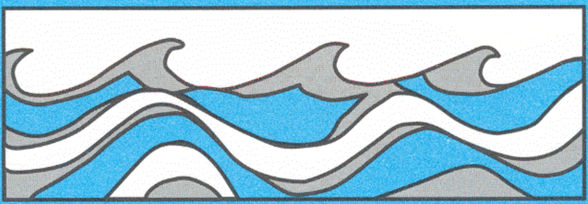
University of Washington
Department of Civil and Environmental Engineering

HYDROLOGIC MODELING AND DATA REQUIRMENTS FOR ANALYSIS OF URBAN STREAMFLOW MANAGEMENT ALTERNATIVES

Gary J. Kemp
Stephen J. Burges



Water Resources Series
Technical Report No. 57
November 1978

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Hydrologic Modeling and Data Requirements For Analysis of Urban Streamflow Management Alternatives

by

Gary J. Kemp and Stephen J. Burges

Technical Report No. 57

November 1978

Project Completion Report:	The Feasibility of Implementing a Continuous Simulation Hydrologic Model for Urban Drainage System Design
Project Period:	October 1, 1977 to September 30, 1978
Principal Investigator:	Stephen J. Burges, Associate Professor of Civil Engineering, University of Washington
OWRT Project Number:	A-092-WASH
OWRT Agreement Number:	14-34-0001-8051

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ABSTRACT

Attention has been focused recently on management of urban runoff as one means of protecting water quality. Experience gained during Area-wide Waste Management planning in King and Snohomish Counties (Washington) has shown that analytical methods currently in use are generally inadequate for comprehensive and reliable watershed analysis. Continuous simulation hydrologic modeling is a tool that may be feasible for providing better information for decision making.

The modeling needs and desires of several potential model users in the two Counties, and their perceptions of models, are identified through personal interviews. The literature is reviewed for the perceptions of professional modelers; these are compared with those of the potential users. Inconsistencies are noted and resolved. Criteria for evaluating continuous simulation models for local use are developed. General characteristics of several models are examined. Variations of the Stanford Watershed Model (SWM) are found to be the only models having the desired characteristics and are evaluated as a group in detail. It is concluded that the SWM can provide better information than more commonly used methods. It is recommended that the Hydrocomp Simulation Processor II (HSP II) should be implemented as the model best suited to local needs. The primary model limitation is its demands for data, particularly rainfall records, and the cost associated with data development and handling.

A system of data development in conjunction with establishment of watershed planning priorities is suggested. Other recommendations for implementation are made. The recommendations for use of the Continuous Simulation approach are not limited to the two counties examined here.

Keywords: Urban Hydrology; Hydrologic Modeling; Water Resources Planning

PREFACE

The work reported here resulted from our interest in developing ways to improve urban watershed planning and management. Professional model builders have made claims of varying validity about particular model capabilities. Various model users have encountered many and different types of difficulties when using models with which they had not had extensive experience. We were particularly interested in finding ways to incorporate known empirical knowledge of watershed dynamics into planning at both the land development (small parcels) and total watershed scales.

Mathematical representations of urban surface hydrologic phenomena are of two types: event based, and continuous simulation. Criteria reflecting both user needs and model capabilities were sought to determine which methods were suitable for analyzing urban runoff management strategies. The work reported here supports the continuous simulation approach; the best model appears to be HSP II (the Hydrocomp Simulation Processor II) which will be available publicly from the Athens, Georgia Office of the Environmental Protection Agency (EPA) after November 1, 1978. Our recommendation of this model is in no way an endorsement of Hydrocomp, Palo Alto; at present, however, their approach satisfies all criteria developed here.

While the approach developed here was for a specific location the methods are applicable anywhere. The important issue for anyone attempting to determine which approach to implement is to explore the totality of user needs, model capabilities, and model data needs. Cost effectiveness can be assessed for establishing relevant data networks throughout one or several counties to obtain economies of scale.

ACKNOWLEDGEMENTS

We would like to express our appreciation to the persons who participated in this work via personal interviews: Clair Olivers (City of Everett); John Galt and Tracy Gill (Snohomish County): John Buffo, Jeff Bauman, Barry Uchida, and Rod Spencer (Municipality of Metropolitan Seattle); and Tom Nesbitt, Donovan Tracy, Brad Gillespie, and George Wanamaker (King County). Without their cooperation it would not have been possible to identify local modeling needs. Many others contributed to the development of our ideas; we apologize for not listing them all.

Many thanks go to Jennifer Brown, without whose fast and accurate assistance this report would still be in preparation, and to Mike Bertman, who helped with the graphics. Ellen Phillips typed the final manuscript.

The work reported here was originally presented by the first author in partial fulfillment of the requirements of the M.S.E. degree. The work was supported by a grant from the Office of Water Research and Technology administered by the State of Washington Water Research Center.

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CHAPTER 1

INTRODUCTION

HISTORICAL BACKGROUND

Management of urban runoff has been focused until recently on two complementary issues: prevention of flood damage and conversion of wetland to intensive urban uses by draining. In both cases, the usual approach has been to collect water at many points within a property and direct it off-site via pipes. Traditional design methods have supported this "out of sight, out of mind" philosophy which had its origins in remarkably effective means for improving public health and making urban areas more livable.

Recent events, however, have revealed the shortcomings of this approach. Water quality issues have been stressed by an expanding public consciousness and given statutory emphasis by the Federal Water Pollution Control Act Amendments of 1972 [Public Law (PL) 92-500]. Urban drainage management has been analyzed under Section 208 of PL 92-500, which deals with areawide waste management planning, and more specifically, with control of non-point sources of pollution. In this context, it is no longer appropriate nor acceptable to discharge runoff downstream from one's property without considering the possible consequences and providing mitigating measures as needed. Since the careful consideration of urban runoff quantity is a prerequisite for adequate analysis of quality problems, and because hydrologic systems in urban and suburban areas are complex (see McPherson and Schneider, 1974), more sophisticated analytical methods than those generally in use may be justified.

METHODS PRESENTLY USED FOR SYSTEM PLANNING AND DESIGN

Most urban drainage system design to date has been based on the so-called "Rational Equation," which relates peak runoff rate to watershed area, percent imperviousness, and rainfall intensity. This approach results in a conservative design well suited to the collection and conveyance application mentioned above, but which is not appropriate for use in predominantly pervious areas, large watersheds, areas undergoing land use modification, and many other applications. The weaknesses of the method are well documented in the literature (e.g., Chow, 1964; McPherson and Schneider, 1974), yet its use persists. Despite the fact that it has been largely discredited, new applications continue to be published, particularly in journals directed at public works officials (Yrjanainen and Warren, 1973); Mitci, 1974; Pagan, 1974; Overton and Meadows, 1976). Such applications may, indeed, be valid for some circumstances; the fact remains that if the basic assumptions of the Rational Method are not met, any application may be badly in error.

Many designers and planners have recognized the need for more flexible and realistic tools. To meet this end, cause-effect models using rainfall as the driving function have been developed. Linsley (1971), Huber (1975), and Brandstetter (1976) have identified many available models; there are undoubtedly many more which were not listed. All models currently in use are of two types: single event or continuous simulation.

The large majority of models are of the event type, defined below. Definition of "continuous simulation" is deferred until some additional background has been provided.

An "event" model derives its name from the fact that it is concerned with representing a single rainfall-runoff occurrence. The input to the model may range from a single number representing peak rainfall intensity, e.g., models based on the Rational Method, to a sequence of rainfall volumes completely specifying the time distribution of rainfall (hyetograph). The internal representation of the rainfall-runoff process may also vary from a simple linear relationship to non-linear functions representing the physical processes in the watershed. The model output is a representation of surface runoff resulting from the storm used as input, generally including an estimate of peak rate and total volume of runoff. An estimate of the time record of runoff (hydrograph) may also be provided based on short time intervals. If precipitation is specified for ten minute intervals, the hydrograph is also given for that time step.

Regardless of the characteristics of a given model, all event models are concerned with only the single runoff record resulting from a single precipitation event, either observed or hypothesized for planning or design. For example, a design application may use a hypothesized hyetograph for a 25-year return period storm of six hour duration.

The primary problem arising from the use of event models is that there is no fixed relationship between the probability of the selected design rainfall event and the probability of the resulting runoff. The implicit (and erroneous) assumption of event models is that the two probabilities are the same. McPherson and Schneider (1974) identified this as a significant modeling difficulty; Linsley (1971) and Olivers (1976) showed some of the variation in runoff that may result for a given set of initial conditions and different rainfall patterns.

During much of 1976 and 1977 the first author worked on the urban runoff management elements of the SNOMET/King County 208 and the King County/Cedar-River Basins 208, hereafter called the SNOMET[*] and METRO[*] 208's, respectively. Figure 1.1 shows the 208 planning boundaries within the two counties. Project elements included the evaluation of existing procedures for runoff management and development of strategies for controlling urban non-point pollution sources. The capabilities of the analytical methods, including computer models, currently used were compared with the questions they were being asked to answer and, in many cases, were determined to be inadequate.

Chapter 2 discusses the background of drainage management in King and Snohomish Counties, the goals and expectations of municipal planners and engineers, and problems experienced in the past in detail. In particular, three factors are important here:

1. Despite the availability of computer models for drainage planning and design, they were not well utilized prior to the 208 planning.
2. Although the practice of rapid collection and discharge of runoff was recognized at the policy level as incompatible with water quality and aesthetic goals, the analytical methods in use were not correspondingly modified, resulting in de facto continuation of the old policy.
3. Attempts during the 208 planning to apply the Environmental Protection Agency (EPA), Storm Water Management Model (SWMM Huber, et al., 1975, 1976) and another event model (Systems Control, Inc., _et al._, 1973, and modifications revealed significant shortcomings of both models as planning and design tools.

PROJECT PURPOSE AND SCOPE

In view of the apparent inadequacies of the major analytical techniques currently in use, the objective of this work is to evaluate another modeling tool which is available but has not been utilized widely in urban runoff management applications: continuous simulation hydrologic models.

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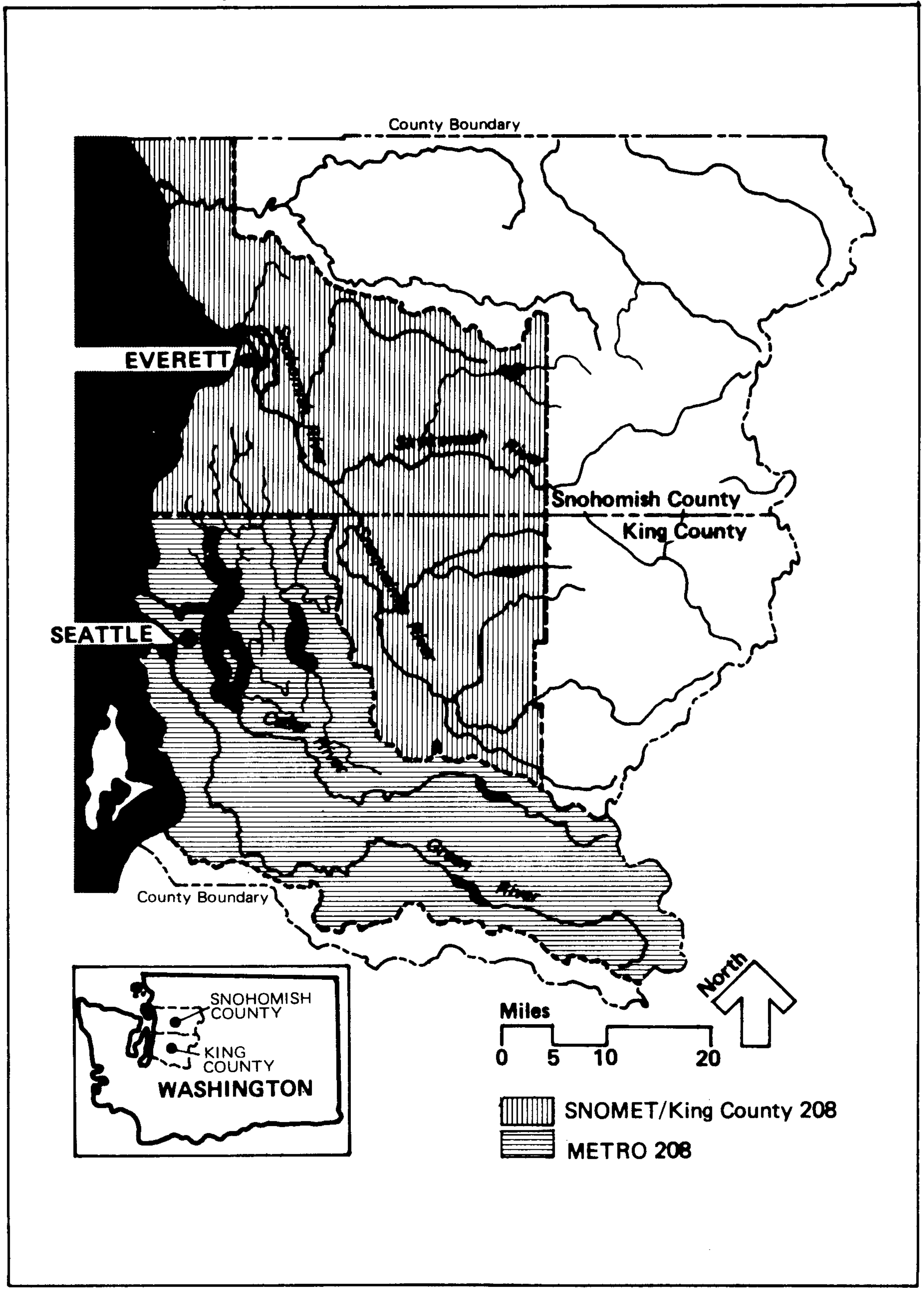
[*] SNOMET is an acronym for Snohomish County Metropolitan Municipal Corporation, and METRO is derived from Municipality of Metropolitan Seattle.

FIGURE 1.1 King and Snohomish Counties, Washington, and 208 Planning Areas



A continuous simulation model differs from an event model by providing a running account of all moisture entering and leaving the boundaries of a watershed (or sub-area) over an extended period of time. The term "continuous" is derived from the nature of the model output, which depicts the continuous streamflow at one or more locations in the watershed. An example, output might be hourly flows for a ten-year period, or daily flows over 25-years plus hourly flows for the largest flood within each year. The exact nature of the output can be varied for a given application, but the general idea is to simulate, or "synthesize" the flow sequence which would have been recorded for a given watershed condition if a streamgage had been in position for the extended time period (James, 1965).

An equation or series of equations represents each of the component processes of the hydrologic cycle, e.g., infiltration, surface runoff, or groundwater (base) flow. By defining properly the parameters of the equations, watershed dynamics are modeled conceptually and water movement accounted for from the time it enters as precipitation to the time it exits as streamflow, evapotranspiration, or inactive groundwater loss. By making appropriate changes in the parameters, some gross effects of land use changes and channel modifications may be modeled. A long synthesized record can be developed for each watershed condition, providing a basis for probability analysis, performance analysis of alternative management strategies, etc. (James, 1965, 1972).

To facilitate this evaluation, the planning and design objectives of municipal officials are identified via personal interviews with potential model users. Their familiarity with perceptions of various models are assessed and the capabilities desired of any model in addressing the needs of the users are determined. An extensive literature review describes the perceptions of professional modelers relative to modeling approaches, capabilities and limitations. The perceptions of the users and the modelers are then integrated and criteria for model evaluation are developed.

A number of hydrologic computer models reported as having continuous simulation capability are investigated and screened, eliminating those obviously inappropriate in the context of the criteria developed for model evaluation. The characteristics of the remaining models, all of which are derived from the Stanford Watershed Model (Linsley and Crawford, 1960), are then evaluated in detail. The modeling literature is consulted for model documentation and applications. Conclusions are drawn as to the capabilities and limitations of the models in fulfilling the desires of the potential users.

Finally, specific recommendations are made for model application for urban drainage planning and design in King and Snohomish Counties. Necessary implementation steps and additional investigations are also suggested.

CHAPTER 2

URBAN DRAINAGE MODELING:
PERCEPTIONS OF POTENTIAL MODEL USERS

LOCAL PERSPECTIVE

King and Snohomish Counties (Washington) encompass several cities and extensive urban, unincorporated areas, in which much of the growth in the past ten to fifteen years has occurred. Figure 2.1 shows the western part of the two counties and their major cities, and Table 2.1 indicates the population of the major municipalities. Drainage planning has, until recently, been dealt with on a development-by-development basis, relying primarily on Rational Method analysis for system design; comprehensive planning has not been conducted widely.

King County

In 1974 the City of Bellevue initiated steps to form a drainage utility with the specific goal of preserving its extensive natural stream system. Many difficulties, primarily financial and political, caused considerable delay in implementing the concept, however.

Long-range drainage plans for Bellevue were completed in the summer of 1976 and the city has progressed toward implementing them. The plans presented several alternative management scenarios, ranging from a completely structural (i.e., pipe) solution to an option which stressed sacrificial flooding of many areas and controlled release dates from temporary ponding sites.

Since its plans are complete, an analysis of problems and solutions for Bellevue would not be pertinent to this project. Nonetheless, Bellevue's concern for the preservation of its natural stream system set the stage for similar efforts by other jurisdictions.

King County began to deal with urban runoff formally by passing King County Ordinance 2281 in 1975 and amending it as Ordinance 2812 in 1976. Once again, an effort to maintain existing streams as well as to provide drainage provided the impetus. Under Washington State Law, however, (Revised Code of Washington, Chapter 36.94), a county may not provide water, sewer, or drainage utility services until a comprehensive plan for an area has been prepared. A lack of funds for such planning prevented King County from proceeding until the 208 plans were begun.

