacts and helpful in sizing treatment facilities. Each model has its strengths, weaknesses and outright faults for a given application. Over and above the problem with multiple-objective comparisions is the inherent difficulty with any runoff model in the necessarily subjective separation of abstractions (infiltration, depression storage, etc.) from total rainfall to resolve rainfall excess (amount and pattern), which is the input from which an equal volume of direct runoff is generated by models of one kind or another. After analyzing the performance of a variety of models, it was concluded that the weakest link is the proper estimation of rainfall excess.[49] All this is to emphasize that urban hydrology is still, in the absence of an adequate body of field data, more of an art than a science, and that under this circumstance the choice of a model for a given application is largely a matter of taste.

Some Simpler Planning Models

A Simplified Stormwater Management Model has been developed that is an inexpensive, flexible tool for planning and preliminary sizing of stormwater facilities.[50,51] Time and probability considerations are incorporated in the model. Joint usage of a complex model and a simplified planning model, such as this one, is said to be not only compatible but also complementary.

A very simple methodology has been advanced for preliminary screening of stormwater pollution abatement alternatives.[52,53] While the method was conceived for combined sewer system applications, it could as easily be applied to stormwater systems. Developed for use at the national or State decision-making level for early identification of poor candidates for abatement project funding, it might as readily be applied for rough, early assessment of the maximum pollutional impacts of storms at the metropolitan level.

Reported verifications of simple process planning models, including STORM, have been limited, although hearsay indicates that the number of verifications is growing. Because suggested magnitudes of model coefficients are based on the sparse amount of field data available nationally, it is very important that local rainfall-runoff-quality field data be used to calibrate such models for the sake of enhanced reliability of results. Too many planning exercises have proceeded without benefit of local field data, using one model or another.

Receiving Water Modeling

Receiving streams and lakes are the common repository of effluents from just about every community and self-supplied industry in a metropolis, constituting perhaps the most shared aspect of urban water resources. Impressive advances have been made in receiving water modeling. Initial attention was on hydrology and hydraulics in support of flood control objectives. Water quality modeling capability has evolved more recently, with a tendency to use tailor-made models for discharge-quality simulation in planning applications. Earlier development was focused on estuaries. The choice of a model or models to be used in any given planning effort therefore requires careful and discriminating study. Consequently, it is appropriate to cite recent capability summaries. Reference has been made earlier to capabilities of SWMM and other models for simulating receiving water impacts.

A compendium,[44] two companion reports,[54,55] a North American summary,[56] and a text,[57] survey features of large-scale water quality models; and an annotated bibliography of models for tidal rivers, estuaries and coastal waters is available.[58] Tidal water models have been comprehensively classified,[59,60] and capabilities for modeling estuary and streamflow water quality have been assessed.[61]

Aquatic ecosystem submodels have been delineated for process analysis.[62]

Aquatic ecosystem models were surveyed in 1974 for the National Commission on Water Quality via a questionnaire,[63] and while several of the models reported upon therein are more generally applicable, nearly all have been developed or tested on a specific water body and only a fraction of the applications have urban implications.

Water quality modeling for systems containing rivers and reservoirs has been advanced through the issuance of a description of a combination of models.[64] The Hydrologic Engineering Center has since added dynamic flow routing routines.[65] Dynamic or unsteady-flow water quality modeling is particularly important in the case of significant pulse loadings from urban runoff or when man-made controls such as dams are involved.

Although receiving waters represent only a part of the total urban water resource, they commonly traverse entire metropolitan areas and are affected by the actions of a multitude of local jurisdictions. Recent emphasis on regionalized wastewater treatment and disposal has resulted in some receiving water simulation studies on a grand scale.

<u>Role of Models in Operations</u>

Models used for analysis/design applications are more sophisticated than those for planning and thus are more detailed tools. They are used for analyzing individual catchments and subcatchments where the simulation of detailed performance of discrete elements within a subcatchment must be achieved. Whereas hourly rainfall data is an appropriate input for planning models and for simulating flows in larger urban streams, 5-minute interval rainfall data (the shortest duration reported by the National Weather Service) is the appropriate input for simulating flows in sewers and small urban streams for design applications. That is, the level of sophistication of hydrological process modeling for analysis/design becomes a much more important practical consideration than data processing, just the opposite of the emphasis imposed by planning requirements.

