Proceedings
1983 International Symposium on Urban Hydrology, Hydraulics and Sediment Control

July 25-28, 1983

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11,700 km^2. In the Denver metropolitan area the use of radar also showed, according to Henz[13], that for rains larger than 0.5 inch there are preferred tracks which appeared to be linked to repeatable orographic effects and weather causes. These and other studies have shown the importance of considering the preferred directions of travel of rainstorm in urban hydrology. Rain cells have substantial speeds and intensity variations across areas of the size of urban watersheds. James and Robinson[14] have shown that for the City of Hamilton, Ontario, more realistic results are obtained if the kinematics of the storm cells are considered in urban hydrologic studies. A model was presented in which a moving band of rain cells cause rainfall intensities that decay exponentially from the center of the band.

The integration of an automated rainfall data acquisition system and communication system with state-of-the-art rainfall-runoff models makes it possible to develop real time runoff forecasting. This technology has been adopted at a number of sites for flood warning purposes. Gatlinburg, Tennessee (Hauser et al.[15]) and Boulder, Colorado (DeGroot[16]) are examples of two communities which have implemented real time flash flood forecasting systems. In the Boulder case, the forecasts of expected rainfall depth and duration are made using radar and other meteorological tools. Damant et al.[17], however, question the usefulness of radar rain forecasting for wastewater control because of the inherent errors in the forecasts. In their experience in Montreal, using the McGill Weather Radar Observatory and nine recording raingages on the Island of Montreal, they found that the absolute errors in comparing the measured one-hour rain accumulations at the position of the raingages to the forecast accumulations expected 1, 2, and 3 hours in advance, were 68%, 89%, and 102%, respectively with the radar measurement adjusted for individual storm bias. The error could be reduced by reducing the radar resolution from 4.8 km x 7.5 km to 1 km x 1 km, for example. However, much of the error is attributable to the stochastic nature of the rain cells.

Initial Abstraction and Infiltration

Interception, depression storage and infiltration are important abstractions or losses from rainfall, yet their determination is largely uncertain. The Soil Conservation Service (SCS) method has been popular among urban hydrologists for the determination of the initial abstraction and infiltration. However, a number of recent papers have indicated limitations and shortcomings of the method. Hjelmfelt[18] has shown that with this method the infiltration does not approach a terminal equilibrium rate. Morel-Seytoux et al.[19] also point to the fact that the method calculates initial abstractions which are independent of the rainfall intensity, which is not in agreement with the fluid mechanics of infiltration. However, the advantage of the method is that the curve number, CN, is calibrated on a large amount of good data. For this reason Morel-Seytoux and Verdin[20] have related the hydraulic soil parameters to the CN values.

Actually urban runoff models are, in general, more sensitive to the correct determination of the impervious area than to the infiltration. Alley and Veenhuis[21] have shown that large differences in results can be obtained depending on whether the total impervious area is used or the effective impervious area (i.e. that directly connected to the drainage system). Use of the total impervious area may yield overestimated runoff volumes and peak flows. As the intensity of urbanization increases, the effective impervious area increases faster than the total impervious area, thus increases in simulated runoff due to an increase in urbanization may be smaller if the total rather than the effective impervious area is used.

Pollutants

Novotny and Kincaid[22] have shown that acid contribution to urban rainfall is due to traffic and local industrial sources which significantly decrease the pH of local precipitation. However, the dissolution of calcium and magnesium from the pavements is effective in buffering this elevated acidity.

Pollutant quantities in precipitation have been found by Randall et al.[23] to be present in sufficient quantities so as to exert a significant impact on the quality of surface water runoff. The ground surface loadings of atmospheric pollutants are independent of the magnitude or intensity of the rainfall because atmospheric contaminants are washed out during the first stages of rainfall. Highly impervious commercial areas are pollutant sources, but other less impervious land uses are pollution sinks.

Roesner[24] gives an idea of the pollution potential of stormwater by comparing the qualities of combined sewer overflows in San Francisco, and stormwater quality data collected in Seattle to standard water quality for drinking and for swimming. In the first case a large pollution potential exists with respect to suspended solids, COD, BOD, nitrogen, phosphorous and metals while in the second case metals, with iron and lead in particular, exceed the limits of the standards.