FIGURE 2.1 Major Municipalities, King, and Snohomish Counties

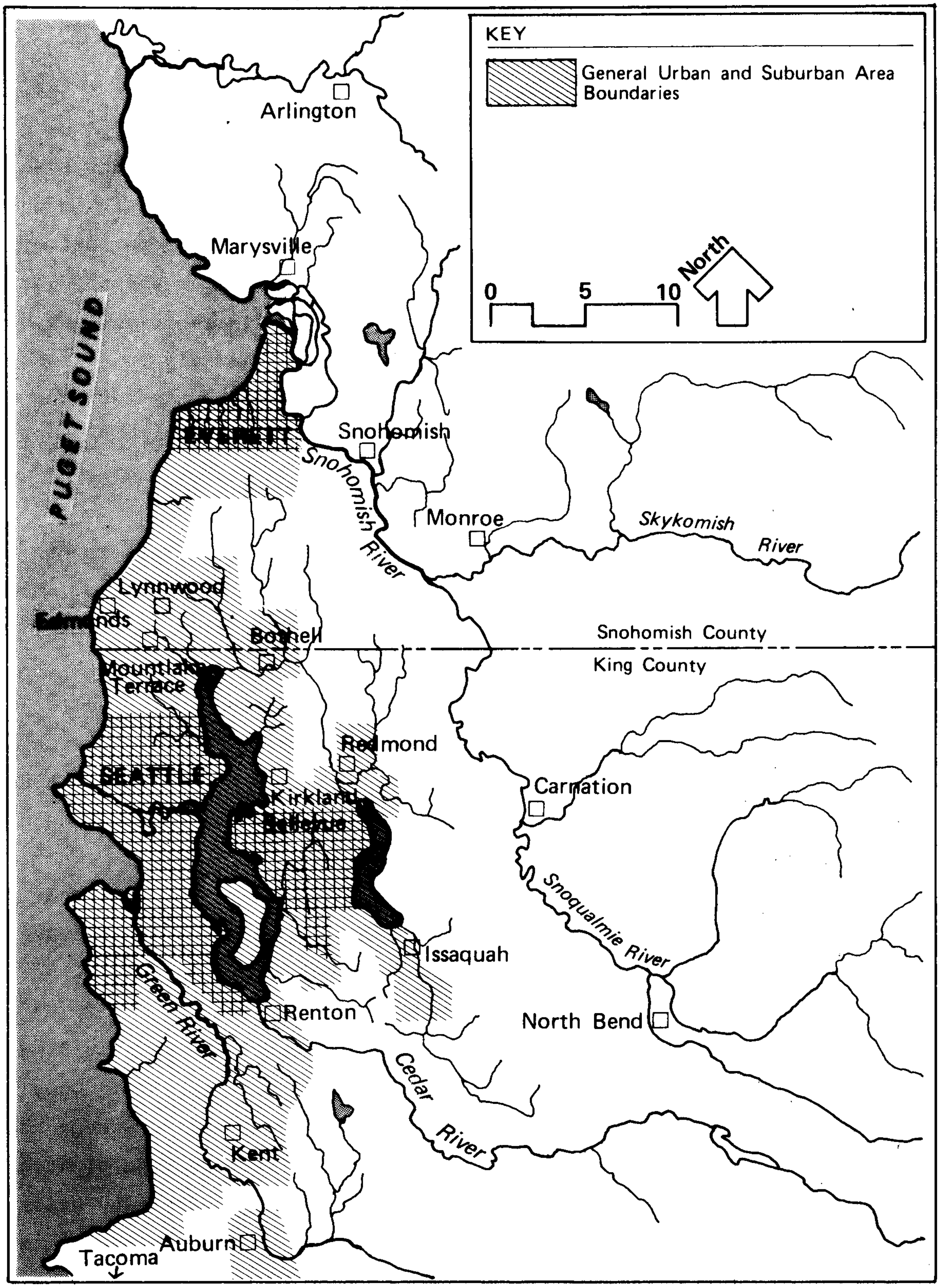


TABLE 2.1

POPULATION OF MAJOR MUNICIPALITIES, KING AND SNOHOMISH COUNTIES, WASHINGTON: 1970 and 1977

Municipality	Population* 1970	1977	Notes
King County	1,159,375	1,164,400	
Unincorporated Area	411,750	423,640	
Auburn	21,653	23,055	(1)
Bellevue	61,196	68,500	
Bothell	4,979	6,295	(1)
Carnation	530	639	(1)
Des Moines	3,951	6,730	(2)
Issaquah	4,341	5,078	(1)
Kent	16,596	18,250	
Kirkland	15,070	15,350	
Normandy Park	4,202	4,500	
Redmond	11,020	17,757	(1)
Renton	25,878	27,150	
Seattle	530,831	500,000	
Snohomish County	265,236	278,200	
Unincorporated Area	127,952	135,715	
Arlington	2,261	2,675	
Brier	3,093	3,000	
Edmonds	23,998	26,115	
Everett	53,622	51,700	
Lynnwood	16,919	21,450	(2)
Marysville	4,343	4,720	
Monroe	2,687	2,725	
Mountlake Terrace	16,600	16,550	
Mukilteo	1,369	1,360	
Snohomish	5,174	4,935	

*1970 figures are official U.S. Census (1970) totals, 1977 figures are taken from "State of Washington Population Trends 1977," Population Studies Division, Office of Financial Management, Olympia, Washington, August 1977.

Notes: (1) 1977 figure is result of official local census.

(2) Large increase in population partly explained by annexation of significant area at expense of county unincorporated area population.

As part of the METRO 208, Juanita Creek was selected as the watershed for which a comprehensive plan would be prepared. Juanita Creek is a seven square mile, partially urban watershed located on the northeast side of Lake Washington and just north of the City of Kirkland (see Figure 2.2). The EPA Storm Water Management Model (SWMM) was chosen as the model to apply, primarily because of its ready availability and because it was considered the top-of-the-line model for such applications (J. Buffo, METRO, 1978; personal communication).

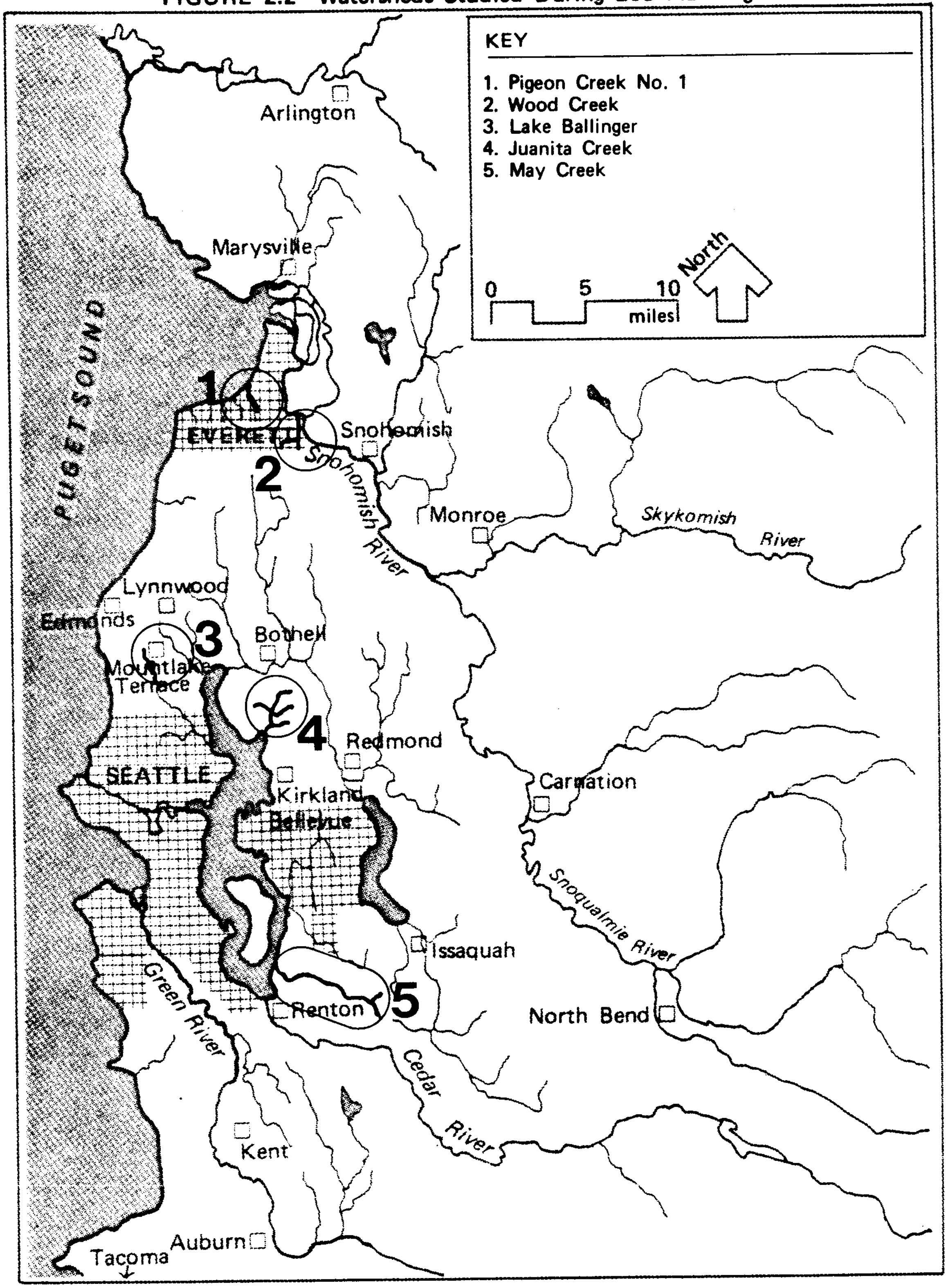
The objective of the Juanita Creek project was to document the procedure necessary to apply SWMM as a comprehensive planning tool in King County. For example, program modifications needed to adapt the program to the King County computer system and input data gathering procedures and format were documented. The experience gained through the use of SWMM in this manner was intended to provide a basis for comprehensive planning in other watersheds.

The Juanita Creek plan was completed in late 1977 after nearly one and one-half years of effort. Although King County intends to use SWMM in the near future for May Creek (see Figure 2.2), this choice is primarily because a better model is not readily available (D. Tracy, King County Planning, 1978; personal communication). Despite the time and money invested in SWMM, the Juanita Creek experience demonstrated several shortcomings of the model as a planning and design tool for the County. These are discussed in the next section of this Chapter.

Other municipalities in King County, such as Auburn, Kent, and Bothell, have done little historically to manage runoff other than by using the Rational Method approach. Since the 208 plans were begun, however, these cities have followed the lead of the County. As a first step, drainage ordinances modeled after King County Ordinance 2812 or the "Model Drainage Ordinance" prepared for the SNOMET 208 are being considered or have been adopted already. Comprehensive planning has not yet begun, however. It is likely, based upon work experience and interviews with public officials in the past, that these cities will continue to lag behind the county, but will eventually adopt whatever procedures King County implements.

Another major jurisdiction within King County is the City of Seattle; the drainage problems of the city are unique in the county in that the city is developed virtually to its maximum potential. Although many drainage problems

FIGURE 2.2 Watersheds Studied During 208 Planning



are evident in the city, measures to deal with them are remedial rather than preventive. Comprehensive plans are underway for two small streams in the city (Longfellow Creek in West Seattle and Thornton Creek in North Seattle), but the options available for effective management are limited. Because comprehensive drainage planning is most effective in a preventive context, and because other local jurisdictions are concerned primarily with preventive planning, analysis of the problems and analytical needs of Seattle are not included here.

Since the 1950's METRO has been the regional agency most concerned with water quality management. METRO was the lead agency for the regional wastewater facilities planning (Section 201, PL 92-500) as well as for the 208 plan. Although METRO has the authority under its enabling legislation (Revised Code of Washington, Chapter 35.58) to coordinate drainage planning, design, and construction, it has not done so to date, preferring rather to have King County act as the lead agency.

This work focusses therefore on the problems, goals, and objectives of King County, the municipality, as the major actor in urban drainage planning and design, and on METRO as the agency most responsible for water quality protection within the geographical boundaries of King County.

Snohomish County

In 1973, the Snohomish County Planning Department began a series of long-range utilities plans using several computer models (Systems Control, Inc., et al, 1973). Population allocation, demand forecasting, and storm drainage planning were some of the components. In addition to providing a means of planning for unincorporated areas, the project was intended to produce a series of models that would be available for continuing use by the County and cities within the County. The model package was called WASH-USE-1.

The drainage program used a modified version of the "Curve Number" rainfall-runoff method developed by the U.S. Department of Agriculture,Soil Conservation Service (Soil Conservation Service, 1972). The program was developed to analyze flood control requirements and did not have provisions appropriate for comprehensive planning, such as the ability to simulate runoff from storms of different return periods.

Since 1973, and prior to 208 planning, some modifications were made to the original WASH-USE-1 model, primarily in data handling; further modifications were made during the SNOMET 208 so that the model now conforms closely to SCS procedures. The model is now called SNODOB and, like SWMM, is an event model.

During the 208 planning, the model was applied to three watersheds: Pidgeon Creek No. 1 and Wood Creek by the City of Everett, and the Lake Ballinger area by METRO and the two counties (see Figure 2.2). In all three cases the model was actually operated by the Snohomish County systems analyst subject to guidance from engineers and planners of the cities and counties.

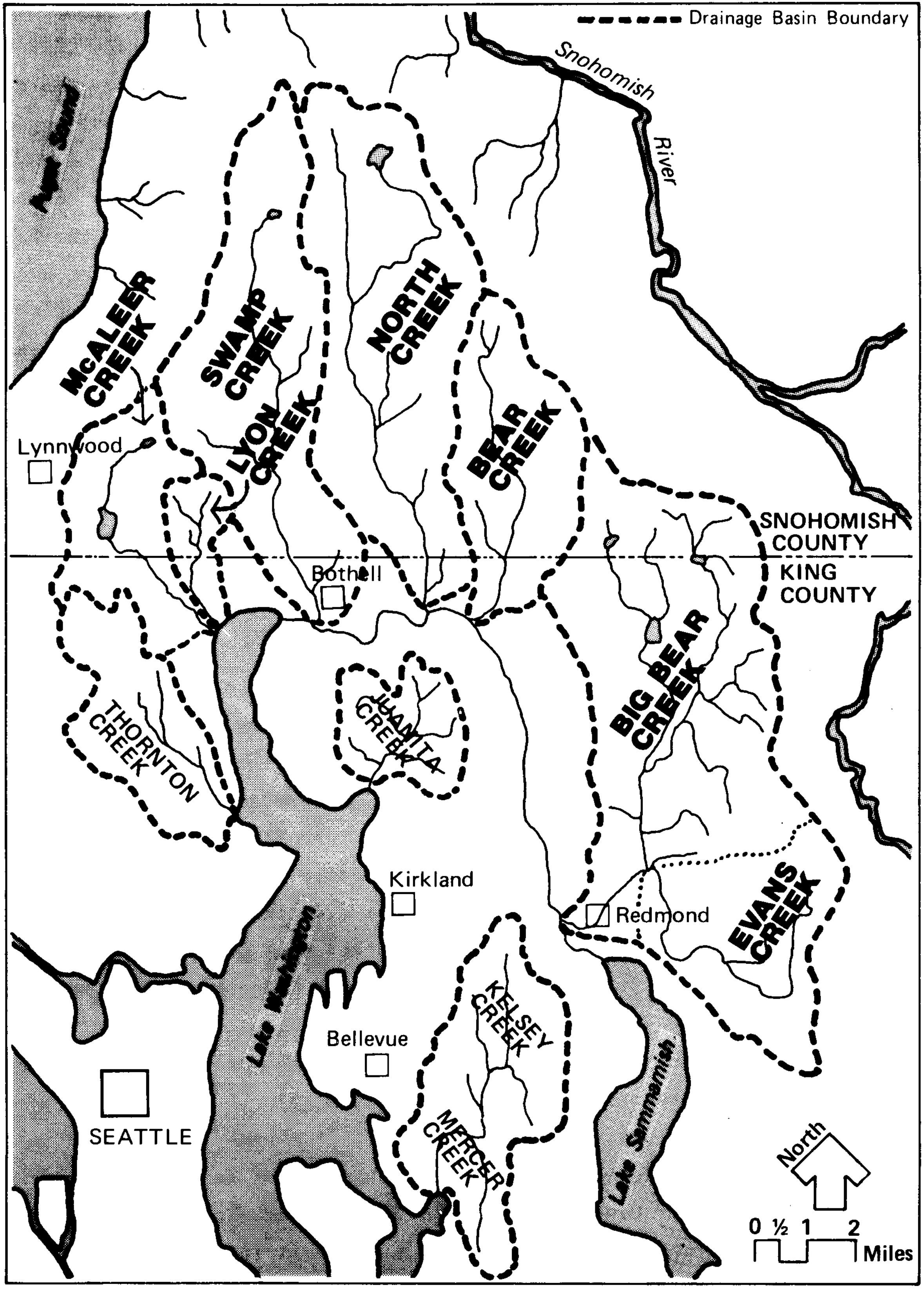
Prior to these applicaitons the model had never been used for comprehensive urban drainage planning by any cities in Snohomish County, nor by the county itself other than the original WASH-USE-1 project. [The models were used during the development of the Snohomish River Basin Plan (Systems Control, Inc., and Snohomish County Planning Department, 1974) as aids for overall water quality management rather than comprehensive planning.] Comprehensive drainage plans based on Rational Method analysis had been prepared in Edmonds and Lynnwood in the early 1960's. These have been updated very recently without the use of computer models (L. Larson and W. Nims, respectively, 1976; personal communications). Everett conducted a preliminary study of drainage problems in the South Everett area in 1973, but did not prepare a comprehensive plan. Mountlake Terrace has never prepared its own plans, although the Lake Ballinger study covered much of that city.

Everett was most active in drainage planning of the cities listed above during the 208 planning. Several small drainage basins in South Everett still hold opportunities for comprehensive planning. In contrast, development in Lynnwood, Edmonds, and Mountlake Terrace has been rapid in recent years, and drainage planning is now limited to anlaysis of small, isolated parcels of land (W. Nims, L. Larson, and C. Rautenberg, respectively, 1976; personal communications). These municipalities have adopted or are considering adoption of the SNOMET Model Ordinance. Nonetheless, it appears that Snohomish County and the City of Everett are at present the primary actors in Snohomish County runoff management. Mountlake Terrace, Lynnwood, and Edmonds will become more important as the planning approach of the two Counties becomes more defined, because of interjurisdictional considerations as described below.

Inter-County Planning

There are six watersheds common to both counties (excluding the Snoqualmie River Basin): McAleer Creek, Lyon Creek, Swamp Creek, North Creek, Bear Creek, and Evans/Big Bear Creek. As many as six municipalities are involved in a given watershed (Swamp Creek). Figure 2.3 shows these basins and the municipalities

FIGURE 2.3 Inter-County Watersheds



involved. Inter-jurisdictional cooperation clearly will be needed for effective drainage management.

The urban drainage element of the Cedar-Green River Basins Study - commonly referred to as the RIBCO Study - (U.S. Army Corps of Engineers, 1974b) analyzed the drainage problems of these six basins (among many others) and presented alternative management plans for each. An earlier version of SWMM than that used for the Juanita Creek study was used for these plans. Although these basin plans did identify potential drainage problem areas, each plan was developed for simplified conditions; closer examination of the channel system data used in modeling and the streamflows upon which the plans were based for North Creek (Kemp and Tang, 1976), Juanita Creek, and May Creek has shown that significant errors may exist in the plans. In addition, these six basins have been undergoing rapid urbanization. Consequently, there is a pressing need for development of updated and accurate comprehensive plans on a multi-jurisdiction basis.

LOCAL PROBLEMS, GOALS, AND NEEDS IN DRAINAGE MANAGEMENT

The two local 208 plans devoted considerable attention to urban drainage management. As a result, the responsible officials in the municipalities involved were in a good position to summarize their experiences, define problems encountered during the planning, and identify their desires and objectives for further urban runoff work. The first author was in an unique position as well, having conducted interviews with officials early in the development of the 208's and participated in the planning, and was therefore in a position to offer firsthand comments.

A runoff management questionnaire, reproduced as Table 2.2, was developed for this project and distributed to the persons identified in Table 2.3. The questionnaire was not intended as a mail-back form but rather as a framework for conducting personal interviews, which were held in early February 1978, and continued at intervals throughout this project. The initial interviews with both King County departments were held jointly, as were those with Snohomish County personnel. Additional comments on the questionnaire were made by Nick Dobos, Snohomish County systems analyst, through John Galt (Snohomish County Planning Department); Craig Thompson (City of Everett,Public Works Department) also provided valuable information through conversations held during 1976.

The interview results are discussed in full in Appendix A and are summarized below. [Comment] denotes comments or clarifications provided by the author.

TABLE 2.2

RUNOFF MANAGEMENT QUESTIONNAIRE

1. What rainfall-runoff prediction method is currently endorsed and/or used by your personnel for drainage planning?

   ______ Rational Method ______SCS Curve Number Method ______Other (Specify)

   Do you consider the method to be adequate? ______ If not, why? Why is the method being used now?

2. What is the average size of development proposals (acres) with which you deal? What is the usual pre-development land use?

3. Have you identified drainage basins which need overall drainage planning (comprehensive planning)? How many? What sizes? (Names and locations, if possible.) Are any of these basins shared with other municipalities? If so, which ones?

4. Do you currently have methods for satisfactorily determining both magnitude and timing of flows from development, sub-watersheds, and entire drainage basins? If so, what methods? What consititutes "satisfactory" for your purposes?

5. Are you familiar with any computer models which could be used for drainage planning? Which model(s)?

   Have you used any models for this purpose? Which one(s)? What level of areal resolution do you perceive necessary to use such models? (Watershed only, sub-watershed, 40 acres, 10 acres, etc.)

6. Based upon your experience with or understanding of computer models, what would you like a model to do and how accurately?

   Determine overland flow rates and volumes?
   Determine channel flow rates and volumes?
   Assist in pipe or channel design?
   Optimize pipe/channel/retention area design?
   Other?

7. Would it be valuable to your planning efforts to know the probability of occurrence of a given flow in a stream? If so, what typical probability levels (recurrence intervals) are of interest?