Models used for operations applications are likely to be more use-specific because of wide diversities in management practices, operating problems and individual service-system configurations. However, the most potentially transferable technology will be for automatic operational control of total community runoff, a capability that has received intensive development attention. The mathematical models required feature control algorithms that have to be painstakingly derived from numerous indicator applications of both detailed analysis/design models (for generalization of the performance of individual process components by simulation) and planning models (for generalization of community-wide system performance by simulation). Here also, analysis/design models are used as tactical tools and planning models are used as tools of strategy.

A computer model has been developed at the University of Toronto for exploring possibilities in the automatic control of existing combined sewer systems.[12b] Extensive research has been carried out at Colorado State University on a planned City-wide automatic control scheme for new storage and conveyance facilities in San Francisco's combined sewer system.[66-68] Metropolitan flood warning systems[69] require incorporation of some sort of hydrologic model. Development of a storm tracking capability is considered to be a necessary adjunct for automation of flood warning systems for combined sewer systems and urban streams.[70] Very little attention has been given to separate storm sewer system modeling for operations because there are normally very few existing components of such systems that can be manipulated.

Role of Simulation in Planning

A special session at the 1976 annual meeting of the American Geophysical Union[71] attempted to define appropriate rationales and incentives for the more extensive use of urban runoff mathematical models for planning, analysis/design and operations. Among the advantages cited for the use of such models for planning were that: tests can be made of alternative future levels of development and their impact on facilities needed in the future; several models well-suited to master planning are in the public domain and are regularly upgraded and made readily available by the Federal agencies that supported their development; when detailed models are used in advanced stages of planning the user is able to understand better the physical performance of a system; the interrelation between land-use projections and planned mitigative programs and their costs can be made more apparent; revisiting plan assumptions to update projects can be done with consistency and relative ease; joint consideration of quantity and quality of runoff in sewered catchments and in streams can be accommodated;

hydrologic-hydraulic effects of future urbanization can be explored; and deficiencies in existing facilities and prevailing management programs can be identified.

The most significant liability in the development of more acceptable measures of reliability of all types of models is the dearth of field data on rainfall-runoff-quality, particularly for sewered catchments. A workshop conducted by the ASCE Urban Water Resources Research Council resolved guidelines for the acquisition of such data by local governments.(72) The spectrum of investigative stages utilizing field data for the sewered areas and receiving waters of a metropolitan area include the following:

- Identification and evaluation of quantity and quality problems.
- Exploration of alternatives for pollution and flooding abatement.
- Analysis of the most attractive alternatives.
- Preliminary design of adopted alternatives.
- Detailed design of adopted alternatives and their implementation.
- Post-implementation operation via a range of possibilities extending from simple monitoring to automatic control.

Total lengths of underground drainage conduits dwarf those of open watercourses in major cities. For example, total lengths in the 97-square miles of the City of Milwaukee as of the beginning of 1970 were as follows:(73)

Lakefront length	-	8-miles
River lengths	-	37-miles
Combined sewers	-	550-miles
Storm sewers	-	820-miles.

These combined and storm sewers are distributed over 465 drainage catchments having a maximum size of 1,820-acres and a median size of 25-acres.(74) When dealing with so many components the model used must be as simple and as flexible as possible. That is, data processing for planning applications becomes a much more important practical consideration than the level of sophistication of detailed hydrological and hydraulic processes modeling. While not shown above, there were also 685-miles of wastewater sewers.

Some Reservations

Because complex processes, such as in the hydrological response of a sewered catchment to a precipitation occurrence, can never be fully replicated in a computation due to incomplete technical understanding of the processes and the infeasibility of detailing the literally myriad pieces involved, resort is made to simulation of response of a conceptually equivalent system. The simulation package is commonly called a "model". Reality dictates that a model should be selected on the bases of the type of application involved, how it is to be used, how much can be invested in its use, how often it would be used, what levels of precision are required or desired, what kinds of outputs are wanted, how much time can be spent to get the model to work, and how much can be committed to verify and calibrate the model. Calibration is the process of varying model parameters to minimize the difference between observed and simulated records.

We have been reminded that until each internal module of an overall catchment model can be independently verified, the model remains strictly a hypothesis with respect to its internal locations and transformations.(75) Because of the very limited amount and kind of field data available, just about all sewer applications model validation has been for total catchment response, at outfalls. That is, under contemporary conditions a distributed system model deteriorates into a lumped system model for all practical purposes. It should therefore be evident that validation using transferred data by the model's developer is not nearly enough. Credibility requires at least token calibration using some local rainfall-runoff-quality data. Unfortunately, the acquisition of such data is commonly regarded as the exclusive problem of local governments, and too many planning and analysis exercises have proceeded without benefit of local field data using one model or another.