Recent studies have suggested that the accumulation of constituents is not linear and that there is a limit to the amount of constituents that can accumulate between storms, regardless of the length of the dry period. Exponential accumulation have been used, for example, by Smith and Alley[25] in the USGS Rainfall-Runoff-Quality model for urban watersheds. To simulate the washoff of constituents from urban land surfaces an exponential decay equation is commonly used. An alternative method has been proposed by Alley et al.[26] which is based on sediment transport equations. This method provides a daily accounting of the particulate buildup and considers bedload, suspended load, particle size fractions and bed armoring.

Impact on Receiving Waters and Control

It has been observed that the average five-day biochemical oxygen demand (BOD_5) concentration in combined sewer overflow is approximately one half that in raw sanitary sewage. Separate sewer stormwater has solids concentrations equal to or greater than untreated sanitary wastewater and the BOD_5 is approximately equal to that of secondary effluents. Urban runoff has thus been identified as a significant pollutant source of receiving streams. EPA's Storm and Combined Sewer Program has investigated the receiving stream impacts. A summary of that investigation has been given by Field and Turkeltaub.

A continuous simulation model for receiving water quality has been developed by Medina et al.[28] to evaluate the stream response to the separate or combined effects of waste inputs from wet-weather urban sources, dry-weather urban sources and upstream sources. The model can be interfaced with continuous urban hydrology simulation models. The model can be used for preliminary planning and screening of areawide urban wastewater treatment alternatives. This evaluation is done in terms of frequency of violation of pollutant concentrations in the receiving stream and in terms of the D.O. profile. The model has been applied to Des Moines, Iowa. In addition, a mathematical model of the pollutant mass transport through various components describes the transient response of storage/treatment systems to variable flows and pollutant concentrations[29,30,31]. The model is based on the one-dimensional, transient concentration of mass equation. This equation is applied to represent the movement, decay, storage and treatment of stormwater runoff pollutants. The response of storage/treatment systems to variable flows and pollutant concentration was obtained under either one of two assumptions: a completely mixed system of constant and variable volume of a one-dimensional advective system with or without dispersion. The methods were successfully applied to the Humbold Avenue detention tank in Milwaukee, Wisconsin and to Des Moines, Iowa and the Des Moines River. These applications showed that the receiving water response is sensitive to the detention time in the storage/treatment facility during periods of urban runoff.

Hydraulic Conveyances

The dominant hydraulic characteristics of urban drainage basins are the large impervious surfaces of streets, parking lots, roofs, etc., the man-made flow conveyances, such as curbs, gutters lined channels and sewers and the appurtenances to guide, contain or modify the quantity or quality of urban runoff. Typical appurtenances are catch basins, storage basins, inlets, manholes, weirs, outfalls, etc... With regard to overland flow Chen[32] has proposed a generalized Manning formula.

$$n = [n_o^2 + (1.486\ \nu\ C/8g\ S_o^{1/2}\ R^{4/3})^2]^{1/2}$$

where n_o and C depend on the slope and roughness concentration. Empirical curves to obtain C and n_o are given for astroturf. This generalized Manning formula is similar to the Colebrook-White equation for pipe flow and is asymptotic to the laminar flow equation and to Manning's formula.

The Federal Highway Administration has sponsored a study of the hydraulic characteristics of three kinds of inlet grates which exhibited bicycle safety and hydraulic and debris handling efficiency. The results have been reported by Chang et al.[33].

Constantinides and Stephenson[34] extended the kinematic wave model for overland flow to account for sheetflow over a topography varying in elevation in two directions.

Substantial effort has been devoted to the formulation and improvement of models for the dynamic flow routing models in sewer systems including the effects of surcharge. Because of moving hydraulic jumps, backwater and water hammer, the pressurization of storm sewers is a very dynamic process which requires the use of the complete dynamic equations. The EXTRAN module of SWMM (version III), for example, performs dynamic routing of stormwater flows through storm drainage systems including branched or looped networks, backwater conditions, free surface flow, pressure flow or surcharge flow, flow reversals, flow transfer by weirs, orifices, pumps and on- and off-line storage (Roesner et al.[35]). A similar simulation model for stormsewers has been developed in the U.K. by the Hydraulics Research Station (Price[36]). A package of subroutines for optimal storm sewer design to be used with a generalized dynamic program code that can consider complex branching networks and user specified cost functions was prepared by Robinson and Labadie[37].