8. Which of the following represent the major issues that a comprehensive plan must address? (Identify others, if necessary)

   (a) Identify areas which, now or in the future, will be subject to:

      (i) flooding.
      (ii) erosion of streambanks and channels
      (iii) sedimentation of stream channels and ponds
      (iv) erosion of land surfaces

   (b) Identify the runoff changes and impacts which would result from a given land use change in a specific area (i.e., proposed development in a specified location)?

   (c) Evaluate optimal land use patterns?

   (d) Evaluate optimal drainage control measures and locations?

   Do you feel that a computer model could be useful in these efforts? What other kinds of models are useful; e.g., judgment and experience?

9. (a) Who would be the user(s) of a model if applied to drainage work by your municipality? What is their expertise?

   (b) If no one currently on your staff would be available to use or has expertise for the use of a model, would you hire someone specifically for this purpose? Would the need to hire an additional person prevent you from using a model altogether?

   (c) Do you see any advantages in having County or regional agency (e.g., METRO) personnel actually operate the computer, subject to the inputs and outputs from your personnel? Would you be more likely to use a model under such circumstances?

10. What issues have we missed that you think are important? Please elaborate during the interview.

Table 2.3

LIST OF MUNICIPAL OFFICIALS WHO PARTICIPATED IN THE RUNOFF MANAGEMENT INTERVIEWS

King County Public Works Department

- Brad Gillespie - Director, Hydraulics Division
- George Wanamaker - Assistant Division Manager, Hydraulics Division

King County Planning and Community Development Department

- Donovan Tracy - Section Chief, Regional Planning Section
- Tom Nesbitt - Planner, Regional Planning Section

Municipality of Metropolitan Seattle (METRO)

- Jeff Bauman - Senior Water Quality Planner
- John Buffo - Scientific Systems Analyst
- Rod Spencer - Associate Water Quality Planner
- Barry Uchida - Associate Water Quality Planner

City of Everett Public Works Department

- Clair Olivers - Assistant Engineer

Snohomish County Public Works Department

- Tracy Gill - Hydraulics Engineer

Snohomish County Planning Department

- John Galt - Subdivision Hearing Examiner; formerly Section Head, Resource Planning, and Project Manager, SNOMET/King County 208

Rainfall - Runoff Methods

Despite recognition that it is inappropriate in most applications, the Rational Method continues to be used for virtually all of the drainage plan development in the two counties. The SCS curve number method has been used in the remainder. This situation persists because of inertia on the part of the public works staff caused by their lack of familiarity with the newer technique, despite the fact that the SCS method was demonstrated during the 208 planning and documented in the SNOMET 208 Stormwater Management Procedures and Methods Manual (URS Company, 1977a). The persons interviewed indicated familiarity with these contradictions, but offered no solution other than encouragement of the use of the SCS method.

These two models have been applied for developments up to several hundred acres. This size is really no different than subwatershed for most drainage basins in the two-County area. The computer model SNODOB, using the SCS method, has also been applied to watershed planning as described earlier. Difficulties encountered with both SNODOB and SWMM are described later in this section.

The areal resolution desired of both computer models ranges from fewer than five acres to more than 50 square miles. The interviewees recognized that this may be asking too much of a single model, however. Concern was expressed that a gap exists between small area models (e.g. Rational Method for areas smaller than five acres) and watershed models. Perhaps more accurately, the concern is that the results provided by small area models (including SNODOB as used for development planning) may not be compatible with those provided by a model of the entire watershed.

> [Comment]: Consider the case in which a comprehensive plan is developed using SWMM, and a certain management strategy is chosen based upon output from the model. The comprehensive plan is then used as a guide for drainage system development in the watershed (e.g., type of development and runoff controls required at a given location) as it undergoes the transition from rural to urban conditions. Each development is required to provide a drainage plan in compliance with the comprehensive plan.
>
> Suppose the plan requires that postdevelopment peak runoff be limited to the predevelopment level (the "no increase-in-peak" provision). Whereas selection of this management strategy was based on an accurate representation of predevelopment conditions for the watershed and its subareas, the use of the Rational Method for each development plan produces a result quite unintended by the comprehensive plan. The Rational Method always predicts direct runoff, but many undeveloped parcels in reality never experience overland flow (James, 1965; UNESCO, 1974; Overton and Meadows, 1976; see also, Appendix A). The implications of this misrepresentation

> are significant. Postdevelopment runoff for each development would be allowed at the rate indicated by the Rational Method; the aggregate effect of many developments could be streamflows many times those upon which the comprehensive plan was based. Not only would the watershed planning criteria be violated, but additional expenditures would be required to correct problems caused by the high flows allowed by the Rational Method. This situation could be avoided if development plans were based on a better model.

The reality of this concern is stressed by the fact that a large majority of new developments in both counties and Everett involve fewer than 40 acres. In a typical watershed of ten square miles this means that more than 150 developments could be proposed before urbanization became complete. Since nearly all predevelopment land-use is either pasture land or second growth forest and underbrush, neither of which typically experience overland flow, the importance of this modeling inconsistency is apparent.

Comprehensive Planning Capability

It would be desirable for watershed models to provide estimates of overland and channel flow rates and volumes at many points in a watershed, with an accuracy of within ten percent, according to the interviews, but system optimization was not mentioned as a major factor. Flow recurrence interval (return period) information is also desired. Current procedure is to use either a 10- or 25-year design storm in development planning, depending on the area contributing runoff to the parcel. This policy is based on engineering judgment rather than on any economic or environmental benefit-cost evaluation. Furthermore, it does not account for differences between watersheds in the severity of problems associated with a given flow, or in mitigating measures that might be feasible. There is, however, recognition that such an evaluation would be desirable, and would be facilitated by better knowledge of flow frequencies for various watershed conditions.

> [Comment]: Analysis of the hydrologic response of a watershed to a range of storms of known return periods and durations for a given land-use pattern would be useful. It would allow the decision maker to compare the benefit gained (in aesthetic conditions preserved, environmental damage avoided, and monetary damages reduced) by providing management measures for each event with the cost of each management plan. The worst case for which management measures could be justified for the basin would then be selected for design. Although this would certainly be an improvement over the current 10- or 25-year storm approach, it still overlooks the difference between rainfall event probability and runoff probability. Analysis of a range of flows of known probability would be the ideal approach.
>
> Schaake, et al, (1967) examined rainfall and runoff records for several very small areas (0.2 - 153 acres) in Baltimore, using a

> modified Rational Method, and concluded that it may be possible to establish relationships between rainfall probability and runoff probability. They cautioned, however, that their results were specific to precipitation patterns in Baltimore and very small urban, predominantly impervious areas, and should not be transferred to other locales. Such results apparently have not been reported elsewhere.
>
> The accuracy limits expressed above reveal a possible misconception of the capabilities of models. Although it would be desirable to estimate flows with certainty, this is not generally possible without sacrificing the ability of a model to represent conditions other than those for which it was calibrated. Model calibration issues are discussed further in Chapter 3.

Ideally, comprehensive drainage planning would be conducted concurrently with land-use planning for the maximum effectiveness of both. This is strongly desired by the persons interviewed. As a practical matter, this is not usually the case, primarily because there are no funds allocated specifically for drainage work on a regular basis. The issue of funding is raised again in a later section of this Chapter.

Regardless of whether drainage and land-use planning occur simultaneously, a comprehensive drainage plan should identify areas that will experience flooding, erosion, or sedimentation in the future, evaluate the hydrologic effects of alternative land-use patterns, and determine the effectiveness of alternative control measures and their locations. Conducted separately, this procedure could assist land-use planning, but simultaneous land-use and drainage plan preparation could help optimize both land-use patterns and drainage control measures within the framework of the goals of the community for the stream system.

Computer models are perceived as an important part of such a planning procedure. The complexity of the interactions between precipitation, land surfaces, and runoff, and the repetitive calculations needed to represent the system for several alternatives are factors that suggest computer calculation. In addition to the topics described above, the interviewees showed a desire to be able to evaluate the effect of specific land-use changes in specific locations, but expressed doubt as to the ability of models to provide such information reliably. This skepticism relates to the modeling gap between small-area and watershed models discussed earlier, and perhaps to experience with the two models currently available, SWMM and SNODOB.

> [Comment]: Difficulties encountered with the models in comprehensive planning applications are summarized below. Comments on SWMM are taken in part from Tang, et al, (1977).

SWMM

1. The representation of impervious area makes no allowance for its distribution and location in a subwatershed, necessitating definition of small, uniform subareas. Impervious area dominates the runoff simulation, making this an important point. The need to use small areas is a handicap in analyzing alternative land use scenarios, as manipulation of numerous catchments is cumbersome.

2. Both optional runoff routing programs have difficulties. The less expensive, but less accurate RUNOFF module is not capable of representing natural channel routing effects on hydrograph shape, timing, or peak flow, having been developed to simulate overland flow (i.e., surface runoff) and flow in simple pipe networks. RUNOFF is also incapable of representing surcharged flow, backwater effects, or pond storage. The more accurate extended transport (EXTRAN) module employs differential equations for continuity and momentum and is able to represent channel routing effects in addition to the other conditions listed above. The equations require that a very short time step (10 seconds for Juanita Creek) must be used to ensure that the solution will converge. This results in extremely high computer costs.

3. Time-varying response and antecedent conditions are not well represented. The non-linear infiltration function was found to be ineffective for calibration unless a very large storm was used. See Chapter 3 for further discussion of non-linearity.

SNODOB

1. The routing module suffers the same difficulties as SWMM - RUNOFF. Solution instability was also noted at one-hour time steps in the City of Everett application.

2. Non-linear rainfall-runoff relationships, in particular antecedent conditions and hydrograph relationships, are not well represented. Variable response during an event can only be modeled by changing the selected Curve Number in the SCS method.

In addition, calibration of both models required arbitrary modification of parameter values from those indicated by both the literature and physical measurement. For example, the impervious area, originally measured, had to be changed for SWMM, and the basic land-use Curve Numbers were increased for SNODOB.

> [Comment]: This forced calibration suggests that the modeling of the physical processes in these models may not be correct in this geographical area, and that both models were not calibrated to represent adequately the desired large design event conditions. See Chapter 3 for further discussion of calibration.

Two favorable aspects of the models were the ease with which land-use options could be modeled by SNODOB since subcatchments need not be of uniform land-use, and the availability of estimated subcatchment flows from SWMM for potential evaluation of subarea runoff management alternatives.

Planning Priorities/User Identification

Official planning priorities have not been established at this writing (September, 1978), primarily because issues of funding and planning coordination have not been resolved. The 208-planning demonstration basins were selected primarily because each showed a need for planning based on current problems, but also because the jurisdictional coordination aspects of planning were easily managed.

The consensus of the interviewees was that the six watersheds that straddle the line between King and Snohomish Counties should receive top priority. Rate of development, status of existing problems, and potential for future degradation of the stream systems are important factors in this evaluation. North Creek and Swamp Creek are considered of highest priority at this time.

The King County Planning Department has identified 26 basins (including the six above) that are in various stages of transition between 100 percent undeveloped and 100 percent urban or suburban conditions. Planning priorities were suggested during the 208 planning (D. Tracy, King County Planning, memorandum to I. Berteig, 1976). A standard method for establishing priorities has been developed recently, but no official position has been adopted (T. Nesbitt, King County Planning, internal memorandum, 1978; and personal communication). The lack of a reliable source of funds for planning and implementation has limited comprehensive plan development and further implementation efforts.

A comprehensive plan is being prepared for May Creek (between Bellevue and Renton) because of the opportunity for coordination with development of the Newcastle Community Plan. The SWMM is being used for this watershed.

Snohomish County has identified only Quilceda Creek in addition to the six inter-County basins as being in need of comprehensive planning. Everett has identified several small watersheds that drain to Puget Sound and the Snohomish River (like Pigeon Creek No. 1 and Wood Creek, respectively). Neither jurisdiction has established priorities other than the inter-County watersheds. The remaining plans will be completed as funds become available.

Probable model users are the planning and public works staff of each municipality. METRO would like to maintain water quality and oversight functions, leaving the technical details to other municipalities. Both counties, METRO, and Everett have on their staffs personnel familiar to some degree with hydrologic modeling. Nonetheless, it is possible that additional persons with modeling experience will be needed as drainage planning receives more attention.

The lack of revenue will cause delays in planning and implementation. Whether the funding question will be solved is not clear now. Many approaches are available, as documented in the 208 studies. It is possible that a general revenue source will be developed for planning, and utility district assessments will be used for implementation. At such time as funding is assured, each municipality will make the decision to hire new staff or a consultant for drainage work.

Several possible advantages of designating a county or regional agency as the technical leader were observed. First, most communities have neither the personnel nor the expertise to apply sophisticated planning tools like computer models. Having a larger agency provide these services through inter-jurisdictional agreements might enable wider use of the tools.

Second, planning in multi-jurisdictional basins could be facilitated by having a county or regional agency automatically assume the lead any time more than one municipality was involved. This might also facilitate inter-agency action on acquisition or preservation of critical wetlands and many other important aspects of planning coordination. A Memorandum of Understanding for Coordinated Surface Water Planning, originally dated April 12, 1978, has been signed by seven municipalities involved in the inter-county basins at this writing. This memo outlines general coordination and planning philosophy, and may serve as the basis for more specific agreements for the individual watersheds.

Other Comments of Interviewees

Concern was expressed over the present policy requiring on-site detention of runoff (in all cases) on four grounds:

1. The policy overlooks possible harmful effects of the uniform detention requirement (see Hardt and Burges, 1976) which could be alleviated by selective detention or regional facilities;

2. Economies of scale (e.g., regional detention) are not realized, and the potential increase in cost of improved conveyance systems, easements, etc., from each subwatershed to regional ponds is not considered;

3. The Rational Method analysis used as the basis for development drainage plans is not compatible with stream protection goals because artificially high predevelopment flows are indicated, thus allowing excessive flows after development; the use of

different design events for each development as required by the Rational Method may also be incompatible with comprehensive plan recommendations;

4. Design storm return intervals currently required for development planning have not been selected on the basis of basin wide flow return period analysis of benefit-cost considerations.

Another major concern was the desire that any useful model should be able to simulate water quality. Water quality is the chief concern of METRO, and quality improvement was the major goal of the 208 plans. The state of the art in quality modeling is not up to the task at this time, however.

> [Comment]: A wash off function for use in quality modeling must be developed for each pollutant of interest and must be based on locally gathered data. METRO has developed a number of such functions, but cautions that there is too much variation in pollutant wash off both within and between storms for the relationships to be valid for all cases of interest. Although it may be possible to model a range of events to evaluate relative severity, it is not possible to model instantaneous water quality (J. Buffo, METRO, 1978; personal communication).
>
> The current design event approach has significant limitations even in this context. The effects of many pollutants are chronic, i.e., long term. Examples include metals, pesticides, and nutrients. Event models could not aid in evaluation of chronic effects even if the functions were much better known than now.
>
> All quality modeling, including continuous simulation, uses the wash off concept now. Since runoff is a major carrier for pollutants entering streams and lakes, a better representation of watershed hydrology than exists with event models should provide a better model of water quality. A continuous simulation hydrologic model is capable of representing both major events and long term runoff and baseflow conditions. Thus, within the limitations of the pollutant wash-off functions, a continuous simulation model should facilitate evaluation of both acute and chronic impacts.

SUMMARY

Although drainage of land and collection and discharge of runoff have been longstanding practices in King and Snohomish Counties, past practices have only recently been examined as to their adequacy. The use of computer models as design and planning tools dates back only a short time, and has met with mixed success. It has been recognized that traditional Rational Method analysis is not compatible with goals for preservation of natural streams, but the more elaborate event models such as EPA, SWMM and SNODOB have exhibited problems as well.

Major problems in computer model applications to date include solution instability under conditions of interest for design and planning, inadequate routing algorithms, inflexibility in dealing with alternative land-use scenarios and runoff control strategies, and difficulty in determining model parameters.

Event models like SWMM and SNODOB suffer several additional general shortcomings in watershed, or comprehensive planning, related to the non-linear relationships between rainfall return period and resulting runoff (see Appendix A). Runoff probabilities are not known and event models provide no means for their evaluation. It is therefore not possible to perform extensive and reliable alternatives analyses, nor to justify a "worst case" for design on the basis of its probable costs and benefits.

Nonetheless, computer models are perceived by potential users as valuable tools for performing the repetitive calculations required in drainage planning and design. Desired areal resolution for models ranges from a few acres for small developments to many square miles for watershed planning. The users would like a model to provide estimates of overland and channel flow rates and volumes for a variety of conditions with accuracies with ten percent.

Comprehensive drainage planning should take place concurrently with land-use planning for maximum effectiveness of both. Issues that should be addressed in comprehensive planning include identification of areas susceptible to erosion, sedimentation, and flooding; evaluation of the hydrologic effects of alternative land-use patterns; evaluation of the effectiveness of alternative drainage control measures and locations in dealing with problems and community goals; and, if possible, identification of the hydrologic effects of specific land-use changes in specific areas (e.g., would it be better for a shopping center to locate at A or B?).

Potential near future users of continuous simulation hydrologic models are the planning and public works staffs of King and Snohomish Counties, METRO, and the City of Everett. Some staff expertise in modeling already exists, but it is probable that additional specialized personnel will be needed for full scale implementation of a comprehensive planning and facilities design program. Alternatively, outside consultants could be engaged to conduct some of the program. Development of a stable source of revenue specifically for drainage work is a major obstacle to further progress in this area.

Possible advantages of regional agency (or county) administration of a drainage program involving continuous simulation include improved availability and financial feasibility of more sophisticated planning and design tools for individual communities that would otherwise have inadequate resources for their use. Intergovernmental cooperation might also be facilitated in those watersheds that cross jurisdictional boundaries.

The perceptions, desires, needs, and capabilities of the potential users identified in this chapter and summarized above are used in conjunction with the literature review in Chapter 3 to develop criteria for evaluation of continuous simulation models for application in King and Snohomish Counties.

CHAPTER 3

HYDROLOGIC MODELING:
LITERATURE REVIEW

INTRODUCTION

The development of the high-speed digital computer has prompted application of many models of components of the hydrologic cycle that previously were computationally unmanageable for large-scale use. Most of the theories being applied today were developed many years ago, but have been combined only recently in comprehensive hydrologic models (Dawdy, et al, 1972).

The reasons for developing hydrologic models are as numerous as the potential uses. Schaake (1971) suggests several broad areas of application of models to urban runoff issues (p. 351):

1. "Serve as a tool in the solution of practical problems relating to utilization of water supplies, alleviation of flood hazards, etc.
2. Serve as a tool in determining possible actions man may take to obtain specified system response characteristics
3. Supply information about possible system response with suitable precision and accuracy on the basis of limited input data
4. Enhance our understanding of the hydrologic process
5. Serve as a basis for testing hypotheses that certain forces or phenomena cause the system to respond in some particular way
6. Summarize the essential properties of sets of data
7. Anticipate the response of a system if certain modifications are made to the structure of the system
8. Serve as a basis for conveying information to decision makers about a system to explain the reasons for actions that need to be taken
9. Serve as a basis for designing or verifying simpler models."

Several of these areas apply directly to urban runoff management decision-making (items 1-3, 7-9). The remainder are more theoretical applications which relate directly to model structure.

Given that computers are capable of solving complex, multi-variate calculations in a short time, and that computer models may be applied to urban runoff management problems, the question then is whether a model should be developed and implemented in a given situation. In answering this question it is important to know both the uses to which the model is to be put (see Chapter 2) and its capabilities and limitations.

This chapter presents a review of the hydrologic modeling literature to identify the perceptions of professional modelers as to the capabilities and limitation of hydrologic models. Chapter 4 analyzes these findings in the context of urban drainage management, compares them with the desires and needs of the potential users identified in Chapter 2, and develops a set of criteria for evaluation of any continuous simulation model prior to implementation.