Calibration and validation is further confused by the fact that much more field data are available for partially sewered catchments, where flow is measured in receiving watercourses, than for totally sewered catchments. (That water quality samples have been taken for only a fraction of these gaging sites does not help). Adding streamflow hydraulics to sewer hydraulics hardly simplifies the lumped system dilemma alluded to above, yet much of the data used to verify various models has been from such mixed catchments. This should add additional incentive for calibration with local data.

Concluded in a comprehensive Canadian study was that sufficient information is not available on relationships between street surface contaminants, their pollutional characteristics, and the manner in which they are transported during storm runoff periods. Also concluded was that basically only one type of model exists for analysis of urban runoff quality, and that the accuracy of the water quality computations using models extant has not been sufficiently established to be used with confidence for prediction purposes, in particular the formulation relating water quality with land use.[40]

Because relatively few runoff-quality field gagings in sewered catchments have been made, and these have been mostly at outfalls, source quality has been investigated principally as a function of street surface pollutants accumulated between rainfalls. In order to accommodate cause-effect relationships required for modeling, it is current practice to estimate potential street loadings, separately for individual parameters, on the basis of the few documented solids-accumulation histories. Arbitrary allowances are then added to account for off-street contaminant accumulations, expressed as multiples of the potential street loadings. Thus, no direct verification of the hypothesized buildup of pollutants and their transport to receiving waters is presently available. It is reasoned that when "pollutographs" generated by models reasonably approximate field observations for a catchment, that the overall accumulation and transport hypothesis is validated. As a result, it might be concluded that model development has already greatly outstripped the data base for model validation, in the sense of bracketing probable reliability.

Against this historical perspective is a viewpoint that deserves quoting: "There does not seem to be a 'perfect' model for analysis of stormwater. The models are either too complicated, do not allow for distributed inputs and parameters, do not simulate continuous streamflow, or have not been tested extensively on hydrologic data. ..... There remains much uncertainty in stormwater modeling. There appear to be enough parametric models available which have been shown to be feasible conceptualizations of the stormwater runoff process. What is needed now is a continued and accelerated verification of the existing models and a follow-up regionalization of the parameters."(76) All this will take some time.

A viewpoint from the United Kingdom is instructive: "Progress in hydrological modeling inevitably appears to involve more complicated procedures for the designer to implement and more information to be gathered. It is vital for the researcher to be aware of this and to ensure that recommended improvements are truly beneficial. For example, the present use of the U.K. RRL method is probabilistically unsound and too simple in terms of scientific hydrology. But unless a new method can be shown to give more accurately sized pipes and less costly protection against surface flooding, no amount of technical elegance will persuade the engineering profession to adopt it. It is this reluctance to accept anything which appears more complicated than is considered necessary that is sometimes responsible for recommendations that we return to simpler techniques. ..... Urban hydrological modeling in the U.K. continues to be geared primarily to the improvement of sewer design methods. The common aim is to seek a compromise between the mainly old, established, easily applied but theoretically unattractive methods, and the highly complex analytical models based on physical laws."(77)

Although the results are hardly universal, limited comparative study of models in Canada gives some indication of levels of reliability currently achievable: "On the average, about 70% of the simulated runoff volumes and peak flows, and 85% of the times to peak, were within ±20% of the observed values".(78,79) The tests were on data from catchments with a single gaging station.

Concluding Remarks

The principal local detrimental effects of flooding are damage to the belowground sections of buildings and hindrance of traffic. Human life is seldom threatened by the flooding of urban drainage facilities. Such facilities are designed so they will be overtaxed infrequently and provision of complete protection from flooding can only rarely be justified. A monumental question in the use of models is the choice of storms to be applied.(80) Storm definitions used for deriving river basin extremes are irrelevant because urban sewer systems are expected to be overtaxed much more frequently than major river structures whose failures could be catastrophic.