Detention Basins

As urbanization causes a reduction in the natural retention capacity of the watershed, man-made detention storages are often utilized to reduce the peak rate of runoff, often to the predevelopment value. Detention basins are used as the primary stormwater management control in response to the storm sewer overloads resulting from rapid development of urban areas. A survey of local and public agencies throughout the United States and parts of Canada was conducted in 1980 by the American Public Works Association to determine the current practices in stormwater management with emphasis on detention storage. An analysis of this survey by Poertner[38] showed an average of 58 detention facilities per community and that nearly 40% of the communities without detention facilities indicated that they are being built or planned. The dry type basin is the most popular followed by shallow storage of runoff on parking lots. 12% of the detention facilities are reported in use for groundwater recharge while 3% have specific multiple purpose uses.

The growing importance of detention facilities as a technique of stormwater management is reflected by the special conference held in the summer of 1982 on the planning, design and operation of these facilities (DeGroot[39]).

Sometimes detention basins are used indiscriminately on all new developments rather than when they are deemed necessary. It must be remembered that although detention basins are effective in controlling some flooding problems, they also create some maintenance, health and other problems. As a result Debo[40] recommends that local ordinances include a comprehensive stormwater management program which addresses such questions as maintenance and location of detention facilities to produce the most benefits, interrelationship between separate detention facilities, etc. In a study of the Denver area Urbonas and Glidden[41] found that randomly located detention ponds to control the 100 year flood can be effective for smaller watersheds while their effectiveness decreases as the watershed size increases, and such ponds are not effective in controlling more frequently occurring storms.

Further research is needed in developing the tradeoffs between onsite and regional detention. If there are several detention basins, the interaction (timing) between several outflow hydrographs must be considered so that the peak flow rate from each individual area does not exceed the percentage of predevelopment flow rate that is contributing to critical downstream points. This concept of release rate percentage was developed in a pilot study recently completed for Allegheny County (Pittsburgh area) by Lakatos and Kropp[42], and by Smith and

Lakatos[43]. This study followed the guidelines of the 1978 Pennsylvania Storm Water Management Act which requires individual counties to prepare management plans on a watershed basis.

Research is needed for the development of methodologies for the optimal planning and placement of a detention basin network to achieve the best performance of the overall system. Flores et al.[44] and Mays and Bedient[45] have proposed a dynamic programming model for the determination of size and location at minimum cost. Flores et al. applied the dynamic programming algorithm to three synthetic watersheds representative of the Houston area. Based on the results of this study they concluded that detention storage is usually only needed in the upper part of the urban watershed. Mays and Bedient extended this study. Their methodology can handle constraint on discharge, storage and basin area. The depth of the basin must be specified and the detention basin is assumed to have vertical sides. The methodology does not optimize the size of the basin spillway, nor does it consider quality constraints.

Dendrou and Delleur[46] presented a coordination resource allocation approach to explicitly resolve the choice of site location and size of detention facilities on a watershed wide basis. The storage capacity of each subbasin is allocated so that it satisfies a portion of the uphill storage requirement, subject to local topographic constraints. The controlled overflows and pollutant loads are likewise allocated to the several subbasins. The allocation of storage and overflows from each subbasin is solved by considering two levels of decision: one at the local level concerned with the sizing of the detention basins so as to avoid flooding, the other at the watershed level concerned with the most economical treatment plant and detention storage allocation while maintaining acceptable pollution standards.

While various stormwater management techniques have been proposed for improving the quality of urban runoff, the use of detention basins is probably the most effective. Whipple[47] remarks that insufficient information is available regarding the efficiency of basins for the removal of different kinds of pollutants or regarding the integration of the quality and quantity requirements. However, Whipple states that in order to provide removal of particulate pollutants at moderate costs, the water quality and flood control objectives must be achieved in the same structure. As small floods have much higher concentrations of pollutants, a dual purpose detention basin should hold the runoff from small storms for a prolonged duration while the basin should operate for flood control of the larger storms. This may be achieved by using two outlets, a retention outlet, typically a small outlet slightly higher than the permanent pool level, and another outlet or spillway for flood control. For this reason Rossmiller[48] has summarized the hydraulics of outlet structures for detention facilities.

Kamedulski and McCuen[49] examined the response to flow and discharge of a dual purpose detention basin in Montgomery County, MD. For detention storage to provide optimum protection and to meet the intent of the stormwater policies the design must consider land use, storm duration, simultaneous consideration of volume and outlet characteristics and soil characteristics as they affect the trap efficiency.

Randall et al.[50] summarize the results of a laboratory study of the efficiency of sedimentation for the removal of pollutants from urban stormwater. They conclude that TS, lead and BOD, in that order, were removed most effectively, and that substantial reductions were obtained for all other pollutants except the soluble forms of nitrogen. Further, they found that, except for lead, the pollutant removals did not correlate well with TSS removal.