MODELING FUNDAMENTALS

Dawdy, et al, (1972) state that a mathematical hydrologic model (as opposed to physical and analog models) is a collection of equations and logical statements intended to approximate the physical laws governing desired components of the rainfall-runoff cycle, such as infiltration and surface runoff. If the cause-effect relationships of modeled processes and the inputs are known with certainty, the output is also certain. Models that make these assumptions are known as deterministic, whereas those that acknowledge the uncertainty in inputs, mathematical representations, and outputs are known as stochastic. A further division is possible for each type, i.e. "conceptual" (based on theory) or "empirical" (based on observation). Clarke (1973) defines these terms in detail, and observes that there is no clear boundary between the conceptual and the empirical; many theoretical formulae contain empirical components (e.g. constants) while empirical representations may contain parameters for which theoretical expressions eventually may be found.

Continuous simulation hydrologic models are considered generally to be "stochastic-conceptual" (Clarke, 1973), or "parametric" (Dawdy, et al, 1972; Carey and Haan, 1975; Overton and Meadows, 1976). The latter label results from a strict definition of stochastic as "purely random" and deterministic as "completely without uncertainty". Parametric models are a compromise between the two concepts in that determinism is implied by the use of the equations in the model and stochasticism is embodied in the variability of the model inputs, parameters, and output.

The important aspect of these definitions is that hydrologic modelers recognize that there is no such thing as pure determinism in representing the hydrologic cycle (Amorocho and Hart, 1964; Amorocho, 1967; Dawdy, 1971; Clarke, 1973; Overton and Meadows, 1976). Dawdy (1971) explains that the output of a supposedly deterministic model is actually only an expected, or mean, result because of the assumptions required to formulate the model. This lack of exactness results from two causes:

1. Imperfect knowledge of the physics of the many hydrologic processes; and
2. Errors in the observations upon which the model output is based (e.g. precipitation, impervious area, channel configuration) and against which the model is tested (e.g. streamflow);

Furthermore, even if the system mathematics were perfectly known, input data errors would create erroneous output, while errors in recorded observations for model testing could suggest the use of an incorrect model (Amorocho and Hart, 1964; James, 1965, 1972; Linsley, et al, 1975).

Two other factors rule against maximum detail in modeling the physical processes (overton and Meadows, 1976; James and Burges, 1978):

1. The unavailability of the information needed by the differential equations which provide the most detailed representations for small, homogeneous areas and short time steps; and
2. The massive number of calculations (and corresponding computer time) required.

As a result, aggregate areas and lumped equations based on time steps of hours or days are used.

The importance of this aggregation will vary according to the intended model use. For example, the unit hydrograph concept has been applied widely for flood and reservoir analysis in watersheds for which sufficient flow records exist to define the unit graph and watershed modification is not an issue (c.f. Linsley, et al, 1975; pp. 234-248). The basic concept of this approach is that the derived hydrograph represents the lumped response of the watershed subareas, i.e. the composite effects of basin characteristics such as shape, size, slope, and channel configuration, on the hydrograph. This lumped representation is compatible with its usual single location application, but would be inappropriate for subarea analysis. Neither would it be applicable to the watershed under any conditions of change since the characteristic response would be altered along with land-use.

Amorocho and Hart (1964) descirbe a situation in which subareas are modeled but a single point, total watershed output is desired. Assuming that aggregation exists in each subarea, the output may still be acceptable due to dampening of the errors in each subarea representation. Amorocho (1967) similarly states that, although lumped representation to some degree is required even for very small areas, it should be recognized that the observations against which the model is to be tested are also lumped outputs. This being the case, the modeler must establish an acceptable error limit and attempt to minimize the probability that the model error will exceed the error bound. Thus, subarea modeling, even if imprecise, may be appropriate in any given situation.

Conversely, Amorocho and Hart (1964) point out that aggregation by area and simplification of the descriptive equations may result in errors when the model is applied to conditions other than those for which it was intended initially, and loss of desirable representation of small scale physical system variations.

These potential difficulties in subarea representation therefore require a trade off decision between use of a tailored (i.e. custon built) model for a given area and applications, and use of a general model which provides adequate detail for the specific case as well as correct enough representation of the physical component processes to enable use of the model outside its calibration conditions (Overton and Meadows, 1976; James and Burges, 1978).

NON-LINEARITIES

It is clear that it is possible to obtain useful representation of single location watershed runoff via lumped models like the unit hydrograph. Spatial variability of important parameters or variables (e.g. land-use or infiltration rate) or inputs (e.g. precipitation) may be handled by the use of subareas within the watershed. In either case, however, the applicability of a particular model to conditions (either within or between watersheds) other than those from which it was derived is extremely limited. The major cause of this limitation is non-linear hydrologic system response to different inputs under various conditions.

Amorocho (1967) provides an illustration of non-linearity using the unit hydrograph model. Unit graphs were derived for five storms on the same small catchment in Illinois. Rather than showing a single unit response (i.e. linear response), five distinctly different unit graphs resulted. Similar results obtained by other researchers are reported in the same paper, and by Overton and Meadows (1976). Although it is sometimes possible to approximate the output of a non-linear system via manipulation of the linear model (e.g. superposition of unit hydrographs derived from storms of equal duration and varying intensity), or by the use of polynomial or power equations as described by

Amorocho (1967), such black box representations do not identify cause-effect mechanisms. As indicated in the preceding sections, a black box representation may be appropriate for a single application of a model for which total watershed response is desired, but it is inappropriate where subwatershed response is required as well.

Hydrologic system non-linearity is caused by the time variability of the processes involved (e.g. seasonal differences resulting from varying vegetal cover), as well as by system "memory" (Amorocho, 1967). That is, the output (streamflow) observed today is in part determined by events which occurred yesterday and the day before, which were in turn influenced by variable prior events.

Postulation of input-output relationships for hydrologic models is therefore influenced by past variability. If a model is to be used in a predictive mode, accurate representation of the physical processes is imperative. Amorocho (1967) underscores this apparent limitation in the state of the art in hydrologic modeling by comparison to other engineering models (p. 863):

> "The coarseness of this idealization (lumping necessitated by incomplete data and knowledge of the physical processes) is, in fact, several orders of magnitude greater than that involved in the averaging and lumping processes employed in the analysis of nearly all mechanical and electrical engineering systems. Because no model can represent a prototype with complete faithfulness, it can only be hoped, at best, that the operations of the prototype and that of the system defined strictly by the model structure are equivalent."

The implication of this statement seems to be that considerable investigation into physical process dynamics is needed before the modeling resolution available to the hydrologist will approach that obtained in other disciplines. In the meantime, aggregated models must be used, bearing in mind their strengths and weaknesses.

An added manifestation of hydrologic system non-linearity is the interrelationships between system parameters. To model the effects of urbanization, for example, it is not sufficient to alter only the impervious area factor as models based on the rational method would suggest. Important factors that are changed typically by urbanization include channel length, slope, and geometry; overland flow length; and infiltration rate. Elimination of natural lowland and depression areas as storage sites is another factor which should be considered (James, 1965; Clarke, 1973).

The importance of adequate representation of the physical processes in dealing with system non-linearity is apparent. This applies both to intra- and inter-watershed applications beyond the range of recorded observations.

DATA ISSUES

Recorded observations of precipitation and streamflow are central to the application of hydrologic models; precipitation is the driving force and streamflow a major measure of model output. Their importance is emphasized by returning to a point made earlier: even if the rainfall-runoff process were perfectly understood and modeled without regard to computer cost, errors in input precipitation data would prevent the model from correctly replicating observed flows, and streamflow data errors would indicate model error when there was none. The predictive value of the model would be impaired as a consequence.

The most critical data problem cited in the literature is the lack of precipitation data directly applicable to the watershed under study (Amorocho, and Hart, 1964; James, 1965, 1972; among many others). Errors may be both random and systematic. It is not uncommon for the nearest continuous recording raingage to be many miles from the watershed of interest. If a daily total precipitation record exists for a station within the basin, it may be possible to establish a relationship between this and the distant continuous (hourly) record. The daily total could then be divided into appropriate hourly increments. This would constitute a partial correction of systematic error. James and Burges (1978) discuss this concept, but describe additional difficulties which may be encountered in obtaining representative precipitation records.

Temporal and areal variability of precipitation are the principal causes of errors. Orographic effects and varying storm direction and intensity patterns can cause significant differences between a distant hourly record and the real watershed precipitation. Rainfall for major storms which follow a predictable track can often be transferred or adjusted satisfactorily via time-shift or scaling procedures (primarily systematic errors). Minor fronts present greater difficulties (both random and systematic errors), and convective storms are virtually impossible to transfer (random errors only).

Modeling work conducted by the authors for Kelsey Creek in Bellevue, Washington, using the Seattle-Tacoma International Airport precipitation record revealed several instances in a three-year period (water years 1967-1969) in which the model simulated major runoff events that were not reflected in the streamflow record. The reverse situation also existed (i.e. recorded hydrographs but no precipitation recorded at the airport to force simulation of a corresponding runoff event). These are examples of random errors. It was suspected that the Seattle-Tacoma gage record also contained a systematic under representation error of between five and ten percent relative to real conditions in the Kelsey Creek system based on comparison of the total recorded and simulated flows. Kelsey Creek is centered 13 miles northeast of the airport, which demonstrates the spatial variability problem.

The precipitation record may also fail to reflect differences in rainfall timing between the raingage station and the watershed. In such circumstances a simulated hydrograph will always fail to replicate recorded flows precisely in time, unless an appropriate time shift can be identified.

While these problems may not seem significant,if it is desired to analyze only a single storm for design purposes as is frequently the case (e.g. the SWMM and SNODOB models), they are crucial to the accurate representation of a long term sequence of flows, particularly if antecedent conditions are to be considered. James (1965, 1972) states that randomness in meteorological events can be handled by using a long record for model calibration and simulation. Systematic errors, however, may be more difficult to eliminate. (Model calibration is discussed in the next section of this chapter).

Streamflow records, the other major portion of the data base needed by a model, may also contain both random and systematic errors. In terms of evaluating continuous simulation hydrologic models, random errors may not be significant (Linsley, et al, 1975), but systematic errors may be fatal.

James and Burges (1978) describe several sources of errors, including inoperative or malfunctioning equipment, data transcription errors, and systematic measurement error. Examples of systematic error could be the failure of the measurement to reflect iced-over conditions on the stream, or the location of a stage recording gage just upstream from a flow restriction that creates a backwater effect and artificially high stream stages. Examination of the precipitation and streamflow records for events indicated by only one of the records may provide clues as to the causes of the suspected error.

Many other data are needed for a complex model, including information describing watershed (or subcatchment) area, impervious area, infiltration and exfiltration rates, land slope, and channel configuration. None of these data can be a perfect representation of the real system in minute detail. The model can therefore provide results only within the limits of the data regardless of the precision of the model mathematics. The case of channel description illustrates this well.

The rate (velocity) of flow in a channel is determined by channel slope, cross section, bed material, and upstream and downstream flow conditions. Whereas these factors may be known to a large degree for man made channels (e.g. lined, trapezoidal channels or pipe systems), there is usually considerable variation in the natural system, since the physical characteristics of a natural stream channel are in turn determined by the slope of the land through which it flows, the quantity of water carried on both short and long term bases (i.e. both peak and base flows), and the materials of which the stream bed and banks are composed.

Variations in natural channel characteristics may therefore occur over very short distances, necessitating considerable field measurement, approximation and aggregation, or both, to define the channel data and reduce them to manageable proportions. Consequently, it is virtually impossible to specify completely the data required to model flow in natural channels with the precision allowed in theory. Even man made system characteristics are not known with certainty due to measurement errors, differences between the system as designed and as actually installed, and uncertainties in evaluating the flow resistance characteristics of various materials.

In summary, therefore, an adequate data base is critical for successful application of any model. The flexibility of a given model in accepting data of varying resolution, and the manner of their use, may be important characteristics in evaluating a model as a potential planning and design tool.

CALIBRATION

Success or acceptance of a model is judged ultimately by its ability to replicate desired aspects of a recorded streamflow record, perhaps flood peaks only, low flows only, or both. James and Burges (1978) observe that a user might require three separate model calibrations in such an instance. This procedure would be time consuming and costly, and might suggest that the model was not representing the important physical processes with sufficient accuracy to be both applicable to the full desired range of events. Such selective calibration can be a valid technique, but caution must be exercised in the process because of several potential hazards.

Perhaps foremost among these is the lack of appropriate data. Linsley, et al, (1975) observe that subwatershed data should be available if subwatershed output is desired. They caution, however, that little real resolution may be gained if subwatershed precipitation must be estimated from some other gage record.

Another issue related to selective event calibration is that the observed record very seldom contains the desired design or planning event (Amorocho and Hart, 1964; Linsley, et al, 1975). This is a particular problem in urban and suburban watershed applications where it is not uncommon to find fewer than ten years of streamgage record, and frequently no record at all. Not only is definition of event probability from a short record statistically invalid (see Linsley, et al, 1975, pp. 339-340), but the record may not contain data necessary for proper simulation of the event which is selected.

Consider, for example, a case where it is desired to simulate major flood events not represented in the stream record. It is possible that the "50-year" flood occurs when many natural depressions overflow to the channel, but that this condition has not occurred during the period of record. The model would therefore fail to represent adequately the desired conditions because its parameters could not be adjusted appropriately. Without a good representation of the physical processes, the modeler could be at a loss in this situation.

Amorocho and Hart (1964) caution against over adjustment of model subroutines (e.g., land runoff, channel flow, etc.) or calibration parameters to fit an observed record closely, since it may be possible to obtain the same subjective fit to a recorded event (or series of events) with a number of different parameter combinaitons. The hazard then is that the physical relationships between subroutines and parameters may be distorted or lost entirely; the model results will therefore fail to represent the desired phenomena when applied outside the data conditions for which the model was calibrated.

James (1972) emphasizes that conceptual boundaries between model components do not necessarily exist, e.g. infiltration rate affects overland flow, but overland flow also contributes a delayed infiltration component (Crawford and Linsley, 1966). Thus, it is important to keep in mind the physical meaning of and relationships between parameters, variables, and subroutines when performing a calibration, i.e. calibration is a function of model structure. For example, in a given watershed two models may use different values for impervious area - one measured and fixed, and the other varied for calibration.

The calibration difficulties described above are important in watershed modeling, but are even more significant if subwatershed output is desired. James and Burges (1978) reiterate the requirement for subwatershed streamflow data expressed by Linsley, et al, (1975), and state that the general lumping (aggregation) process and compensating errors in model representation among subwatersheds may result in a false sense of knowledge of the real system. Expressed alternatively, where only a single station (watershed) streamflow record is available, a model may replicate the record only because over and under simulation errors in the subareas offset each other. Use of the individual subarea simulations for design or planning could result in serious decision errors.

The model may be used with greater confidence if the physical processes are well represented. The decision process may also be enhanced if the model provides many opportunities for comparison with the observed record, as opposed to a single peak flow rate or single hydrograph. This issue is discussed below.

Even in situation where adequate data exist and physical relationships are maintained, a significant issue that remains is: What criteria should be used for calibration?

Event models are generally calibrated against two or three hydrographs and verified against one or two more (see Tang, et al, 1977, for the application of SWMM to Juanita Creek). The hazards described above regarding the lack of subarea data, selective event calibration, possible offsetting subarea errors, and extension of the model beyond the conditions described by calibration events are particularly acute in this case. Calibration criteria usually are "adequate" replication of peak runoff magnitude and timing, runoff volume, and overall hydrograph shape. The definition of adequate is necessarily subjective, because too few observations are used to apply any other approach.

James and Burges (1978) state that a good calibration should be both reproducible and independent of the user (i.e. different persons should achieve the same results), the reason being that differences in judgment among users could dominate the real physical differences it is desired to simulate. An inherent weakness of event model calibration is apparent when viewed this way.

Subjective (i.e., non-mathematical) trial and error calibration is often employed for large, multi-parameter models. Clarke (1973) and Overton and Meadows (1976) observe that this procedure may require an awesome effort. Nevertheless, it is apparently facilitated greatly by expertise in hydrologic concepts and familiarity with both the model and the watershed, since the technique is used widely and with success (James, 1965; Linsley, et al, 1975;

Overton and Meadows, 1976). A factor which works in favor of continuous simulation in this regard is the long record, and hence the large number of observations, available for comparison.

For example, if a three-year streamflow sequence is generated for calibration, three annual total runoff figures and annual peak flows, 36 monthly total flows, perhaps 12 major flood hydrographs (assuming four per year), and many lesser event hydrographs will be available for comparison with the recorded series. Verification of the calibration on three additional years of data would provide an equivalent number of new observations for comparison.

The types of comparisons that may be made are many, and are discussed at length by Clarke (1973), Aitken (1973), Wallis and Todini (1974), and Bates (1976), among others. The general methods involve analysis of the errors between the modeled and the recorded data (the model residuals) using graphical and statistical methods. James (1965) and Linsley, et al, (1975) offer the following criteria for assessing a calibration:

1. Model errors at hydrograph peaks should be random (i.e., both over and under simulation);
2. Model errors in simulating the number of hours of flow above a specified level should be random (check for major hydrograph volume);
3. Simulated hydrograph shape for all events should be consistent with recorded flows (check for response time and recession rates);
4. Monthly and annual flow totals should show reasonable agreement with the recorded and agree with seasonal variations observed (check for overall water accounting).

This multiple check approach is very important. Clarke (1973) stresses that use of any single criterion, especially a programmed "minimize the error" test (e.g., minimize the sum of the squared deviations between simulated and recorded flows), is very hazardous because of the possibility that physical relationships and parameter interrelatedness may be overlooked. Models that provide many opportunities for comparison may be calibrated with greater confidence that they are performing as desired. Calibration may even be conducted using a subset of parameters which affect a specific aspect of the simulation (e.g., peak timing) if enough basis for comparison is provided.

Another advantage of multi-parameter, continuous simulation over event modeling is the greater opportunity for testing the physical reasonableness of the parameters and the various storage components of the model (James and

Burges, 1978). For example, if evapotranspiration is modeled it may be compared to recorded pan evaporation; soil moisture or groundwater storage may be checked for typical seasonal fluctuations.

James and Burges (1978) summarize potential criteria for evaluating model success in fitting an observed record as follows (pp. 18-19):

1. Subjective judgment;
2. Statistics based on the complete sequence of flows (e.g., sum of squared daily deviations);
3. Statistics based on a subset of the sequence which is of interest (e.g., sum of squared deviations for low flow periods);
4. Statistics based on flow and other physical measurements (e.g., soil moisture or impervious area);
5. Statistics on changes in flow from one time period to the next;
6. Analysis of the magnitude and pattern of systematic and random errors by graphical or statistical means (e.g., distribution and correlation structure of errors, etc.);
7. Evaluation of the impacts on calibration of uncertainties in parameters, initial conditions, inputs, and model equations through sensitivity analysis (see McCuen, 1973; Wood, 1976; Coleman and De Coursey, 1976).

Parameter adjustment may be subjective, may make use of the statistics to define an objective function for a systematic variation of parameter values within established ranges, or may use rules derived from the sensitivity analysis.

Two summary observations are in order regarding model calibration. First, reiterating the point made earlier, the data base is critical to model value. Input data errors, particularly systematic precipitation representation error, may render calibration invalid for any circumstances other than those represented by the data. The value of the model as a predictive tool is thereby negated.

Streamflow measurement error is no less important. Both random and systematic errors may result from data deficiencies or from errors in the model itself. Although examination of model residuals for randomness is straightforward, basic statistical and visual fitting methods do not detect systematic error. Aitken (1973), Wallis and Todini (1974), and Bates (1976) suggest additional methods for detecting systematic errors, but this remains a serious problem.

Second, all statistical and graphical calibration tests, and therefore the model which results from a given calibration, assume time invariance of the system under observation. Calibration using a data record for a period during which the watershed underwent rapid change will result in model parameters that cannot be associated accurately with any particular watershed condition; consequently, the important hydrologic effects of the changes will be obscured in the analysis. The resulting model will not be capable of use in a predictive mode (Amorocho and Hart, 1964).

Urban applications of hydrologic models are concerned most frequently with predicting the effects of watershed changes, so that by anticipating problems appropriate management strategies may be developed to mitigate or eliminate the expected impacts. Selection of a reasonably stable watershed condition for calibration and verification is therefore imperative if the model is to be valuable in planning and design. Absolute stasis is seldom a reality, but a watershed may be considered hydrologically stable if it has not undergone rapid or widespread urbanization or channel modification during the period under analysis.