In terms of actual objective functions, the mean frequencies of occurrence of flow peaks and volumes and quality constituent amounts are the issue, not the frequencies of the input rainfall. Furthermore, because there are inherent non-linearities in most methods for processing inputs for linear models, and dynamic models are non-linear by definition, the statistics of the rainfall input array may differ appreciably from those of some or all of the arrays for runoff and quality characteristics. Attempting to assign a mean frequency of probable occurrence to a "design storm" can be meaningless because of likely statistical nonhomogeneity of rainfall, runoff and quality, and such an approach neglects the effects of prior storms on the runoff from a given storm. However, once we must extrapolate beyond the period of available rainfall records (50 to 70 years or so) for streamflow simulations, it is obvious that no reasonably reliable storm analysis criteria exist (such as for 100-year streamflow simulations) and in that circumstance there is no valid argument against the use of synthetic storms as inputs to models, as in river basin hydrology. But there are ways to test the validity of rare events by means of simulations using available rainfall records.[81] Even if very simple procedures are used, e.g. to determine only a peak flow rate, the collateral, occasional monitoring of computations by means of one of the more complete models can serve as an auxiliary guide to sharper judgment.

This paper has appeared, in a longer version, in a report for Ecole Polytechnique of Montreal.[82]

References

1. Schneider, W. J., and J. E. Goddard, Extent and Development of Urban Flood Plains, U.S. Geological Survey Circular 601-J, GPO, Washington, D.C., 14 pp., 1974.

2. McPherson, M. B., Urban Runoff Control Planning, U.S. EPA Miscellaneous Report Series, No. EPA-600/9-78-035, Office of Research and Development, Washington, D.C., 187 pp., October, 1978.

3. Massing, H., "Urban Hydrology Studies and Mathematical Modeling in the Federal Republic of Germany," ASCE UWRR Program Technical Memorandum No. IHP-6, ASCE, New York, N.Y., 50 pp., September, 1976. (NTIS No. PB 267 364).

4. McPherson, M. B., "Urban Hydrological Modeling and Catchment Research in the U.S.A.," ASCE UWRR Program Technical Memorandum No. IHP-1, ASCE, New York, N.Y., 49 pp., November, 1975. (NTIS No. PB 260 685).

5. Unesco, Research on Urban Hydrology, Volume 1, Technical Papers in Hydrology 15, Imprimerie Beugnet, Paris, 185 pp., 1977.

6. Geiger, W. F., and H. R. Dorsch, Quantity-Quality-Simulation (QQS), A Detailed Continuous Planning Model for Urban Runoff Control - "Vol. I, Model Description, Verification and Testing, and Applications," U.S. EPA Municipal Environmental Research Laboratory, EPA-600/2-80-001, 87 pp., March, 1980.

7. Desbordes, M., and D. Normand, "Urban Hydrological Modeling and Catchment Research in France," ASCE UWRR Program Technical Memorandum No. IHP-8, ASCE, New York, N.Y., 58 pp., November, 1976. (NTIS No. PB 267 524).

8. Huber, W. C., and J. P. Heaney, Urban Rainfall-Runoff-Quality Data Base, U.S. EPA Special Reports Series, EPA-600/8-77-009, 167 pp., July, 1977, et seq.

9. Metcalf and Eddy, University of Florida and Water Resources Engineers, Storm Water Management Model, Water Pollution Control Series, GPO, Washington, D.C.: Vol. I, "Final Report," 11024DOC07/71, July, 1971; and Vol. II, "Verification and Testing," 11024DOC08/71, August, 1971.

10. Torno, H. C., "Storm Water Management Models," pp. 82-89 in Urban Runoff, Quantity and Quality, ASCE, New York, N.Y., 1975.

11. University of Florida, Storm Water Management Model User's Manual, Version II, U.S. EPA Environmental Protection Technology Series, EPA-670/2-75-017, Cincinnati, Ohio 45268, 350 pp., March, 1975.

12. Torno, Harry C., Editor, Proceedings, Stormwater Management Model (SWMM) Users Group Meeting, 13-14 November, 1978, EPA Miscellaneous Report Series, No. EPA-600/9-79-003, 237 pp., November, 1978:
    a. "Revised SWMM Storage/Treatment," by S. J. Nix, J. P. Heaney and W. C. Huber, pp. 1-27.
    b. "Model for Selection of Stormwater Control Alternatives," R. Bedrosyan and J. Ganczarck, pp. 50-87.
    c. "A Pre- and Post-Processing Program Package for the Storm Water Management Model," by W. James, pp. 218-233.

13. Torno, H. C., Editor, Proceedings Stormwater Management Model (SWMM) Users Group Meeting May 4-5, 1978, U.S. EPA Miscellaneous Report Series, EPA-600/9-78-019, 244 pp., July, 1978.