Combined Sewer Overflows

Chan and Bras[51] derived the probability density function for the volume of water above a given threshold discharge. This is based on the joint probability density function of rainfall intensity and duration along with expressions based on the kinematic wave theory of overland flow. The distribution can be applied to the design of detention volume for combined sewer overflows. Loganathan and Delleur[52] in addition derived the distribution of pollutant concentration level in the water receiving body based on probability distributions of runoff volume and of concentration of pollutant upstream of the overflow point. The exceedence probability of combined sewer overflows depends on the rate of treatment, storage volume and an urbanization factor. This implies that the minimization of the overflow pollution will increase the drainage cost. The results of this analytical model compared well with those of the simulation model 'STORM'. The derived distribution of pollutant concentration in the river downstream of the overflow point makes it possible to formulate a multiple objective optimization which minimizes the risk of polluting the river downstream, minimizes the cost of land development and drainage and provides the best land use plan.

Field[53] summarized EPA's storm and combined sewer program which emphasizes an optimal use of existing sewerage system for the dual purpose of combined sewer drainage and overflow pollution control. Porous pavements were also investigated Field et al.[54]. A wide number of management alternatives for wet and dry weather wastewater transport, ranging from special sewer shapes, use of polymer injections to several mechanical regulators and concentrators have been investigated.

Elementary Rainfall-Runoff Models

One of the significant advances in the past few years has been the increased use of computers. Many of the usual desktop procedures have been programmed for programmable calculators and for mini and micro-computers. The books by Croley[55,56] are examples of this trend. Many programs have become available in BASIC which is the computer language most often used with personal micro-computers. For example, a recent article in Civil Engineering[57] gave a BASIC program for flood routing. Micro-computers, according to W. James and Robinson[14], provide an excellent tool for urban stormwater management. Micro-computers can receive digital information from remote raingages, streamflow sewers, process the information in a useful format, store it on disc or cassette, or transmit it to a central computer for further analysis (Ormsbee and Delleur[58]). The unit hydrograph has been the object of several studies. Among these is the study by Pederson et al.[59] which extends the theory of the single linear reservoir model and presents a new relationship to estimate the reservoir constant. In a comparison of several peak discharge and unit hydrograph methods, Riley[60] states that Espey's 10-minute unit hydrograph and the SCS dimensionless unit hydrograph are acceptable desktop methods.

Large Scale Models

During the last five years simulation models have been gaining ground over mathematical and conceptual models in terms of use and confidence in the results. Dendrou[61] has given an overview of urban stormwater models. From this review it is clear that the number of simulation models has not increased significantly but that many have been substantially improved and extended.

Characteristic of these improvements is the Storm Water Management Model (SWMM), developed and maintained by the U.S. Environmental Protection Agency, which has been extensively modified and extended by Huber et al.[62]. The principal changes in Version III include continuous simulation, revised storage/treatment routines, snowmelt, runoff quality generation, updated graphical and tabular output and scour-deposition in the Transport Block. The most significant change is the inclusion of the Extended Transport Block (EXTRAN) for quantity routing. EXTRAN developed by Roesner et al.[35], solves the complete St. Venant equations and accounts for backwater, looped connections, surcharging and pressure flow. Comparisons between SWMM and other models have been given by Huber and Heany[63]. EPA has organized user group meetings that have met biannually in the US and in Canada. These meetings have served as a forum for discussions of new applications of SWMM and new developments in urban runoff modeling.

The second version of the USGS Distributed Routing Rainfall-Runoff Model (DR_3M-QUAL) consists of two separate programs documented by Alley and Smith[64]. The rainfall-runoff part has been extended and provides three options for the kinematic wave routing. These include a formulation of the method of characteristics which in turn includes a method for avoiding the kinematic shock problem. The other two routing options include implicit and explicit finite difference solutions. The quality component of the model is new. It considers three sources of pollutants in the runoff: the contributions from the impervious areas, from the pervious areas and the precipitation contributions. Between storms a daily accounting is maintained of the pollutants on the impervious areas. The quality component of the model can be applied on either a lumped or a distributed parameter basis. For the distributed parameter simulation a Lagrangian method is used to simulate the transport of constituents through the channel segments. A plug flow scheme is used to model the transport of constituents through reservoir segments.