APPLICATIONS

Once a continuous simulation model has been calibrated and verified, it is used to simulate a long sequence (generally greater than 20 years) of streamflows using available long-term precipitation and evaporation records as inputs. Dawdy, et al, (1972) and Clarke (1973) note that specific uses of continuous simulation models may include:

1. Forecasting for facility operation and design;
2. Extending an observed discharge record;
3. Predicting the effects of changes in watershed and channel conditions (particularly those induced by man); and
4. Creating a discharge record for an ungaged site based on model parameters derived from similar, nearby watersheds.

As mentioned above, models do not usually account for time-variance of the system. Consider the case where a watershed was completely rural for 25 years, followed by five years of gradual development and five years stability. Stream gage records exist only for the last ten years. The model is calibrated and verified on the last five years, and then run using 35 years of precipitation data. The simulated streamflow will not represent the flows that would have been recorded had a gage been in place for the entire 35 years. Rather, the simulated series represents the flow that would have occurred if the watershed conditions represented by the last five-years had actually existed for the entire period.

James (1965) states that this type of synthetic record has its greatest utility where the observed record is long enough under relatively steady-state watershed condition for parameter estimation, but is too short for reliable probability studies. This latter condition could be due to changes in watershed condition or simply to inadequate record length. Where a watershed has undergone changes that would invalidate a traditional probability analysis, a long, simulated sequence would still be needed to evaluate probabilities associated with the altered watershed condition. Probabilities associated with high or low flows, or any other aspect of the extended record could be determined.

The effects of urbanization on watershed response may be modeled in three fundamental ways:

1. Identify the changes in parameters and variables associated with urbanization through field observation, measurement, and experience (judgment) but without direct benefit of calibration because sufficient data are not available to represent all conditions of interest (James, 1965);

2. Identify typical runoff hydrographs for unit areas representing the full range of conditions of interest through model calibration, verifications and application to several watersheds (or subareas, for which data exist) selected for their representativeness (Lumb and James, 1976);

3. Calibrate and verify the model for each watershed to be analyzed, identify the future watershed conditions to model, and make appropriate changes in model parameters and variables for each condition before generating an extended streamflow record.

While the last approach would provide more specific information about a given watershed response in a given situation, it would also be much more data demanding than the other approaches. The second approach provides a possible compromise between the basically theoretical approach (1), and the individual watershed application (3). These options represent a trade off that must be considered prior to final implementation.

SUMMARY

Professional modelers agree that all hydrologic models are approximations of the physical system, whether black box representations or detailed models of the component processes. Modeling uncertainties stem from several sources, among them incomplete knowledge of the physical processes and inadequate or inaccurate data for input to or comparison with the model. Even if a model were a perfect representation of the real world, data errors would prevent its use with confidence.

Although the best theoretical approximations of physical processes would be provided by differential equations, their use is restricted by a lack of needed data on a small space-time grid, and by the excessive computer cost incurred in their solution over time spans of interest to the planner or designer (i.e., hours, days, years). All models in practical use are therefore lumped representations to some degree. Aggregation may be acceptable depending on the application, notably when the hydrograph at a single site is desired and watershed change is not an issue. Since neither condition exists in most urban drainage applications, the limitations imposed by lumped modeling must be considered:

1. The validity of the model outside the conditions for which it was tested (i.e., in the predictive mode) may be impaired; and
2. The representation of important small scale phenomena of interest may be lost.

Non-linear response of watersheds to varying inputs under varying antecedent conditions is a primary cause of predictive limitations. Spatial and temporal variability of physical watershed conditions and precipitation are, in turn, responsible for non-linear response. Streamflow today is, in addition, influenced by variable past events. To deal adequately with non-linear responses it is important to represent the component physical processes and their interrelationships.

Adequate data are critical to good modeling. Hydrologic models are particularly dependent on good precipitation and streamflow records, which may contain both systematic and random errors. Inadequate representation of watershed precipitation is the single largest source of modeling difficulty cited in the literature. Use by continuous simulation models of many years of data may solve problems of random errors, but systematic error is much more difficult to correct. Streamflow records, although lesser causes of error in general than rainfall data, are nonetheless important as a measure of model success. Errors or imprecision may also be imparted by other data used by a model, such as channel descriptions or land slope and cover information.

When subwatershed simulation is desired, it is important that subwatershed data be available both to test and run the model. Otherwise, model calibration may be subject to many difficulties. Use of subarea components when only a single, total watershed record is available may lead to arbitrary adjustment of parameters describing each subarea; offsetting subarea errors may allow calibration to the single record but loss of the physical meaning of the subarea modeling. It is also possible to achieve the same subjective degree of fit to an observed record with many different parameter combinations. Predictive ability of the model would be extremely limited in either case.

Advantages of a multi-parametric, physical component approach to watershed modeling are therefore seen in dealing with non-linearities and subwatershed rainfall-runoff response. Representation of the physical interactions allows for accounting of antecedent conditions at any time and provides the modeler with better information upon which to base a decision as to the reasonableness of subarea representation when observed data are not available.

Continuous simulation models additionally provide many more opportunities to test physical representation. Many flood hydrographs, low flow periods, peak flows, and total runoff volumes may be compared to the observed record. Much greater confidence that systematic error does not exist may be attached to such a model than to a one or two event calibration. Use of several criteria for the fit of the calibration also improves the credibility of the model. It is therefore more likely that the physical relationships will be preserved and the capability of the model for predictive use enhanced.

Potential applications of continuous simulation models include forecasting for design and operation, extending existing stream records, creating records for ungaged streams and analyzing the effects of watershed changes. Such models are most useful when a sufficient streamflow data base exists for parameter identification but the record is too short for probability analysis. In any case, the models are necessary for probability analysis for watershed conditions not represented by the record. In this context, it is important that the stream record for a period during which watershed conditions were relatively stable be used for calibration and verification. Otherwise, it may not be possible to identify the important effects of watershed changes, nor to identify the changes in model parameters needed for predictive application.

The effects of urbanization on watershed hydrology may be modeled in three ways:

1. General, conceptual changes in model parameters and output without direct calibration to the watershed;

2. Development of characteristic hydrographs for unit areas of various land-uses for combination in an appropriate manner for a given watershed; and
3. Calibration and verification of the model for each watershed.

Specificity of representation in the last case may offset its increased data and time requirements, whereas either of the first two methods may be appropriate for a given use and are less data and time demanding.

CHAPTER 4

DEVELOPMENT OF EVALUATIVE CRITERIA

INTRODUCTION

Determining that existing analytical methods are inadequate requires knowledge of the questions they are being asked to answer and the accuracy required for their application. It also requires that the capabilities and limitations of the methods are known for comparison. It does little good, however, to decide that available tools are inadequate if no better methods exist. The Rational Method was probably determined to be better than whatever methods were used prior to its initial application. As its limitations have become known and as drainage management has become more complex, other methods have been developed, including computer models.

Before any model can be implemented, its potential users must be convinced it will provide better information than the methods of analysis already in use, and that it will do so at a reasonable cost. These criteria apply to the first decision to use a model as well as to any subsequent decision to try a new or to modify an old one. Specifically, the output desired by the decision maker should be sensitive to the change in model or internal structure, and the value gained from the added information should justify the increased cost of the improved model (James and Burges, 1978).

The new model must be evaluated against the same questions and accuracy limits as the methods that were found to be inadequate. Reaching a sound decision therefore requires that a rational, defensible set of criteria must be developed for model evaluation.

COMPARISON OF VIEWS OF MODELERS AND POTENTIAL USERS

A comparison of the views of potential model users and professional modelers based on the results of the runoff management questionnaire (Chapter 2) and the literature review (Chapter 3) is pertinent for the following reasons:

1. It may help to differentiate the needs of the users from their desires;
2. It may help to determine the reasonableness of the desires of the users;
3. It may serve to focus attention on misconceptions of the users relative to modeling in general; and
4. It may aid in identifying evaluative criteria that are reflective of both the requirements of the users and the capabilities of models.

Several topic areas for discussion are suggested indirectly by Chapters 2 and 3:

1. Model Uses;
2. Inputs the Model Should Accept;
3. Desired Model Outputs;
4. Physical Processes to Represent;
5. Areal Resolution; and
6. Accuracy Limits.

These areas parallel criteria for model evaluation developed by Schaake (1971) and James and Burges (1978). Additional issues will be introduced following brief discussion of the six items above.

Model Uses

Two basic applications of computer models are desired by the users: development planning and watershed (comprehensive) planning. In the former case the pre and postdevelopment runoff conditions are desired so that on-site runoff management measures (particularly detention facilities) may be evaluated and designed. Watershed modeling is desired to include:

1. Identification of existing and future runoff related problems such as flooding, erosion, or sedimentation;
2. Evaluation of the hydrologic effects of alternative land-use patterns (i.e., changes form existing conditions); and
3. Evaluation of the effectiveness of alternative runoff control measures and their locations, in combination with the land-use options in (2), in dealing with the problems in (1) and in addressing any other identified community goals for the watershed such as fishery enhancement or natural stream preservation.

Model outputs associated with these issues are discussed later. The hydrologic modeling literature indicates that models may be applied to watersheds and their subareas, subject to recognition of the limitations imposed by data availability. The literature stresses the need for subarea data if subarea representation is desired, but also states that this limitation may be overcome to a large degree by adequate representation of the real physical processes controlling rainfall-runoff response. Nevertheless, it is never possible for a model to reproduce exactly the runoff hydrograph from very small areas because of imprecision in mathematical expressions of physical processes and inaccuracy or unavailability of data.

Limitations in subarea representation are shared by all mathematical models, an apparent constraint in analyzing drainage plans for developments. In particular, it would not be appropriate to use a continuous simulation model to evaluate such plans. The data required to calibrate a continuous simulation model for every development, or even for similar developments, could be prohibitive both in volume and cost. The example cited in Chapter 2 of a ten square mile watershed in which more than 150 separate developments could be proposed before urbanization was complete emphasizes this point. Even if data are obtained, operating the model may be prohibitively expensive.

At the other end of the modeling continuum is the Rational Method, the only truly appropriate application of which is for drainage network design based solely on peak flow rate for very small, highly impervious areas. If predevelopment runoff is needed as a datum, the Rational Method is inappropriate given the typical nonurban land-uses in this area.

An intermediate level of analysis is therefore needed for development planning. The SCS Curve Number method may be more appropriate, since it reflects the local natural runoff conditions better than does the Rational Method and is programmed easily, as demonstrated by SNODOB. Experience of the author indicates that it does not, however, represent the direct runoff contribution of impervious surfaces in the postdevelopment setting without changing drastically the Curve Number selected originally as representative of the soil/land-use combination of interest. A better approach may be to model the impervious and pervious areas separately and combine their hydrographs at the point of interest. This approach has been incorporated as an option in the forthcoming Hydrocomp Simulation Processor II continuous simulation model (R. Johanson, Hydrocomp Inc., 1978; personal communication), but has not yet been documented in the literature.

Other computer models like SWMM do not seem appropriate for development planning because of the mathematical function and data problems cited earlier. In addition, the Juanita Creek project showed that the runoff response of SWMM is dominated by impervious area in developed portions of a watershed, but data were not available to document the representation of nonurban areas. The model outputs that were obtained for several nonurban subareas indicated very rapid runoff response, however, suggesting that the model may not represent predevelopment conditions adequately.

Inputs the Model Should Accept

In addition to the obvious need for precipitation and streamflow data

(data issues are discussed in a later section) the users would like a computer model to be able to model alternative land-use configurations. For example, a watershed may be expected to change from ten to sixty percent urbanized. Both the types of urbanization that take place (e.g., single family or multi-family residential, commercial, and industrial areas) and their location are variable and can be altered if the planning process shows a need to do so. The desire of the users to interface the land-use and drainage planning processes requires that alternatives be handled easily.

Difficulty in modeling land-use was one of the problems encountered in the use of SWMM, whereas SNODOB was quite flexible in that regard. (Area weighting of the Curve Numbers in SNODOB creates this flexibility. The limitations of the Curve Numbers in modeling impervious areas was discussed above, however.) The literature cites modeling of land-use alternatives as a significant application of continuous simulation models. The procedure requires recognition of the many factors affected by urbanization; identification of the nature of watershed change associated with a given land-use, and the corresponding model parameter changes are, therefore, crucial to land-use modeling. For example, impervious area, overland flow length, surface detention, and channel length are factors changed by urbanization that must be modeled by appropriate parameter changes. This procedure is not necessarily straightforward and would be facilitated by modeling experience, knowledge of the watershed, and adequate data.

An additional caution is in order. Because aggregation is required in modeling in general, it does not seem possible for any model to simulate accurately the effects of land-use changes on a small scale. This problem is somewhat intermediate between development planning and watershed modeling. It therefore appears appropriate to model land-use changes of subwatershed scale. Otherwise, the true effect of smaller scale changes may be hidden by the lumping process required by data limitations and model mathematics.

Desired Model Outputs

To facilitate the three watershed planning analyses described earlier, the users would like a model to provide estimates of overland and channel flow rates and volumes at many locations within a watershed. In combination with the desired land-use modeling this indicates a desire for this information on a fairly fine space-time grid. Inclusion of the development planning application makes the desired resolution even finer. These model "requirements" may be discussed on two levels.

First, as indicated above, computer models in general are not able to provide reliable estimates of rainfall-runoff response for small, individual parcels as desired for development applications. At a larger scale, however, almost all models are designed to provide at least peak rate and volume estimates at the outlet from each modeled subarea, where the outlet may be a storm sewer or natural channel (thereby satisfying the channel flow requirement). In all cases, overland flow is a component, along with impervious area runoff, interflow, and base flow (depending on the model), contributing to the outlet hydrograph. In no case is overland flow at a point represented; models represent total overland flow (and total impervious area flow, interflow and baseflow) occurring within any modeled area.

It is therefore apparent that point estimates of overland flow are not provided by models. Used in conjunction with other total flows from a modeled area, however, overland flow estimates can provide important information for model calibration. For example, if a model is simulating runoff that responds too quickly to precipitation it may mean that too much water is being allocated to impervious area and direct overland flows. Separate accounting of each component runoff process can facilitate model calibration. As has been stressed previously, it is important for a continuous simulation model to represent physical processes as well as possible so that the problems inherent in model aggregation are minimized and the predictive ability of the model outside the range of calibration data is preserved.

Another output issue that bears on model evaluation is the format and content of the computer printout, i.e., what data are presented and in what form. Although the desires of the users are not identified explicitly in this regard, it is safe to say that both numerical and graphical displays would be useful. This issue is discussed later in this Chapter.

Finally, the users expressed a desire for reliable information on flow probabilities for use in conjunction with both development and comprehensive planning. The literature recognizes that no event model is capable of providing such information, but that continuous simulation models may facilitate such analysis. A continuous simulation model provides an extended flow sequence for probability analysis comparable to observed flow records. Moreover, a model may be used to produce long records for any number of alternative watershed conditions, and probability analysis may be conducted for each. Observed streamflow records cannot be used in the latter manner unless long records exist both prior to and following an identifiable change. Any alternative future conditions cannot be analyzed with historical flow sequences in any case.

Physical Processes to Represent

Only two physical processes were explicitly desired by the persons interviewed: overland flow and channel routing. The preceding section showed that the former is an important part of continuous simulation, but cannot be represented as desired by the users. Channel routing is obviously important in correctly representing flow in pipe and natural channels. The problems that were encountered with channel routing routines during application of SWMM and SNODOB were detailed in Chapter 2. The desire of the users is that important phenomena such as backwater effects, surcharged pipe flow, and pond and channel storage should be represented, without resorting to mathematical expressions that result in excessive cost or solution instability.

This modeling desire results in part from the concept of identifying runoff related problem areas. Areas subject of flooding, for example, are located frequently just upstream from a flow constriction that creates a backwater, such as a road culvert. It is precisly these short (typically 40 to 100 foot) segments in a conveyance system that cause solution instability, or excessive cost if the former problem is corrected by using very short time steps. The other alternative is to combine channel segments, whereby the originally intended detail is lost and true channel routing may be distorted. A significant tradeoff decision therefore results from the desire for spatial analytical detail as well as overall routing accuracy.

Hydrologic models use either the detailed or simplified theoretical routing approaches exemplified by SWMM EXTRAN or RUNOFF, respectively, and termed "hydraulic routing methods," or less theoretical techniques called "hydrolic routing methods," including Muskingum routing and time-area curves (Linsley, et al, 1975; Viessman, et al, 1977). The result is that either simple or sophisticated runoff routing functions can be included with any model, provided the costs are acceptable.

A pertinent question, however, is what level of detail is really needed by the users. If runoff is to be simulated for many, very small areas and combined in pipe or stream systems throughout a watershed, then a detailed hydraulic routing procedure may be necessary. Small scale detail in representing the runoff process is not generally achievable, however, according to the literature reviewed in Chapter 3. As a result, it seems of little value to represent the conveyance system in great detail within modeled subareas.

Furthermore, the literature is emphatic in stating the need for subarea data for subarea modeling. Events within a subarea are represented by lumped expressions that approximate the subarea data. It therefore seems reasonable to reduce the level of modeling detail within subareas with respect to both the specification of the conveyance system and the mathematical expressions used for routing. Detailed routing would begin at the point where subarea flows are first combined.

This conclusion leads, in turn, to another question: at what point are subarea flows analyzed in sufficient detail to identify internal flooding, undersized culverts, and other pertinent conditions? An answer is deferred until the section on implementation in Chapter 6.

The lack of an explicit desire to model flow components other than overland and channel flow cannot be construed as a desire that they not be represented. Impervious area flow, abstraction, or infiltration are calculated by all models to some degree. Event models do not keep track of these components throughout the event, however, whereas the accounting of all flows is central to continuous simulation. Two factors suggest that the users do in fact desire a full accounting of flow components:

1. The desire for information on flow probability and therefore the need to account for antecedent conditions on a continual basis;
2. The desire for water quality modeling and therefore the need for representation of interflow and base flow components so that long term (chronic) effects may be modeled along with short term, event (acute) impacts.

Representation of the full set of flow components including overland and channel flows can assist calibration and improve reliability of a model.

Areal Resolution

The potential users desire to apply computer models to areas ranging from about two acres to nearly 60 square miles, with watershed planning constituting all applications above 500 acres (see Appendix A). Development planning applications would range from the low figure up to approximately 300 acres (0.5 square miles), and an overlap in areal application would occur when watershed planning was extended to subareas as desired.

The Juanita Creek comprehensive plan may be cited as an example of the last case, above. The watershed has an area of approximately seven square miles, and was modeled as 82 separate subcatchment areas ranging from 3 to 304 acres in size. This fine scale division of the watershed was dictated by two factors: the handling of impervious area by SWMM; and the desire for fine scale modeling of land-use effects and identification of runoff related problems.

The inability of models to represent small scale phenomena properly has been stressed previously. The conclusion is that no single model (neither simple- empirical nor complex- theoretical) can be used at both ends of the areal continuum desired by the users. The practical lower limit of areal application of continuous simulation models has not been mentioned in the literature reviewed, but probably would be determined by data availability. It would be possible in theory to calibrate, verify and operate a continuous simulation model for any size area given adequate data, but computation and budgetary limitations would make this impractical for widespread application. As long as prediction of events outside the range of observed conditions is desired, either because of altered land-use or because design flows are not reflected in stream records, empirical models like the unit hydrograph method cannot be used. Models that represent the important physical processes are required, and areal lumping is a fact of life in such models.

It is appropriate to ask whether it is necessary to model land area in the fine detail used for Juanita Creek, i.e., areas as small as 3 acres. If several adjacent areas are or will be of the same basic land-use, they could be modeled as a single subarea. The internal detail desired by the users would be lost, but the realities of small area modeling should, by now, have raised serious questions as to the accuracy of the fine scale output in the first place. Continuous simulation in particular can provide information upon which much greater confidence can be placed for the combined areas because of the advantages of long records described in Chapter 3. Modeling of the channel downstream from the combined areas could be as detailed as desired, and the greater confidence bestowed on the lumped area outputs could also be transferred to the downstream modeling results.