14. Jewell, T. K., T. M. Nunno and D. D. Adrian, "Methodology for Calibrating Stormwater Models," J.Envir.Engrg.Div., ASCE Proc., Vol. 104, No. EE3, pp. 485-501, June, 1978.

15. Linsley, R., and N. Crawford, "Continuous Simulation Models in Urban Hydrology," Geophysical Research Letters, Vol. 1, No. 1, pp. 59-62, May, 1974.

16. Donigian, A. S., Jr., and N. H. Crawford, Modeling Nonpoint Pollution from the Land Surface, U.S. EPA Ecological Research Series EPA-600/3-76-083, 279 pp., July, 1976. (NTIS No. PB 257 089).

17. Litwin, Y. J., and A. S. Donigian, Jr., "Continuous Simulation of Nonpoint Pollution," J.WPCF, Vol. 50, No. 10, pp. 2348-2361, October, 1978.

18. Bravo, C. A., B. M. Harley, F. E. Perkins and P. S. Eagleson, "A Linear Distributed Model of Catchment Runoff," MIT Hydrodynamics Laboratory Report No. 123, Cambridge, Mass., 147 pp., June, 1970. (NTIS No. PB 194 289).

19. Terstriep, M. L., and J. B. Stall, The Illinois Urban Drainage Area Simulator, ILLUDAS, Bulletin 58, Illinois State Water Survey, Urbana, 90 pp., 1974.

20. Terstriep, M. L., and J. B. Stall, "Urban Runoff by Road Research Laboratory Method," J.Hyd.Div., ASCE Proc., Vol. 95, No. HY6, pp. 1809-1834, November, 1969. Authors' closure to discussion: Vol. 97, No. HY4, pp. 574-579, April, 1971.

21. Stall, John B., and Michael L. Terstriep, Storm Sewer Design — An Evaluation of the RRL Method, Environmental Protection Technology Series EPA-R2-72-068, GPO, Washington, D.C., 73 pp., October, 1972. (NTIS No. PB 214 314).

22. Terstriep, M. L., G. M. Bender and D. J. Benoit, "Buildup, Strength, and Washoff of Urban Pollutants," paper presented at ASCE Convention and Exposition, Chicago, October 16-20, 1978, ASCE Preprint 3439, 29 pp.

23. Mays, L. S., H. G. Wenzel, Jr., and J. C. Liebman, "Model for Layout and Design of Sewer Systems," J.Wat.Resour.Plan. & Mgt.Div., ASCE Proc., Vol. 102, No. WR2, pp. 385-405, November, 1976.

24. Dendrou, S. A., J. J. Talavage and J. W. Delleur, "Optimal Planning for Urban Storm Drainage Systems," J.Wat.Resour.Plan. & Mgt.Div., ASCE Proc., Vol. 104, No. WR1, pp. 17-33, November, 1978.

25. Jennings, M. E., and H. C. Mattraw, "Comparison of the Predictive Accuracy of

Models of Urban Flow and Water-Quality Processes," pp. 239-243 in "Proceedings National Symposium on Urban Hydrology, Hydraulics and Sediment Control," Report UKY BU111, University of Kentucky, Lexington, 386 pp., December, 1976.

26. Dawdy, D. R., J. C. Schaake, Jr., and W. M. Alley, Computer Program Documentation, User's Manual, Distributed Routing Rainfall-Runoff Model, USGS Water-Resources Investigations 78-90, Gulf Coast Hydroscience Center, NS TL Station, Miss., 146 pp., September, 1978.

27. Hydrologic Engineering Center, Corps of Engineers, "Hydrologic Engineering Methods for Water Resources Development: Volume 4, Hydrograph Analysis," Publication HEC-IHD-400, Davis, California, 122 pp., October, 1973. (NTIS No. AD 774 261).

28. Hydrologic Engineering Center, Corps of Engineers, "HEC-1, Flood Hydrograph Package," Generalized Computer Program 723-010, 609 2nd Street, Davis, California 95616, 186 pp., January, 1973.

29. Abbott, Jess, Testing of Several Runoff Models on an Urban Watershed, The Hydrologic Engineering Center, Corps of Engineers, Technical Paper No. 59, Davis, California, 43 pp., October, 1978.

30. Soil Conservation Service, Urban Hydrology for Small Watersheds, U.S. Department of Agriculture, Technical Release No. 55, 91 pp., January, 1975.