In view of the expansion and increased use of urban hydrologic models it is desirable to consider the optimal estimation of parameters and to compare the several objective functions used in optimal parameter estimation. Rao and Han[65] have shown that the regeneration and prediction performances of the models ILLUDAS, SWMM and MINNOUR are improved through parameter optimization. Methods of parameter estimation based on least squares were less effective than those based on the maximum likelihood method, and in particular, the method proposed by Sorooshian and Dracup[66] was particularly effective. Examples of applications of the principal models have been given by Torno[67].

Nationwide Urban Runoff Program

The Environmental Protection Agency developed the Nationwide Urban Runoff Program (NURP) in response to the Clean Water Act of 1977. During the period of 1978-1983 NURP will assess the nature, cause and severity of urban runoff problems and the means of controlling the nonpoint sources of pollution from urban areas. The final report is due to Congress later in 1983. The U.S. Geological Survey is cooperating in the data acquisition of many of the projects.

The overall goal of NURP is to develop information that will assist in determining whether or not urban runoff is causing water quality problems and, in the event that it is, to provide a basis for realistic control options[68]. Fourteen individual NURP projects emphasize water quality impacts on rivers and streams, four on bays and estuaries, eight on lakes and two on groundwater. These 28 projects nationwide cover a wide range of climatic and hydrologic regimes.

Some of the tentative conclusions obtained from the preliminary report of EPA are the following. The data base significantly exceeds the total pool of data available from other sources. This will, of course, improve the confidence in any conclusion obtained. The underlying probability distribution for COD, suspended solids, total phosphorus, lead and copper appears to be lognormal. This makes it possible, for example, to define storm runoff concentrations in a concise way, to make statements concerning the frequency with which concentration of any magnitude will occur and to examine water quality impacts in terms of potential for significant threats to beneficial use. Figure 1, taken from EPA's preliminary report, illustrates the rationale which NURP expects to use to evaluate the extent to which pollutants discharged by intermittent, variable urban runoff may impair beneficial uses of receiving waters. Figure 1a shows the frequency with which various concentration levels occur in the receiving water body. This is to be compared to receiving water target concentrations that relate to specific beneficial use or different degrees of impairment of the water body. Figure 1b illustrates the benefit to be expected for different degrees of control of urban runoff. Heavy metals (especially lead, zinc and copper) are much more prevalent in urban runoff than organic priority pollutants, thus heavy metals appear to have the greatest potential for impact on aquatic life while organic priority pollutants do not appear to pose a threat to fresh aquatic life. Groundwater does not appear to be threatened by pollutants in urban runoff caused to percolate through the ground. Some detention basins are very effective at reducing pollutant concentrations in urban runoff; while some detention basins have a variable performance, being fairly good for some storm events and quite poor for others, some other detention basins consistently perform poorly. Finally, street sweeping is effective in its original purpose.

The most important results of NURP and detailed reports of several of the specific projects were presented at a special Symposium convened by the author as part of the Spring Meeting of the American

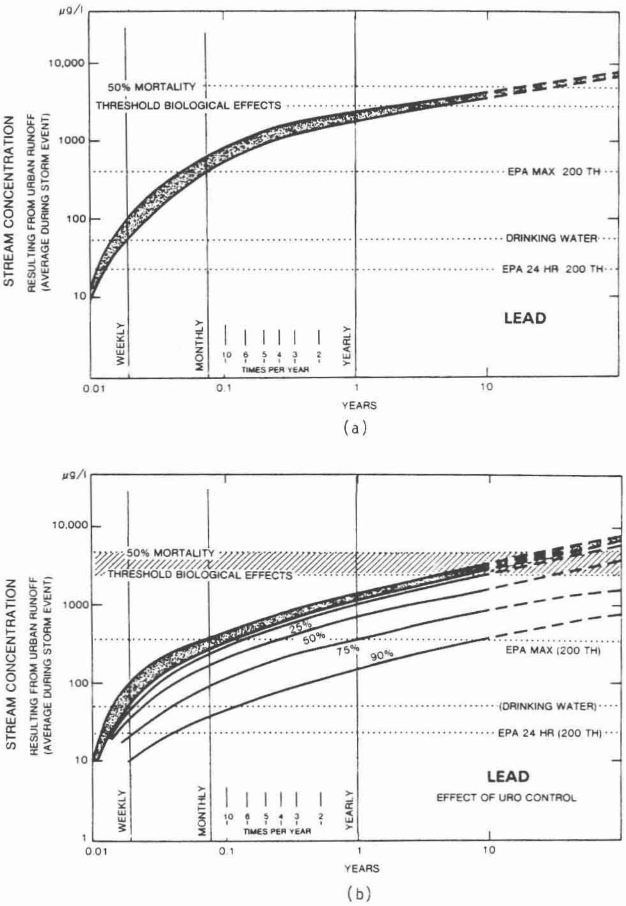

Figure 1. Mean Recurrence Intervals for Lead Concentrations.