If one accepts the proposition that small scale land-use effects and rainfall-runoff relationships cannot be modeled as desired for development planning or watershed planning as exemplified by Juanita Creek, then aggregation in subarea modeling will be acceptable in watershed planning.

Accuracy Limits

The issue of accuracy in modeling was discussed in Chapter 3. The interviews showed a desire for accuracies of better than ten percent in estimating peak flow, timing, and volume of overland and channel runoff. The realities of modeling overland flow, discussed above, limit a discussion of its accuracy to general consideration of total runoff for a subarea. Simulated channel flows may be examined readily for accuracy relative to observed data.

The literature makes no positive statements about accuracy limits. If a model is required only to replicate an observed record, particularly a single event, it is possible to obtain an "accuracy" of virtually 100 percent in timing, volume, and peak. This can be accomplished by force fitting model parameters to obtain the desired output. Many hydrologic modelers warn against this approach if predictive simulation is required, however.

In the latter case, which constitutes the most important anticipated model application, the physical meaning of and relationships between model parameters and equations must be preserved. This means that any individual rainfall-runoff event may not be reproduced within the desired limits. Continuous simulation offers significant advantages over event models in assessing the model residuals.

It is probably not possible for multi-event models in general, nor for any models used in a predictive mode, to attain the accuracy levels desired. A continuous simulation model, by providing many opportunities for comparison between recorded and simulated flows, can provide important information regarding overall model accuracy. The idea in any calibration is to maximize accuracy (minimize error) subject to the constraint of maintaining the predictive reliability of the model.

OTHER ISSUES

The preceding discussion is summarized in Table 4.1. Some additional ideas on model evaluation adapted from Schaake (1971) and James and Burges (1978) are introduced here in preparation for development of evaluative criteria:

1. User expertise;
2. Budgetary or computer limitation and time constraints; and
3. Data availability.

User Expertise

The interviews indicated that both Counties, METRO, and the City of Everett have on their staffs personnel familiar to some extent with hydrologic models and their application.

In particular, some METRO personnel are already familiar with continuous simulation, having used the Hydrocomp Simulation Program (HSP: Hydrocomp Inc., 1969, 1972) extensively during the Water Resource Management Study portion of the RIBCO study (CH2M-Hill, 1974; METRO and City of Seattle Water Department, 1974). The HSP model was applied as an overall resource management tool in the RIBCO work. Individual drainage basins were not modeled in detail using HSP, however, but were analyzed in a separate part of the RIBCO study by the Corps of Engineers using an original verison of SWMM (U.S. Army Corps of Engineers, 1974b). Given the position of METRO in desiring to maintain only oversight and water quality functions, it is nonetheless apparent that additional modeling expertise will be needed in the municipalities examined by this work.

While added staff or outside consultants will be needed for the actual model operation, existing staff members are fully capable of analyzing and interpreting model output for planning and design. Although hydrologic modeling is thought of generally as an engineering discipline, it seems to be the planning personnel who perceive the possible uses of a model for King and Snohomish Counties. (Planning personnel have not been interviewed in Everett).

The expertise of the direct model users is very important, as is the familiarity of the decision makers with models and their use. In a report on environmental modeling and decision making in the United States, the Holcomb Research Institute (1976) concludes that decision makers are frequently apprehensive about the use of unfamiliar tools such as models, the investments needed, and the quality of the results provided. Model applications for short term decision making are more likely to gain approval than long term uses. The report further concludes that model success depends to a large degree on the extent of interaction between modelers and decision makers in establishing model needs, goals, and objectives. Methods of facilitating this interaction include use of a middleman or policy analyst familiar with both technical modeling and policy matters, provision of appropriate model output displays for the decision maker, and adequate documentation of the capabilities, limitations, and applications of the proposed models.

TABLE 4.1

SUMMARY OF COMPARISON BETWEEN USER AND MODELER PERCEPTIONS OF HYDROLOGIC MODELS

	Category	USERS - Preceptions and Desires	MODELERS - Perceptions	Inconsistencies Between Perceptions
I.	Model Uses	Development Planning - estimate pre- and post-development runoff. Watershed Planning - identify runoff-related problems by type and area; evaluate effects of land use change; evaluate alternative control measures.	Models not appropriate for small area use because of data inadequacy and mathematical uncertainty. Watershed and sub-area applications valid accuracy depends on data availability.	A gap is apparent between appropriate use of the Rational Method (very small, impervious areas) or other impirical small area models, and watershed models. No single model type appears adequate for both development and comprehensive planning.
I.	Inputs the Model Should Accept	Meteorological Data Streamflow Data Land Use Information - e.g. single-family or multi-family residential, commercial, industrial, open space, etc.	Meteorological and streamflow data are basic model needs. Land use modeling depends on ability to identify appropriate changes in model parameter values, considering relationships between equations and parameters; small-scale change difficult to model (see I.)	Fine-scale effects of land-use change on runoff cannot be modeled accurately unless very detailed data are available to establish specific parameter changes. Aggregate land-use representation must therefore be used.
III.	Desired Model Outputs	Overland flow rate and volume at many locations in watershed. Channel flow rate and volume at many channel locations. Numerical and graphical displays of flows, statistics, and other information. Information on flow probabilities, particularly for future watershed conditions.	Overland flow rate and volume are modeled only as areal totals, not as point simulations. Channel hydrographs are provided by all models except those based on Rational Method. Type of output display is flexible and depends on model. Event models are incapable of providing probability information, whereas continuous simulation models do provide such information.	Overland flow is important as a component of the total rainfall-runoff process, particularly when compared to other flow components during model calibration. Point estimates of overland flow are not modeled and fine-scale areal detail is therefore not achieved (see I, above). Event models currently in use provide no reliable information on flow probabilities.

TABLE 4.1 (Concluded)

SUMMARY OF COMPARISON BETWEEN USER AND MODELER PERCEPTIONS OF HYDROLOGIC MODELS

	Category	USERS - Preceptions and Desires	MODELERS - Perceptions	Inconsistencies Between Perceptions
IV.	Physical Processes To Represent	Explicit Desires - Overland flow (see III, above) - Channel routing that represents backwater effects, surcharged flow, reservoir and channel storage and other conditions, and that allows fine-scale conveyance system analysis. Implicit Desires - Account for interflow, baseflow etc., based on desire for probability information and the importance of antecedent conditions thereto.	See III, above, for overland flow modeling. Most models can be adapted to include simple or sophisticated channel routing. If sophisticated routing is used, computational costs must be balanced against precision yielded. Analytical detail used should be compatible with rainfall-runoff simulation detail (i.e. inaccuracies in the latter cannot be compensated for by the detailed routing. Other hydrologic processes accounted for in varying detail depending on the model. Complete representation of processes is valuable during calibration.	Less-precise hydrologic routing, or continuity-only approaches, may be appropriate for many applications (as opposed to using the full hydraulic equations of continuity and momentum. In particular, the former approaches may be appropriate since fine-scale detail in land runoff simulation is not feasible (see I, II, above). Detailed hydraulic routing could be done after general watershed response was established using other methods, or could be done for the main channel only.
V.	Areal Resolution	Development Planning - Two to approximately 300 acres (0.5 square miles). Watershed Planning - 500 acres (or fewer) to 60 square miles, with sub-watershed areas correspondingly smaller.	See I, above for development planning. Areal aggregation is required by lack of knowledge of physical processes in fine detail and by lack of data. Lower limit of applicability of a given model is function of model structure and the data base.	No single model is appropriate at both ends of areal scale desired by users. Data availability defines lower limit for conceptual models. Aggregate area representation consistent with available data must be acceptable if confidence in results is to be maintained, particularly for predicting future conditions.
VI.	Accuracy Limits	Desire estimates of peak flow, timing, and volume of overland and channel runoff within ± ten percent accuracy compared to historical flow record (see III, above, for overland flow). Desire predictive accuracy of same flow characteristics within ± ten percent	No theoretical limits to accuracy are expressed in literature. Very close reproduction of an historical record (particularly single event) possible but resulting model often is not applicable to any other conditions. Predictive accuracy assured only by maintaining physical meaning of and relationships between parameters during calibration.	Desired predictive accuracy probably very difficult to attain with any model. Sound physical basis enhances potential for accuracy; calibration must be conducted to maintain physical meaning of equations and parameters. Adequate prediction is very difficult, perhaps impossible, with event models because desired future conditions are not represented by the calibration events and antecedent conditions are not accounted for.

Once the planning and engineering personnel are convinced that a new model will provide better answers and should be implemented, they must therefore transfer their convictions to the policy making public officials and institute a continual program of interaction for there to be any long term success in the runoff management program.

Budgetary or Computer Limitations and Time Constraints

Funding limitations, in particular, the lack of monies appropriated specifically for drainage planning and design, have been cited as the major reason for the lack of comprehensive planning prior to the 208 studies. The two counties operate under an additional funding constraint, in that they may not provide drainage utility services without having first completed a comprehensive plan for an area under the provisions of the "County Services Act" (State of Washington, Revised Code 36.94, 1967; and amendments). Once a plan has been completed, a utility local improvement district may be formed and assessments collected for detailed design and construction of community drainage facilities. Funds for initial planning must be obtained elsewhere, such as from grants or general revenue sources.

Sources of funding to ensure the viability of a drainage management program were suggested by the SNOMET and METRO 208's, but the issue of general funding remains unresolved at this writing. If an appropriate means of funding is developed, the question of funding level will have to be addressed. The section in Chapter 5 on data needs provides information that may be useful in determining funding needs, either with or without continuous simulation modeling.

There are probably no computer limitations pertinent to the selection of a continuous simulation model. Both Counties and METRO have their own computer services. In addition, the University of Washington and Boeing Computer Services systems could be available. (Boeing Computer Services was used by the consultants for the modeling of Juanita Creek).

No time constraints have been identified explicitly at this stage. Although the need for comprehensive planning is recognized, particularly for the six intercounty basins, the lack of definitive planning priorities and intergovernmental agreements suggests that such planning is not imminent. In addition, even with increased funding and staffing King County anticipates being able to complete just two comprehensive plans per year (T. Nesbitt, King County Planning, internal memorandum, 1978; and personal communication). The result is that although timely planning is desired it is more likely that additional delays will occur.

It is therefore concluded that no significant time constraints (other than associated with data as discussed below) would affect the feasibility of implementing a continuous simulation model.

Data Availability

The need for representative data has been stressed repeatedly. This section documents briefly the existing precipitation, evapotranspiration, and streamflow data bases available for modeling use. The status of precipitation and evapotranspiration records are summarized in Table 4.2, streamflow records in Table 4.3; the station locations are shown in Figures 4.1 and 4.2, respectively.

At first glance it may seem that available data are extensive and perhaps adequate. This is not quite the case, however, as closer examination shows. Precipitation data, for example, represent the City of Seattle very well since Weather Service stations have existed for extended periods at Boeing Field in the south-end; downtown, the University of Washington, and Naval Air Station Sand Point in the central section; and Maple Leaf Reservoir and Jackson Park in the north. The systems maintained by the City of Seattle and METRO provide even better coverage over the last 10 to 15-years. Not all of these records are equally valuable; the hourly records are most desirable, the daily less so. In addition, the longest city record, Seattle Downtown (Lake Union), actually represents at least two different locations since the station was first established - one near the present Federal Office Building and the other on Lake Union. (Precise locations were not published prior to April 1948; see Table 4.2). The extent to which these changes in location have altered the character of the record is unknown.

The Tacoma, Everett (city), Kent and Bothell stations have been moved a number of times, as well. Changes in station elevation at a given site probably do not affect the record, but cause even more difficulty when combined with a station move because orographic (elevation induced) effects may become important.

Outside Seattle, gage coverage is much less extensive. The Seattle-Tacoma International Airport (Sea-Tac) gage is the only one between Seattle and the King-Pierce County line (Tacoma is about 10 miles farther south), and has been an hourly record only since 1965. The stations at Carnation and Snoqualmie Falls are considerably beyond the boundaries of areas currently experiencing urbanization, but may be needed to represent precipitation in the eastern parts of suburban King County. Monroe represents a similar situation in Snohomish County. In addition, the daily records for Monroe, Kent, etc., would be most useful if

TABLE 4.2

STATUS OF PRECIPITATION AND EVAPORATION DATA

I. Precipitation Records

Station Name	Location (Deg. Min) N. Lat.; W. long. [1]	Elevation (feet) [1]	Type of Record [2,3]	Period of Record [3]	Comments
A. Seattle - City (Downtown)	47.39; 122.18	19	H,R	11/1972 - present	Recording gage established 1/1939 but data not published; data for 1890-1897 not published but available through archives
	47.36; 122.20	14	H,R/D	3/1936 - 10/1972	
	?	125, 248, 123, 119, ?	D	?/1890 - 2/1936	
B. Seattle - University of Washington	47.39; 122.17	95, 113	D	6/1964 - present	Data may exist for period 1/1918-5/1926 in the archives
	47.39; 122.18	60, 30, 112	D	2/1938 - 5/1964	
	?	160	D	6/1926 - 1/1938	
	?	170	D	3/1910 - 12/1917	
C. Seattle - Airport (Boeing Field)	47.32; 122.18	14	H,R/D	7/1928 - 10/1967	Hourly data published beginning 10/1940; possibly available earlier
D. Seattle - Naval Air Station (Sand Point)	47.41; 122.16	21, 41	D	9/1929 - 3/1964	Data may exist through 1971, when station was closed
E. Seattle - Maple Leaf Reservoir	47.42; 122.19	422	D	5/1941 - 5/1961	See Section II., evaporation data
F. Seattle - Jackson Park	47.44; 122.19	335	D	1/1961 - present	
G. Seattle - Tacoma International Airport	47.27; 122.18	400, 386, 379	H,R/6,R/6	1/1953 - present	Hourly data published beginning 10/1965; 6-Hour published Beginning 5/1948; 6-Hour storage apparently began 3/1946, but not published until 5/1948
	47.26; 122.20	379	6	4/1948 - 12/1952	
	?	379	6/D	1/1945 - 3/1948	
H. Tacoma - City	47.15; 122.26	Various	H,R	7/1947 - present	Hourly data published since 1/1940; records for pre-1898 not published but available from archives
	?	109	H,R/D	1/1925 - 6/1947	
	?	194, 213,	D	?/1884 - 12/1924	
	?	137, ?	D		
I. Everett - City	46,59; 122.11	60	H,R	3/1969 - present	Hourly data published since 10/1940
	47.59; 122.12	99	H,R	6/1958 - 2/1969	
	47.47; 122.13	120	H,R	4/1948 - 5/1958	
	?	127, 123, 166	H,R/D	1/1915 - 3/1948	
J. Everett - Airport	47.54; 122.17	598	H,R	3/1950 - 7/1952	
K. Kent - City	47.24; 122.15	32	D	7/1967 - present	Many nearby sites since 1941
	47.24; 122.15	40	D	10/1948 - 6/1967	
	47.24; 122.15	32	D	3/1921 - 9/1948	
	?	53	D	6/1912 - 2/1921	
L. Carnation	47.41; 121.59	50, 40	H,R	10/1940 - present	
M. Snoqualmie Falls	47.33; 121.15	440	H,R/D	2/1948 - present	Hourly data published since 8/1954
	47.31; 121.51	430	D	8/1930 - 1/1948	
	?	594, 667, 410, 667	D	10/1898 - 7/1930	
N. Monroe	47.51; 121.59	120	D	2/1929 - present	
O. Bethel	47.46; 122.13	105	D	10/1956 - 5/1959	
	47.47; 122.13	100	D	8/1932 - 9/1956	
	?	54	D	1/1931 - 7/1932	

TABLE 4.2 (Concluded)

STATUS OF PRECIPITATION AND EVAPORATION DATA

I. Precipitation Records

Station Name	Location (Deg. Min) N. Lat.; W. long. [1]	Elevation (feet) [1]	Type of Record [2,3]	Period of Record [3]	Comments
P. Snohomish	?	55, 100, 50	D	4/1894 - 4/1920	Data prior to 1898 not published but available in archives
Q. Auburn	City of Auburn sewage lagoon (see comment)	60 (see comment)	D	7/1955 - 1976	Data not published. Reference for existence of station is METRO and City of Seattle Water Department (1974)
R. City of Seattle Network	20 stations throughout City	Various from about 10 to 450	H,R	Network started 1960. Record length varies for each station	Data not published, but are converted to punch cards and summarized regularly
S. METRO Network	11 stations	Various from about 10 to 50	H,R (see comment)	Network started 1972. Record length varies	Data are telemetered to central control for monitoring on continuous basis and hourly summaries are prepared

II. Evaporation Records

Station Name	Location (Deg. Min) N. Lat.; W. long. [1]	Elevation (feet) [1]	Type of Record [2,3]	Period of Record [3]	Comments
A. Seattle - Maple Leaf Reservoir	47.42; 122.19	422	D	5/1941 - 10/1960	Year-round data, but data are occasionally reported as totals for several days.
B. Puyallup - 2W Experimental Station	47.12; 122.12	50	D	3/1961 - present	Readings are suspended each winter; record each year covers approximately mid-March to mid-November

Notes:

[1] Precise locations were not reported prior to April, 1948. Station elevation and observer are reported consistently. Exact location information may be available from data archives. Where precise station location is shown for period before April 1948, it has been inferred from the reported station elevation record.

[2] Key to Type of Record:
H = Hourly or finer increments
6 = Six-hour total
D = Daily total
R = Recording gage (other precipitation records are storage totals only)

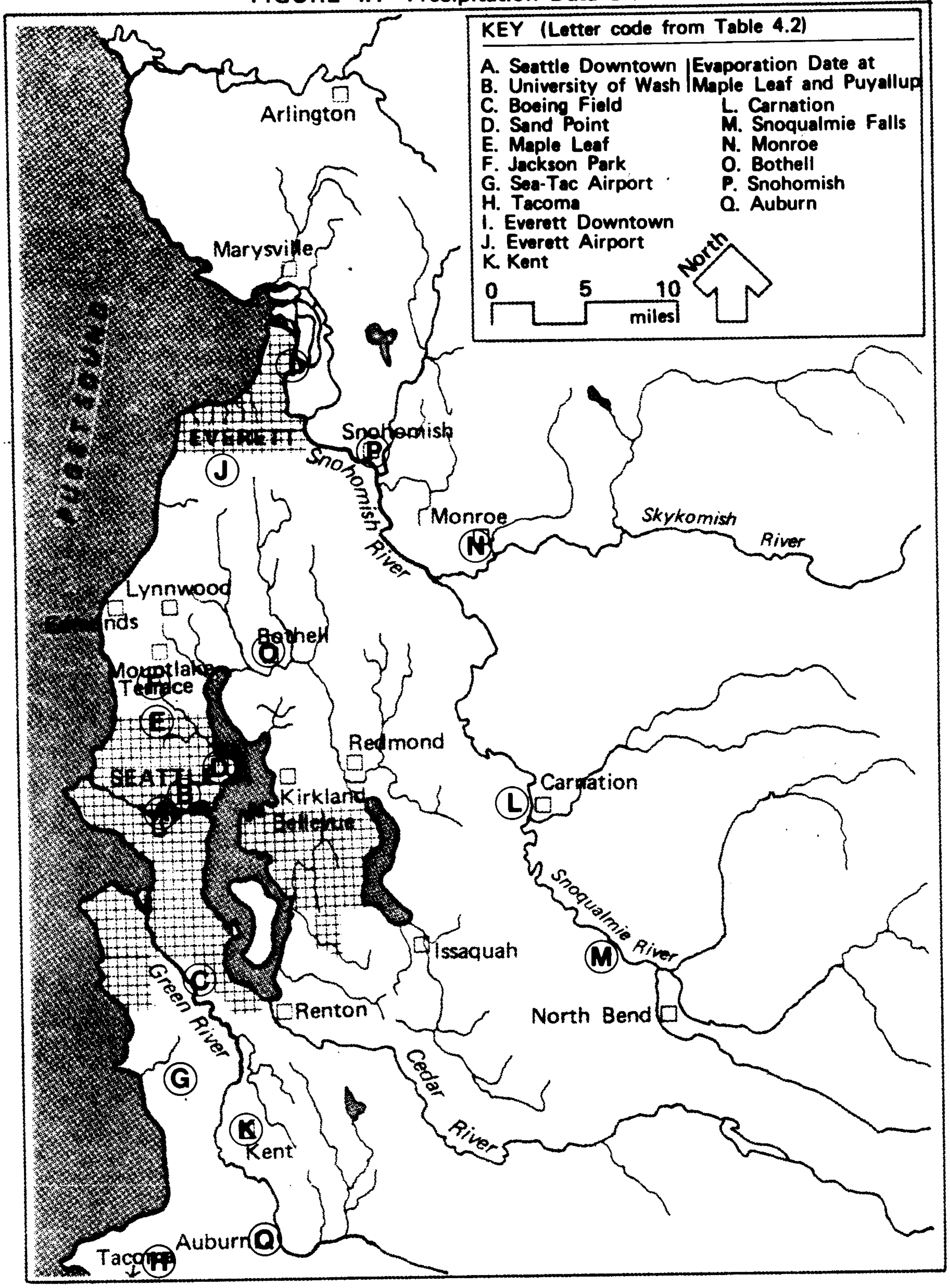
[3] Record type and length established by examination of U.S. Weather Service published records except as noted. It is possible that additional data exist in some form in data archives and could be obtained, coded, and used for modeling.