31. Espey, W. H., Jr., D. G. Altman and C. B. Graves, Jr., "Nomographs for Ten-Minute Unit Hydrographs for Small Urban Watersheds," ASCE UWRR Program Technical Memorandum No. 32, ASCE, New York, N.Y., 22 pp., December, 1977. (NTIS No. PB 282 158).

32. Roesner, L. A., et al., A Model for Evaluating Runoff-Quality in Metropolitan Master Planning, The Hydrologic Engineering Center, Corps of Engineers, Technical Paper No. 58, Davis, California, 73 pp., April, 1974.

33. Hydrologic Engineering Center, Corps of Engineers, "Storage, Treatment, Overflow, Runoff Model (STORM), Users' Manual," Computer Program 723-S8-L7520, 609 2nd Street, Davis, California 95616, 170 pp., August, 1977.

34. Hydrologic Engineering Center, Corps of Engineers, "Guidelines for Calibration and Application of STORM," Training Document No. 8, 609 2nd Street, Davis, California 95616, 48 pp., December, 1977.

35. Metropolitan Sewerage District of the County of Milwaukee and Stevens, Thompson & Runyan, Inc., "Phase One, Volume One, Technical Report, Combined Sewer Overflow Pollution Abatement," Milwaukee, Wisconsin, 114 pp., 1975.

36. Hayes, Richard J., "HEC Computer Programs for Urban Water Handling: HEC-1, HEC-2, and STORM," pp. 369-377 in "Proceedings, International Symposium on Urban Hydrology, Hydraulics and Sediment Control," Report UKY BU114, University of Kentucky, Lexington, December, 1977.

37. Kühner, Jochen, and Michael Shapiro, Discussion of "Urban Runoff Pollution Control – State-of-the-art," J.Envir.Engrg.Div., ASCE Proc., Vol. 102, No. EE1, pp. 220-223, February, 1976.

38. Meta Systems, Inc., Land Use-Water Quality Relationships, U.S. EPA, Water Quality Guidance report WPD 3-76-02, Water Planning Division, 233 pp., March, 1976.

39. Heaney, J. P., W. C. Huber and S. J. Nix, Storm Water Management Model: Level I – Preliminary Screening Procedures, Environmental Protection Technology Series EPA-600/2-76-275, U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, Ohio, 77 pp., October, 1976. (NTIS No. PB 259 916).

40. Proctor and Redfern, Ltd., and James F. MacLaren, Ltd., Storm Water Management Model Study, Volume II, Research Program for the Abatement of Municipal Pollution under Provisions of the Canada-Ontario Agreement on Great Lakes Water Quality, Research Report No. 48, Environment Canada, Ottawa, 148 pp., September, 1976.

41. Sarma, P. B. S., J. W. Delleur and A. R. Rao, "Comparison of Rainfall-Runoff Models for Urban Areas," J.Hydrology, Vol. 18, pp. 329-347, 1973.

42. Papadakis, Constantine N., and Herbert C. Preul, "Testing of Methods for Determination of Urban Runoff," J.Hyd.Div., ASCE Proc., Vol. 99, No. HY9, pp. 1319-1335, September, 1973. Authors' closure to discussion: Vol. 101, No. HY3, pp. 542-544, March, 1975.

43. Heeps, David P., and Russell G. Mein, "Independent Comparison of Three Urban Runoff Models," J.Hyd.Div., ASCE Proc., Vol. 100, No. HY7, pp. 995-1009, July, 1974. Authors' closure to discussion: Vol. 102, No. HY1, pp. 93-94, January, 1976.

44. Brown, J. W., M. R. Walsh, R. W. McCarley, A. J. Green and H. W. West, "Models and Methods Applicable to Corps of Engineers Urban Studies," U.S. Army Engineer

Waterways Experiment Station Misc. Paper H-74-8, Vicksburg, Mississippi, 420 pp., August, 1974.

45. Marsalek, J., T. M. Dick, P. E. Wisner and W. G. Clarke, "Comparative Evaluation of Three Urban Runoff Models," Water Resources Bulletin, Vol. 11, No. 2, pp. 306-328, April, 1975.

46. Huber, Wayne C., "Modeling for Storm Water Strategies," APWA Reporter, Vol. 42, No. 5, pp. 10-14, May, 1975.

47. Chow, V. T., and B. C. Yen, Urban Stormwater Runoff: Determination of Volumes and Flowrates, Environmental Protection Technology Series EPA-600/2-76-116, GPO, Washington, D.C., 240 pp., May, 1976. (NTIS No. PB 253 410).