Geophysical Union in Baltimore, May 30 - June 3, 1983. Athayde[69] summarized the principal findings from EPA, while Middleburg and Lystrom[70] reviewed the U.S. Geological Survey Urban Studies. Schelly[71] dealt with a situation frequently encountered in water quality data when a number of data values are reported as "less than" some value, usually the detection limit for the particular pollutant, and he proposed a framework for treating this information in a consistent and logical fashion. Driscoll[72] analyzed statistically the performance of recharge basins for control of urban runoff. The level of control is related to size or application density as a function of regional rainfall differences and soil percolation rates. Jennings and Doyle[73] reviewed the use of the deterministic model DR_3M-QUAL in the USGS urban stormwater investigations, the effect of the degree of segmentation detail and water quality results. The effect of coarse as opposed to fine segmentation on the flow was small and the water quality results compared favorably to those obtained by statistical multiple regression. Among the specific projects Hey[74] discussed the Glen Ellyn detention lake near Chicago, Kappel et al.[75] presented the results of the Irondeqoit Creek basin near Rochester, New York, Martin et al.[76] and Katz et al.[77] presented the results of the Baltimore study, Terstriep[78] discussed the merits of street sweeping in Champaign, Illinois, Finan[79] discussed the results of the Winston-Salem-Forsyth County Project, and Ku[80] reviewed the effects of urban storm runoff on groundwater in Long Island, New York.

U.S.G.S. Urban Studies

The U.S. Geological Survey is cooperating in ten projects of the Nationwide Urban Runoff Program. In all of these a comprehensive data base of rainfall, runoff quantity and quality is being collected. The deterministic models DR_3M and DR_3M-QUAL are used in five of these projects[73]. In addition the U.S. Geological Survey has performed studies in other urban areas such as Miami, Florida; Portland, Oregon; and Denver, Colorado. In Florida three small basins were selected in the region of Fort Lauderdale. The basins were homogeneously developed. The land uses were: commercial, single family residential and high traffic volume highway. Regression analyses relating water quality constituents loads to hydrologic and antecedent characteristics of storms were performed. According to Miller and Mattraw[81], the greatest amount of variation was accounted for by the peak discharge for all three types of basin and in addition by the number of hours prior to the storm in which 0.25 inch of rainfall accumulated for the low density residential area and by the rainfall amount for the highway basin. It was also concluded that the atmospheric input to the overall runoff quality from urban basins is important and should be considered as an integral component in any urban runoff program.

The data base being compiled by the U.S.G.S. will contain (1) watershed characteristics such as drainage area, land use and impervious area, (2) unit rainfall and runoff data and (3) water quality data. In addition there is a plan for a compilation of basin characteristics and maps showing the physical features of basins and other information required for the calibration of models.

Conclusions

The completion of the EPA/USGS Nationwide Urban Runoff Program will serve as a catalyst to advance the science of urban hydrology in the United States. A much needed data base has been obtained and a better understanding of the effectiveness of alternative stormwater management techniques has been gained.

Due to the randomness of rainfall and the desirability to characterize the pollution impact of urban runoff on receiving streams, in terms of its magnitude and frequency of occurrence, it is likely that continuous simulation models will play an increasingly dominant role while single event models will tend to be used primarily for the design of storm sewer systems.

It appears that rainfall forecasting coupled with appropriate hydrologic models will produce better predictions of runoff quantity and quality. This could lead to new developments in automatic operation of sewer systems.

In spite of the great advances much research remains to be done. Sonen[82] feels that the current perception of runoff quality tends to be limited to immediate and pressing regulatory requirements. To overcome these limitations he advocates more comprehensive theory and sampling and filling the many information gaps through research.

Perhaps some of these gaps are the response of natural receiving waters to time varying urban runoff loads; rates constants and kinetics of water quality formulation; the transport and deposition of suspended matter; the selection of the proper model; the resolution of conflicting requirements of drainage versus flood control, water quality objectives and budgeting constraints.

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