Sources: U.S. Environmental Data Service (U.S. Weather Service/U.S. Weather Bureau)
- Hourly Precipitation Data: Washington
- Climatological Data: Washington
- Hydrologic Bulletin - Daily and Hourly Precipitation - Region 9: North Pacific District

METRO and City of Seattle Water Department (1974).

Personal Communications - H. Sasaki and R. Tobey, City of Seattle Engineering Department
- J. Buffo, METRO

FIGURE 4.1 Precipitation Data Stations



correlations can be established with hourly records. The hourly data obtained by METRO are of limited usefulness at this time because the records are so short. In addition, all METRO stations are at low elevation and therefore do not represent higher elevations.

Experience of the authors in modeling Kelsey Creek in Bellevue was cited in Chapter 3. METRO has found that a single raingage within a basin may not be sufficient to represent spatial and temporal variation in rainfall (J. Buffo, METRO, 1978; personal communication). The limitations of the existing precipitation data base in an extensive watershed modeling program are therefore apparent.

Evaporation data are collected at relatively few locations, primarily in agricultural areas (e.g., Eastern Washington). The existing records would be more valuable if the period of record for Maple Leaf Reservoir and Puyallup overlapped. As the records exist there is no basis for comparison or correlation. Furthermore, no data exist prior to 1941 to correspond to the long precipitation records available at a few stations. Consequently, evaporation would have to be estimated from other meteorological data (e.g., solar radiation, temperature, dew point, and wind movement) as described by Linsley, et al, (1975). Although this may seem a critical limitation, the documentation of the Hydrocomp Simulation Program (HSP; Hydrocomp Inc., 1969, 1972; a continuous simulation model discussed in Chapter 5), indicates that great precision is not needed since minor errors in daily estimates will not, in the long run, affect the volume of water estimated as lost to evaporation. In the same context, enough similarity in general meteorological conditions exists between Puyallup and Seattle to suggest that no significant error in simulation would result from use of the records without modification.

Streamflow records exist for many of the watersheds that have been mentioned as being in need of comprehensive planning (see Chapter 2; also King County Division of Planning, 1977). The value of the records to an extensive modeling program is less than ideal, however. The most obvious factor is that not all basins have records. Similarly, only Issaquah Creek and Evans/Big Bear Creek have subarea records (see Figure 4.2). The importance of subarea flows for model calibration has been stressed repeatedly.

Another limitation of the streamflow data base is the short record length at most stations. The longest record to date is for North Creek, but the gage was removed in 1972 so no recent data are available. Similar problems exist

TABLE 4.3

STATUS OF STREAM FLOW DATA

Station Name	Area (Sq. Mi.)	USGS Gage Number *Denotes Active	Location	Record Period	Comments**
May Creek	12.5	12-119500	SW 1/4 SE 1/4 S 32 T 24 N R 5E 1 mi. above mouth	June 1945 - Oct. 1950 June 1955 - Sept. 1958 Oct. 1963 - Sept. 1964	Fair records; minor diversions
May Creek	12.7	12-119600	NE 1/4 NW 1/4 S 32 T 24 N R 5E 1/4 mi. above mouth	Aug. 1964 - Sept. 1971	Excellent records; minor diversions
Coal Creek	6.80	12-119700	NW 1/4 SW 1/4 S 16 T 24 N R 5E 3/4 mi. above mouth	Dec. 1963 - Sept. 1968	Excellent records; minor diversions; possible low flow regulation
Mercer Creek	12.0	12-120000*	NW 1/4 NW 1/4 S 4 T 24 N R 5E 1.5 mi. above mouth	June 1955 - present	Good records; minor diversion, extensive development during period of record
Juanita Crek	6.43	12-120500*	SW 1/4 SE 1/4 S 30 T 26 N R 5E 1/4 mi. above mouth	Sept. 1963 - June 1973 Oct. 1973 - April 1974 Oct. 1974 - present	Excellent records; minor diversions, extensive development during period of record, particularly 1968-present
Issaquah Creek	27	12-121000	SW 1/4 NW 1/4 S 15 T 23 N R 6E 4 mi. above E. Fork	June 1945 - Sept. 1964	Excellent records; minor diversions; some supplemental discharge at times
East Fork Issaquah Creek	9.5	12-121510*	NE 1/4 SE 1/4 S 28 T 24 N R 6E 0.1 mi. above mouth	March 1975 - present	Good records; minor diversions; some supplemental discharge at times
Issaquah Creek	54.7	12-121600*	SE 1/4 NW 1/4 S 21 T 24 N R 6E 1/4 mi. below N. Fork, 1 mi. above mouth	September 1963 - present	Good records; many diversions; gravel washing causes 4-5 cfs variation on work days
Tibbetts Creek	3.90	12-121700	SW 1/4 NE 1/4 S 29 T 24 N R 6E 1-1/4 mi. above mouth	Aug. 1963 - Sept. 1968 March 1971 - June 1973 Oct. 1973 - April 1974 Oct. 1974 - Sept. 1976	Good records; minor diversions

TABLE 4.3 (Continued)

STATUS OF STREAM FLOW DATA

Station Name	Area (Sq. Mi.)	USGS Gage Number *Denotes Active	Location	Record Period	Comments**
Cottage Lake Creek	11.0	12-123000	NE 1/4 SE 1/4 S 18 T 26 N R 6E 2 mi. above mouth	June 1955 - Oct. 1965 (Prior to June 1955 at different datum)	Good records; minor diversions; natural regulation upstream
Evans Creek	13.0	12-124000	on N. Line, NE 1/4 NE 1/4 S 7 T 25 N R 6E 3/4 mi. above mouth	June 1955 - June 1973 Oct. 1973 - April 1974 Oct. 1974 - Sept. 1976	Good records; minor diversions
Big Bear Creek	47.5	12-124500	SW 1/4 NE 1/4 S 12 T 25 N R 5E 3/4 mi. above mouth	June 1945 - Nov. 1950 June 1955 - Oct. 1958	Record quality unknown; many small diversions; minor regulation 0.5 mile upstream
Bear Creek	15.3	12-125500	SE 1/4 NE 1/4 S 9 T 26 N R 5E 1/4 mi. above mouth	Jan. 1965 - July 1969	Good to fair records; minor diversions
North Creek	24.6	12-126000	NE 1/ NW 1/4 S 32 T 27 N R 5E 2.5 mi. above mouth	June 1945 - Sept. 1972	Fair records; minor diversions; some regulation for farm use
Swamp Creek	23.1	12-127100*	NE 1/4 S 12 T 26 N R 4E 1/4 mi. above mouth	Oct. 1963 - June 1973 Oct. 1973 - April 1974 Oct. 1974 - present	Excellent records (some rated only fair); minor diversions
Lyon Creek	3.67	12-127300	NW 1/4 SE 1/4 S 10 T 26 N R 4E 700 ft. above mouth	Aug. 1963 - Sept. 1967	Good records; minor diversions
McAleer Creek	7.80	12-127600	SE 1/4 SW 1/4 S 10 T 26 N R 4E 1/4 mi. above mouth	Aug. 1963 - Sept. 1972	Excellent records; minor diversions; minor regulation by Lake Ballinger
Thornton Creek	12.1	12-128000	NE 1/4 SE 1/4 S 34 T 26 N R 4E 1/4 mi. above mouth	July 1945 - Sept. 1946 May 1961 - Sept. 1968	Good records; partial regulation by supplemental flow from City of Seattle; minor diversions

TABLE 4.3 (Concluded)

STATUS OF STREAM FLOW DATA

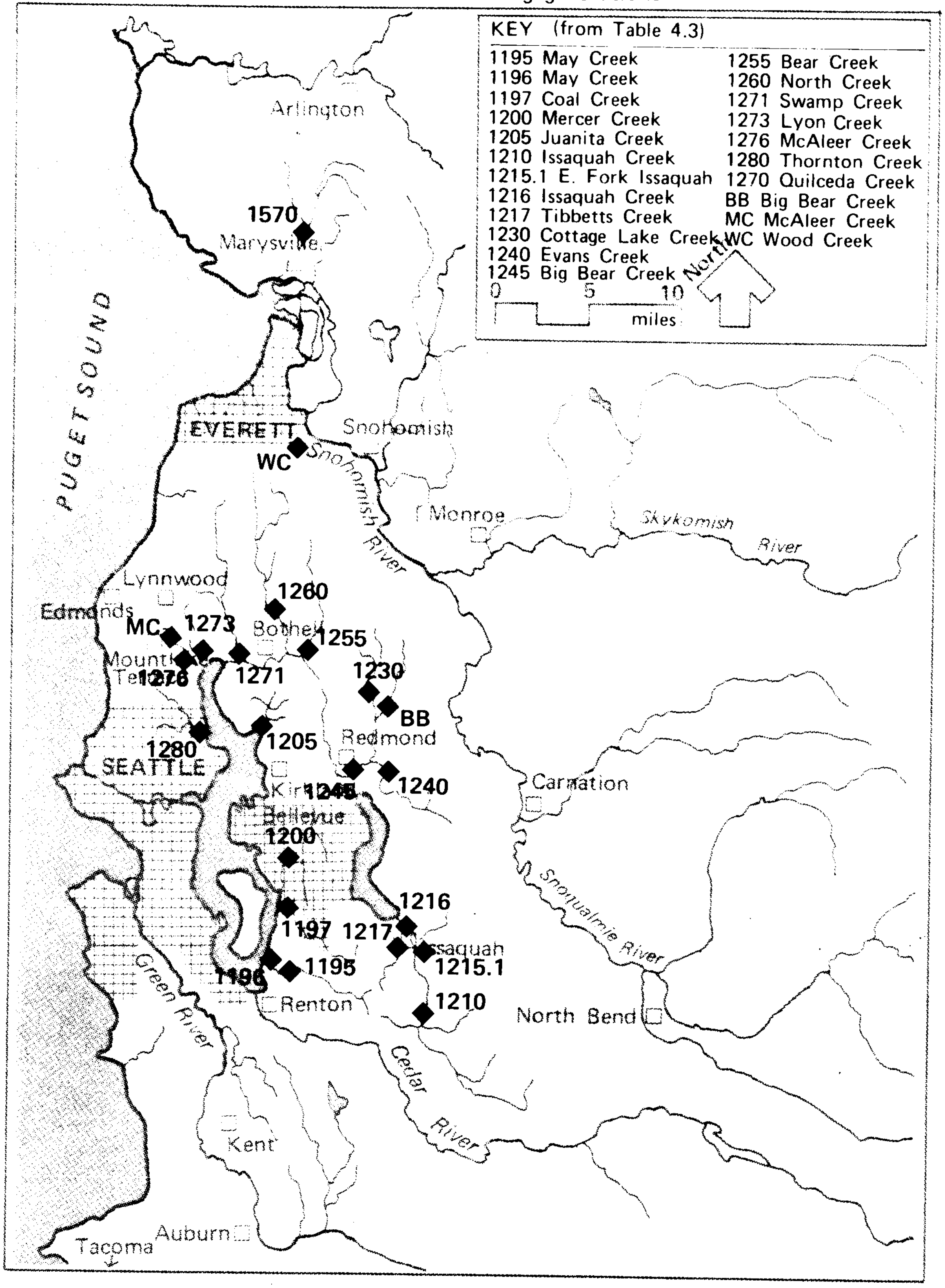
Station Name	Area (mi.2)	USGS Gage Number *Denotes Active	Location	Record Period	Comments**
Quilceda Creek	15.4	12-157000	NE 1/4 NE 1/4 S 9 T 30 N R 5E 300 ft. below Middle Fork	June 1946 - Sept. 1969	Good records; several diversions; regulation during low flow
Big Bear Creek	12.8	unknown (BB)	SW 1/4 S 20 T 26 N R 5E 1 mi. above Cottage Creek	June 1945 - Oct. 1949	Record quality unknown; no regulation or diversion
McAleer Creek	7.48	unknown (MC)	NE 1/4 S 9 T 26 N R 4E 1 mi. above mouth	July 1945 - Sept. 1945 Jan. 1945 - Oct. 1949	Record quality unknown; minor diversions
Wood Creek	1.96	unknown (WC)	E Line S 8 T 28N R 5E at road crossing	July 1946 - Sept. 1948	Record quality unknown; no diversion or regulation

**Record quality defined as:
Excellent = 95 percent of daily flows accurate ± 5%
Good = 95 percent of daily flows accurate ± 10%
Fair = 95 percent of daily flows accurate ± 15%

Source: U.S. Geological Survey - Surface Water Supply of the United States: Part 12: Pacific Slope Basins in Washington. (Water Supply Papers 1316, 1736, 1932, 2132).

- Water Resources Data for Washington (Water Years 1970-1976).

FIGURE 4.2 Streamgage Stations



for the other discontinued stations. The lack of current data could be a significant handicap in evaluating both existing and future conditions during comprehensive planning as desired by the potential model users.

Data conditions are not ideal for the four active stations, either. The Mercer Creek and Juanita Creek watersheds have undergone extensive urbanization during the period since 1968; development continues in both. Swamp Creek has undergone relatively less development, but watershed change is still a factor that could complicate use of the record in modeling. As observed in Chapter 3, calibration of a model when watershed land-use has changed dramatically is difficult because it is not possible generally to identify discrete changes causing identifiable streamflow alterations. Identification of model parameter values, at the same time maintaining their physical meaning, is correspondingly difficult.

A final comment on the status of the data base is in order. Many of the data identified here were gathered, analyzed, and coded for the RIBCO water quality management studies (METRO and City of Seattle Water Department, 1974; CH2M-Hill, 1974) which used HSP for overall plan development (as opposed to detailed watershed studies). The data were stored on disc files in anticipation of further use. When the RIBCO work was completed, however, it was decided to discontinue use of HSP, and it was returned to Hydrocomp (the model was leased for use). Since that time the City of Seattle has attempted to make use of the stored data on two occasions, once through Boeing Computer Services and once through the University of Washington. Both attempts were unsuccessful, apparently in part because the data are stored on a disc that is no longer compatible with local computers. The City and METRO have both decided that the cost of overcoming this difficulty is too high to justify further effort. As a result, the stored data are apparently inaccessible, with the result that future modeling programs may have to start form scratch in compiling, sorting, and coding meteorologic and streamflow data (J. Buffo, METRO, 1978; personal communication).

EVALUATIVE CRITERIA

Based on the preceding sections, criteria against which continuous simulation models will be evaluated have been developed as follows:

1. The model must be capable of representing watershed and subwatershed conditions. The lower bound for areal representation should not be limited by model structure, only by data and computation cost constraints.

2. The model must be capable of representing the effects of land-use changes at the smallest areal level allowed by the data and cost constraints in (1); the manner of such representation should be logical and repeatable.

3. The model must provide estimates of peak rate and volume of runoff at many locations within a watershed, e.g., at a minimum for each modeled subarea, the total watershed, and additional points on the main stem of the conveyance system connecting all subareas.

4. The model should provide both numerical and graphical displays of the simulated flows in a manner that allow examination of individual events as well as daily, monthly, and annual flows, and which can be adapted readily for flow probability and water quality analyses.

5. The model must account for all components of the hydrologic process at the subarea level to maintain its reliability in predictive applications, to facilitate calibration, and to represent long term flow conditions appropriately.

6. The model must be capable of modeling the conveyance system downstream from modeled subareas at any desired level of detail, i.e., it should include optional use of both hydrologic and hydraulic routing methods; it should be capable of representing pond storage, backwater effects, etc., if desired. The method of representation of subarea internal routing should be consistent with other subarea modeling detail.

7. The model must be amenable to calibration that minimizes error but maintains the physical meaning of model components.

8. The model must be understandable both to the direct users on the planning and engineering staffs of the municipalities and to the public officials who must make the final implementation decisions; model output should be in a form amenable to both technical use and public decision making.

9. The model should contain no unnecessary parts that would tend to increase its cost of operation or the complexity of analysis required of its results.

10. The model must be able to make use of the available precipitation, evapotranspiration, and streamflow data in a manner requiring a minimum of data manipulation external to the model; the model must also be able to incorporate new data efficiently and provide information useful in evaluating the type and extent of data needed.

A final criterion not addressed directly to a candidate model is:

11. The data not available through the existing recording network must be obtainable at the spatial and temporal level of detail needed by the model, and must be obtainable at a reasonable cost.

These criteria are used to evaluate various models in Chapter 5.

CHAPTER 5

EVALUATION OF CONTINUOUS SIMULATION HYDROLOGIC MODELS

INTRODUCTION

It was originally envisioned that a number of fundamentally different continuous simulation hydrologic models would be evaluated. Review of the literature and personal communication with some modelers has led to the conclusion, however, that only one fundamental model exists of the type envisioned for the applications identified in the preceding chapter: the Stanford Watershed Model (SWM; Linsley and Crawford, 1960). Many variations of this model are in use today, including the SWM-Version IV (Crawford and Linsley, 1966), the Kentucky Watershed Model (Liou, 1970; James, 1970), and the Hydrocomp Simulation Program (HSP; Hydrocomp, Inc., 1969, 1972). This group of models is evaluated in this chapter, following a brief discussion of the models that were screened from further consideration.

CONTINUOUS SIMULATION MODELS - INITIAL SCREENING

The models identified in the literature as having "continuous simulation capability", defined here as simulation of the system over a long time frame (e.g., several years) using short time increments (e.g., daily or shorter), are listed in Table 5.1.

Each of the models in category (II), above, (Other Continuous Simulation Models) is described briefly below. The reasons for their exclusion are provided.

U.S.D.A. Hydrologic Laboratory Model (USDAHL)

This model was developed for use in small, agricultural watersheds and incorporates detailed soil information and crop management practices as inputs. The treatments of infiltration, soil horizons, and groundwater movement are detailed, but impervious area is not included. The model has not been applied to urban or suburban runoff issues nor is its documentation extensive for agricultural applications. Some use in environmental impact assessment for the Soil Conservation Service is cited. Linsley (1971) and Viessman, et al, (1977) conclude that the USDAHL is not suitable for urban area use; it was not evaluated in the urban runoff model review of Brandstetter (1976).