48. Brandstetter, Albin, Assessment of Mathematical Models for Storm and Combined Sewer Management, Environmental Protection Technology Series EPA-600/2-76-175a, GPO, Washington, D.C., 510 pp., August, 1976. (NTIS No. PB 259 597).

49. Hossain, A., J. W. Delleur and A. R. Rao, "Evaporation, Infiltration and Rainfall-Runoff Processes in Urban Watersheds," Water Resources Center Technical Report No. 41, Purdue University, West Lafayette, Indiana, 63 pp., January, 1974. (NTIS No. PB 229 642).

50. Metcalf & Eddy, Inc., Palo Alto, California, Development and Application of a Simplified Stormwater Management Model, Environmental Protection Technology Series EPA-600/2-76-218, U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, Ohio, 139 pp., August, 1976. (NTIS No. PB 258 074).

51. Lager, J. A., "A Simplified Stormwater Management Model for Planning," pp. 259-279, Short Course Proceedings, Applications of Stormwater Management Models, 1976, Environmental Protection Technology Series EPA-600/2-77-065, U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, Ohio, 435 pp., March, 1977. (NTIS No. PB 265 321).

52. Young, G. K., "Non-Point Source Impact and Urban Holding Capacity," pp. I-98 to I-121 in Proceedings, Urban Stormwater Management Seminars (Atlanta and Denver), U.S. EPA, Water Quality Management Guidance report WPD 03-76-04, Washington, D.C., 482 pp., January, 1976. (NTIS No. PB 260 889).

53. Young, G. K., "Decision Perspectives on Urban Storm Water Pollution," Water Resources Research, Vol. 12, No. 1, pp. 94-100, February, 1976.

54. Systems Control, Inc., Palo Alto, California, "Use of Mathematical Models for Water Quality Planning," WRIS Technical Bulletin No. 3, Department of Ecology, State of Washington, 212 pp., June, 1974.

55. Systems Control, Inc., Evaluation of Water Quality Models: A Management Guide for Planners, Socioeconomic Environmental Studies Series EPA-600/5-76-004, GPO, Washington, D.C., 176 pp., July, 1976.

56. Pentland, R. L., P. J. Reynolds and Asit K. Biswas, "Water Quality Modeling: State-of-the-Art," pp. 481-496, Vol. 3, Proceedings of International Symposium on Modeling Techniques in Water Resources Systems, May 9-12, 1972, Ottawa, Canada.

57. Canale, Raymond P., Ed., Modeling Biochemical Processes in Aquatic Ecosystems, Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 500 pp., February, 1976.

58. Gordon, R., and M. Spaulding, "A Bibliography of Numerical Models for Tidal Rivers, Estuaries and Coastal Waters," Marine Technical Report 32, University of Rhode Island, Narragansett, R.I. 02882, 55 pp., 1974.

59. Hinwood, Jon B., and Ian G. Wallis, "Classification of Models of Tidal Waters," J.Hyd.Div., ASCE Proc., Vol. 101, No. HY10, pp. 1315-1331, October, 1975. Authors' closure to discussion: Vol. 102, No. HY12, pp. 1776-1777, December, 1976.

60. Hinwood, Jon B., and Ian G. Wallis, "Review of Models of Tidal Waters," J.Hyd.Div., ASCE Proc., Vol. 101, No. HY11, pp. 1405-1421, November, 1975. Authors' closure to discussion: Vol. 103, No. HY4, pp. 453-455, April, 1977.

61. Lombardo, P. S., "Critical Review of Currently Available Water Quality Models," Hydrocomp, Inc., 101 pp., July, 1973. (NTIS No. PB 222 265).

62. Lassiter, Ray R., Modeling Dynamics of Biological and Chemical Components of Aquatic Ecosystems, Ecological Research Series EPA-660/3-75-012, GPO, Washington, D.C., 54 pp., May, 1975. (NTIS No. PB 241 987).

63. Parker, R. A., and D. Roop, "Survey of Aquatic Ecosystem Models," The Institute of Ecology, Washington, D.C., 131 pp., 1974.

64. Willey, R. G., Water Quality Evaluation of Aquatic Systems, The Hydrologic Engineering Center, Corps of Engineers, Technical Paper No. 38, Davis,

California, 20 pp., April, 1975.

65. Hydrologic Engineering Center, U.S. Army Corps of Engineers, "Water Quality for River-Reservoir Systems," Davis, California, 279 pp. plus append., October, 1978.

66. Wenzel, H. G., Jr., J. W. Labadie and N. S. Grigg, "Detention Storage Control Strategy Development," J.Wat.Resour.Plan. & Mgt.Div., ASCE Proc., Vol. 102, No. WR1, pp. 117-135, April, 1976.

67. Labadie, J. W., N. S. Grigg and B. H. Bradford, "Automatic Control of Large-Scale Combined Sewer Systems," J.Envir.Engrg.Div., ASCE Proc., Vol. 101, No. EE1, pp. 27-39, February, 1975.

68. Trotta, Paul D., John W. Labadie and Neil S. Grigg, "Automatic Control Strategies for Urban Stormwater," J.Hyd.Div., ASCE Proc., Vol. 103, No. HY12, pp. 1443-1459, December, 1977.

69. Earl, C. T., et al., "Urban Flood Warning and Watershed Management Advances in Metropolitan Melbourne," ASCE UWRR Program Technical Memorandum No. 30, ASCE, New York, N.Y., 72 pp., June, 1976. (NTIS No. PB 259 549).

70. Nguyen, V-T-V., M. B. McPherson and J. Rousselle, "Feasibility of Storm Tracking for Automatic Control of Combined Sewer Systems," ASCE UWRR Program Technical Memorandum No. 35, ASCE, New York, N.Y., 29 pp., November, 1978. (NTIS No. PB 294 611).

71. McPherson, M. B., (Editor), "Utility of Urban Runoff Modeling," ASCE UWRR Program Technical Memorandum No. 31, ASCE, New York, N.Y., 126 pp., July, 1976. (NTIS No. PB 261 460).

72. Alley, William M., Guide for the Collection, Analysis and Use of Urban Stormwater Data, ASCE, New York, N.Y., 115 pp., 1977.

73. Prawdzik, Ted B., Milwaukee DPW, "Environmental and Technical Factors for Open Drainage Channels in Milwaukee," ASCE UWRR Program Technical Memorandum No. 12, ASCE, New York, N.Y., 37 pp., February, 1970. (NTIS No. PB 191 710).

74. Tucker, L. S., "Sewered Drainage Catchments in Major Cities," ASCE UWRR Program Technical Memorandum No. 10, ASCE, New York, N.Y., 71 pp., March 31, 1969. (NTIS No. PB 184 705).

75. Gburek, William J., Discussion of "Hydrologic Consequences of Rainfall

Augmentation," J.Hyd.Div., ASCE Proc., Vol. 97, No. 12, pp. 2114-2115, December, 1971.

76. Overton, Donald E., and Michael E. Meadows, Stormwater Modeling, Academic Press, New York, 358 pp., 1976.

77. Lowing, M. J., "Urban Hydrological Modeling and Catchment Research in the United Kingdom," ASCE UWRR Program Technical Memorandum No. IHP-4, ASCE, New York, N.Y., 23 pp., July, 1976. (NTIS No. PB 262 069).

78. Marsalek, J., "Urban Hydrological Modeling and Catchment Research in Canada," ASCE UWRR Program Technical Memorandum No. IHP-3, ASCE, New York, N.Y., 52 pp., June, 1976. (NTIS No. PB 262 068).

79. Marsalek, J., Urban Hydrological Modeling and Catchment Research in Canada, Technical Bulletin No. 98, Canada Centre for Inland Waters, Burlington, Ontario, 52 pp., 1976.

80. Patry, Gilles, and M. B. McPherson, Editors, "The Design Storm Concept," Seminar Proceedings, Departement de Genie Civil, Groupe de Recherche sur l'Eau en Milieu Urbain, Report EP79-R-20 GREMU-79-01, Campus de l'Université de Montréal, Case Postale 6079, Succursale A, Montréal, Québec H3C 3A7, Canada, 92 pp., December, 1979.

81. Shubinski, Robert P., and William N. Fitch, "Urbanization and Flooding, an Example," pp. 69-73 in Environmental Modeling and Simulation, Office of Research and Development and Office of Planning and Management, U.S. Environmental Protection Agency report EPA-600/9-76-016, 847 pp., July, 1976. (NTIS No. PB 257 142).

82. McPherson, M. B., "Overview of Urban Runoff Tools of Analysis," Departement de Genie Civil, Groupe de Recherche sur l'Eau en Milieu Urbain, Report EP79-R-20 GREMU-79-01, Campus de l'Université de Montréal, Case Postale 6079, Succursale A, Montréal, Québec H3C 3A7, Canada, 31 pp., April, 1979.