TABLE 5.1

CONTINUOUS SIMULATION HYDROLOGIC MODELS

STANFORD WATERSHED MODEL VARIATIONS	
Stanford Watershed Model IV	- Crawford and Linsley (1966)
Kentucky Watershed Model OPSET Addition	- Liou (1970)
Texas Watershed Model	- Claborn and Moore (1970)
National Weather Service Version	- U.S. National Weather Service (1972); also, Anderson (1968), Monro (1971)
Hydrocomp Simulation Program	- Hydrocomp Inc., (1972)
Hydrocomp Simulation Processor II	- Hydrocomp Inc., (1978)
OTHER CONTINUOUS SIMULATION MODELS	
U.S. Department of Agriculture Hydrologic Laboratory Model	- Holtan and Lopez (1973)
Streamflow Synthesis and Reservoir Regulation Model	- U.S. Army Corps of Engineers (1972)
Antecedent Precipitation Index Model	- Sittner, et al, (1969)
Chicago Flow Simulation Model	- City of Chicago (1972)
Corps of Engineers STORM Model	- U.S. Army Corps of Engineers (1974a)
University of Massachusetts Model	- Ray (1973)
Tennessee Valley Authority Daily Flow Model	- Betson (1972)

References cited are primary documentation sources. Secondary sources consulted in compiling the table were: Linsley, (1971); Brandstetter, (1976); Overton and Meadows, (1976); and Viessman, et al, (1977).

Streamflow Synthesis and Reservoir Regulation Model

SSARR was developed for large watersheds for the purposes suggested by its name, e.g., long term flow synthesis and reservoir operation. It has also been used for large scale flood forecasting. Applications have included the Mekong River system in Southeast Asia and the Columbia River system in the U.S.A.. Runoff is modeled by several large area approximations for surface flow, interflow, and base flow. Each flow component is delayed according to different processes and combined to produce the total subarea hydrograph for routing through the channel network. The watershed scale for which the model has been developed and the level of aggregation used in modeling processes within subwatersheds indicate that SSARR is not appropriate for urban applications (Linsley, 1971; Viessman, et al, 1977).

Antecedent Precipitation Index (API) Model

The API model was developed for large scale river simulation and flood forecasting. Outputs are for six-hour periods. A unit hydrograph and series of antecedent condition indices must be developed specifically for any area. Documentation to date has been for only two basins (large by urban standards - 68 and 817 square miles). The time step and areal scale represented in the model are inappropriate for urban uses.

Chicago Flow Simulation Model

This model was developed specifically for use in the Metropolitan Chicago area, and includes many fixed internal expressions that would have to be established for any other area. Its use is primarily for large scale flooding, including snowmelt, for areas served by combined sewers and for nonsewered areas. Many simplifications compatible with large area use are incorporated: the model neglects basin shape, slope, and pervious area surface roughness for sewered areas; it neglects impervious area in nonsewered areas; and it treats all nonsewered areas as having the same surface characteristics. Water quality, flow controls (e.g., weirs), surcharged flow, backwater effects, and other flow aspects are not modeled (Brandstetter, 1976). These factors, and the area specificity of the model, indicate it is not readily adaptable to smaller scale applications in other geographical areas.

Corps of Engineers STORM Model

STORM was developed for evaluation of the stormwater storage and treatment capacities required to reduce untreated overflows below user specified levels. It is adapted for use on a single catchment only and is intended for simulation of areas served by combined sewers, hence, its emphasis on treatment levels and limitation of overflows. The Rational Method is used to generate runoff; neither internal catchment sewer nor channel routing is modeled. Hourly total runoff volumes for the entire area are the output. Brandstetter (1976) concludes the model appears suited for preliminary planning where overflows are an issue. Dendrou and Delleur (1978) similarly conclude the model does not represent urban conditions with enough precision for many applications. Its lack of representation of catchment dynamics (in particular the lack of routing and reliance on the Rational Method), its ability to simulate only a single catchment, and its nonrepresentation of downstream channel routing indicate STORM is not applicable to the issues identified here.

University of Massachusetts Model

Although continuous simulation is a feature of this model, it simulates only impervious area runoff and circular storm sewer flow for use in determining operating procedures for a combined sewer control program. It is clearly not applicable to the current work.

Tennessee Valley Authority Daily Flow Model

As the name implies, this model provides a daily accounting of runoff for large watersheds, consistent with the needs of TVA for reservoir regulation, for power supply, navigation, recreation, etc. Daily rainfall is used with monthly evapotranspiration to generate daily, monthly, and annual streamflows. The model has been developed expressly for TVA and is not appropriate for urban and suburban watershed analysis.

STANFORD WATERSHED MODEL VARIATIONS

The many modifications of the basic Stanford Watershed Model (SWM) have been attempted primarily to tailor it to specific uses or improve a specific aspect of its simulation. In particular of the versions listed herein, the National Weather Service model is intended for large scale uses for river flow and flood flow forecasting along the lines of SSARR (Viessman, et al, 1977). Anderson (1963) made extensive changes in the snowmelt routines. Time steps of six hours are used generally, and several other simplifications have been made (Linsley, 1971). The NWS version is not intended for urban use, and is not discussed further here.

The Boughton Model has been applied in Australia, and uses daily inputs to calculate monthly flows. The simplification indicates it, like the NWS model, is not appropriate for urban watershed modeling.

The version in widest use is SWM-IV (Crawford and Linsley, 1966). (A FORTRAN version programmed by the National Weather Service has been in use at the University of Washington since 1970). Documentation of the mechanics and applications of SWM-IV is by far the most complete; by contrast, the Texas Watershed Model (TWM) apprently has been reported only once in the general literature (Claborn and Moore, 1970), according to Linsley (1971) and Viessman, et al, (1977). The TWM was modified to incorporate factors its developers felt were important in representing the hydrology of semi-arid areas. The lack of documentation and the apparent tailoring of the TWM for hydrologic and meteorologic conditions much different from those in the King and Snohomish County areas preclude its further consideration here.

Documentation of the Kentucky Watershed Model (KWM) and its applications is intermediate between SWM-IV and TWM (e.g., Liou, 1970; James, 1970, 1972; Magette, et al, 1976; Viessman, et al, 1977). In addition to general modifications made for computational efficiency and application in the humid areas for the Eastern United States, a self calibrating version has been developed (KWM-OPSET; Liou, 1970). Applications of OPSET include some urban watersheds as reported by James (1972) and are discussed briefly later in this chapter. The basic model structure of KWM is relatively unchanged from SWM-IV, however.

The Hydrocomp Simulation Program (Hydrocomp, Inc., 1972) is a proprietary version of SWM-IV. Major additions include optional nonlinear channel routing, hydraulic reservoir routing, and water quality routines. Other modifications have been made to improve computational efficiency and add flexibility in modeling unusual conditions. An example of the latter is the ability to model runoff from frozen ground, an important phenomenon in many areas. Full details of the model structure are not available because HSP is owned by Hydrocomp, but its basic structure remains the same as SWM-IV. Application is widespread, and includes several urban area studies (e.g., Crawford, 1971, 1973; METRO and City of Seattle Water Department, 1974).

The more recent Hydrocomp model, HSP II, is under development at this writing, partially under contract to the Environmental Protection Agency for development of a publicly available continuous simulation model. The EPA project is not scheduled for completion until October 1978. As a result, documentation of its improvements will not be available in time for inclusion here (R. Johanson, Hydrocomp, 1978, personal communication). General information is provided by Crawford (1978).

In summary, the best documented and most widely used model is SWM-IV; in particular, the NWS FORTRAN translation used at the University of Washington is well known by the authors. For this reason, the evaluation which follows concentrates on SWM-IV, with reference to known characteristics of other SWM versions as necessary.

FUNDAMENTAL OF STANFORD WATERSHED MODEL VERSION-IV

The details of SWM-IV are provided by Crawford and Linsley (1966). The interested reader is referred to that document, or to Linsley, et al, (1975), or Viessman, et al, (1977), which provide excellent summaries and model flowcharts. Documentation of the model structure is included here only as necessary for evaluation according to the criteria set forth in Chapter 4.

The basic concept of SWM-IV is to provide a continuous accounting of all water entering a modeled area as precipitation (or streamflow for downstream areas) and leaving as streamflow, deep percolation (i.e., loss to deep, inactive groundwater), or evapotranspiration. Hydrologic processes modeled are:

1. Interception storage;
2. Impervious area runoff;
3. Rapid (direct) infiltration;
4. Surface runoff;
5. Delayed infiltration;
6. Interflow (upper soil zone water to channel inflow);
7. Upper soil zone storage;
8. Percolation from upper to lower zone and groundwater;
9. Lower soil zone storage;
10. Groundwater storage;
11. Groundwater flow to channels (baseflow);
12. Groundwater loss to deep, inactive groundwater storage.

In addition, evapotranspiration (ET) is modeled as occurring at the potential rate as long as moisture is available. Recorded pan evaporation data are typically used as model input, after application of an appropriate factor to reflect the difference between pan evaporation and lake evaporation (usually interpreted as equivalent to potential ET). Potential ET is tested for each modeled time step, first against interception storage. The amount not fulfilled from interception storage is then tested against upper soil zone storage, and reduced accordingly. If any potential ET still remains, it may be fulfilled by withdrawals from lower soil zone and goundwater storage, but these latter storages are not depleted at the potential ET rate as are interception and upper zone storage. Input parameters set the rates at which lower zone and groundwater may be depleted, corresponding to the idea that deeper storage would be more difficult to reduce. Water is also lost from the surface of lakes and streams in the model at the potential ET rate.

Precipitation may be both rainfall and snow. If the latter is significant (e.g., the Midwest), snowmelt may also be modeled using appropriate inputs of temperature, solar radiation, wind, and dew point. Time steps for both precipitation and ET should be as short as possible, usually hourly and daily totals respectively. These inputs may be broken down into finer steps if desired.

Each channel flow component (impervious area flow, surface runoff, interflow, baseflow) is calculated for every time step and all are summed to represent the total hydrograph reaching the channel from the modeled area. The internal routing effects of channel travel time are accounted for by use of a "channel time delay histogram", defined by the incremental fraction of area contributing to flow at the point of interest for each time step. The areas are found by identifying lines of equal channel travel time (isochrones) within a modeled area for any assumed flow conditions (e.g., bankfull stage) and finding the area between isochrones. Channel inflows for each time step are routed through the time delay relationship.

Internal channel storage is accounted for by use of a linear reservoir routing function (i.e., outflow is presumed directly proportional to storage - see Viessman, et al, (1977); pp. 244-245). The time delayed inflow is routed through the reservoir function to produce the final channel outflow hydrograph. [The HSP models have been modified to use hydrualic reservoir and channel routing equations (see Viessman, et al, 1977; pp. 249-272) . In many cases the linearity assumptions of the time delay linear reservoir technique may not hold, in which case HSP provides the opportunity to represent the nonlinearity].

Channel flow between precipitation events is simulated as delayed runoff from lower zone and groundwater storages, supplied according to flow recession rates derived from the streamgage record. Year-round flows can therefore be simulated.

Many parameters used by the model are supplied by the user and are obtained via measurement, correlation with measurable quantities, analysis of streamflow data, and judgment. A number of values are varied during calibration as well.

MODEL EVALUATION

Eleven criteria for model evaluation were developed in Chapter 4. The Stanford Watershed Model, and its variations where appropriate, are evaluated against each criterion below.

Areal Representation (1)*

There is no theoretical limit to the number of subareas that may be represented by SWM-IV. In practice, however, flow is generally simulated at gage stations and a few intermediate sites if desired. The area upstream from each flow point may be subdivided according to important topographical considerations or as defined by a Thiessen polygon network where several rain gages are used (see Viessman, et al, 1977; pp. 218-220). Several segments per rain gage may be used, but only one recording gage and one daily or storage record per segment is allowed.

Although many area segments are allowed, flow is generally simulated at a few locations. In any case, the resolution obtainable is a function of the data base. The reliability of the simulation for any single land segment will depend on the quality of its precipitation record and the availability of stream gage records for calibration. The model provides monthly summary data for each segment indicating total channel inflow from impervious area, overland flow, interflow, and baseflow; actual evapotranspiration modeled; and month end quantities stored in interception, upper zone, lower zone, interflow detention, and groundwater. These quantities can seldom be checked directly. They should, however, be examined to ensure reasonable seasonal (e.g., monthly) variation.

Land-Use Representation (2)

Land-use (e.g., single family or multi-family residential, commercial, industrial, open space, etc.) is not an explicity input to any version of SWM-IV. Nonetheless, many of the effects of urbanization have been related to changes in model parameters. Crawford and Linsley (1966) and Hydrocomp (1969, 1972) provide guidelines for parameter selection. James (1965) used a conceptual

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(*) Criterion number from chapter 4.

approach to model urbanization and channelization; this does not provide the specificity desired locally, however. Other researchers (Crawford and Linsley, 1966; James, 1970, 1972; Ross, 1970; Crawford, 1971; Viessman, et al, 1977) have provided examples of parameter values associated with specific urban watershed characteristics derived from their case studies. The variation in parameter values reported suggests that results from other areas would be useful only in providing guidelines, however. Attempts to correlate parameter values with measurable physical characteristics have been inconclusive (Ross, 1970; James, 1972; Shanholtz, et al, 1976).

James (1975), Clarke (1973), and Viessman, et al, (1972) suggest the following factors should be considered when modeling urbanization:

1. Impervious area;
2. Channel type (e.g., pipe versus natural channel), length, slope, and geometry are altered;
3. Overland flow length is decreased (i.e., drainage density is increased);
4. Infiltration rate is decreased;
5. Natural lowland and wetland areas normally acting as storage or infiltration sites are eliminated; and
6. Upper soil zone and surface storage may be decreased by compaction of soil during construction.

It is therefore apparent that detailed modeling of small scale land-use change, to be reliable, would require very extensive data to identify the way in which each of these factors is affected by a given change. Given that such data do not exist, the modeler is left with two choices: use parameters derived for nearby, gaged areas; or use parameters derived by experience and judgment.

The former situation has considerable intuitive appeal. If areas typical of each land-use of interest could be identified and instrumented, the data needed to identify model parameters could be obtained. Two practical limitations arise, however. First, there is considerable small scale areal variation in rainfall-runoff response (see Chapter 3). As a result, the selected "typical" area (e.g., 40 acres of single family residential development) might be truly representative of all, some, or none of the 40 acre single family residential subareas in another watershed. Second, the term "single family residential" may mean that detached dwellings exist at densities of from one to seven or eight per acre. Even if all other factors (e.g., soil type, landscaping, slope, etc.) were identical (an improbably situation), impervious area runoff would be drastically different.

Consequently, development of typical model parameters from selected small areas appears more useful in providing better guidelines for acceptable parameter ranges during calibration than for determining parameters precisely. If this premise is accepted, either judgment must be relied on or larger areas must be modeled. Judgment is frequently an appropriate approach, but more confidence can be placed on results derived from direct observations for a watershed.

Based on these arguments, it appears that the subwatershed land segment approach used by SWM-IV is a logical compromise. Good data are easier to collect for a few, moderate sized areas than for many, very small ones. Reliability of the simulation will increase correspondingly. The effects of land-use changes of subwatershed scale can still be represented, and data for such areas could be as useful in identifying appropriate parameters for smaller areas as small area data from outside the watershed.

In any case, the lack of explicit representation of specific land-uses is not a limitation to the usefulness of SWM-IV, provided data are gathered to allow adequate calibration of subarea parameters.

Flow Representation (3)

As stated above, there is no theoretical limit to the number of flow points that may be simulated. Channel flow (i.e., complete hydrographs) may be simulated at the outlet from each modeled land segment; the reliability of such representation will depend on the availability of data for calibration of segment parameters or the validity of transferring calibration results from similar, nearby areas. As long as modeled subareas correspond to major watershed subbasins (as opposed to very small areas), this potential limitation is minimized.

(Strictly speaking, any model should have data for calibration of subarea flows. Since this is not practical in general, limitations on the validity of individual subarea representations are not an exclusive problem of continuous simulation models. It may be argued logically that accounting for the important physical processes will increase the reliability of flow estimates from ungaged areas.)

HSP includes hydraulic routing algorithms, (as opposed to the time delay/linear reservoir functions of SWM-IV) for greater detail and can simulate main channel hydrographs at any number of points. Hydraulic routing also provides the ability to represent nonlinear channel timing and storage effects if they are important for a given stream.

The continuous streamflow sequence provided by SWM and its variations allows examination of peak flows and volumes for individual events, groups of events, and long term sequences.

Output Displays (4)

Crawford and Linsley (1966) describe the outputs provided by SWM-IV, both standard and optional, as follows:

Basic Output:

1. For each land segment - monthly summary table of all moisture storages and channel flow components.
2. For each flow point - mean daily flow each day and complete hydrograph of any runoff that exceeds a selected threshold value (for major hydrographs).

Optional Output:

1. Statistical comparisons of recorded and simulated daily flows.
2. Graphical plots of recorded and simulated daily flows.
3. Detailed storm analysis including 15-minute rainfall, interception, impervious area flow, overland flow, interflow and baseflow.
4. Storm period summary showing parameter (e.g., storage) variation during storm for consistency examination.
5. Maximum clock hour rainfall and channel inflow values.
6. Daily snowpack data.

Details of output available from the HSP models are not available directly at this time although it is known that water quality may be simulated using the same formulations applied by SWMM (see Chapter 2 and Appendix A). In any event, the long sequence of flows simulated by either model would allow use of any statistical or graphical display desired by the user. James and Burges (1978) suggest that it may be desirable ultimately to operate a model interactively, examining the results of a given computer run in three dimensions on a television display, modifying parameters and variables for another run, and examining the results once again. Addition of such capability to continuous similation models would be desirable.

Physical Process Accounting(5)

Continuous representation of the many processes affecting rainfall-runoff response is the central concept of continuous simulation. The reliability of any subarea simulation depends on data availability and parameter transferability, as has been stressed many times.

Whether snowmelt is an important factor to include is an open question. The RIBCO drainage modeling (U.S. Army Corps of Engineers, 1974b) and overall water resource management modeling (METRO and City of Seattle Water Department, 1974; CH2M-Hill, 1974) did not include snowmelt modeling for this area. Applications of SNODOB (Systems Control, Inc., et al, 1973; Systems Control, Inc. and Snohomish County Planning Department, 1974) for flood analysis assumed a fixed amount of runoff (e.g., two inches over a watershed) attributable to snowmelt but did not model the process physics explicitly.

Because significant snowfall is relatively rare in the Puget Sound lowlands, it is probable that it would not need to be modeled to provide an adequate representation of long term flows. Individual recorded runoff events significantly influenced by snowmelt could be identified from differences between simulated and recorded series. The ability to model snowfall in SWM leaves open the possibility of doing so if it were determined to be important to model validity. (A possible exception to the "do not need to model snowmelt" statement above, is Issaquah Creek, which has its headwaters at an elevation of 3,000 feet. Snowfall in the upper basin may be significant.)

Channel System Representation (6)

Lumb, et al, (1974) report that an urban watershed study conducted at Purdue (Sarma, et al, 1969) found a single linear reservoir to be adequate to represent the time distribution of runoff for watersheds less than five square miles in area. Crawford and Linsley (1966) suggest that for small areas, channel time delay and storage are relatively unimportant compared to land surface effects. (In effect, the probability characteristics of runoff from the outlet of small areas are equivalent to the probabilities of the land runoff.) These results indicate that the typical flow point and land segment breakdown and the routing representation used by SWM-IV are compatible with physical reality for many applications. The hydraulic routing features of HSP may be more desirable, however, if a more detailed representation is required, or channel effects are markedly nonlinear.

Both approaches offer advantages: lesser complexity and cost for the former; greater detail, the ability to simulate flow at intermediate locations, and possibly improved predictive ability because of representation of the actual channel characteristics for the latter (see Linsley, et al, 1975). Keefer (1976) compares single input and multi-input linear routing models with finite difference routing using both continuity and momentum equations and concludes that which model to use depends on what is desired. If precise stage and velocity information are wanted, finite difference methods must be used; if many alternative runs of a calibrated model are desired, the cost savings favor linear methods.

As documented in the literature, neither SWM-IV nor HSP offers both methods of routing. The use of subroutines in the models would make such an option easy to program. This may have been incorporated in HSP II (Hydrocomp, Inc., 1978), for which documentation will not be available in time for this work (R. Johanson, Hydrocomp, 1978; personal communication).

Neither routing method should encounter the solution instability problems documented for SWMM and SNODOB. Two reasons are offered for this conclusion. First, the detail level applied with SWM-IV or HSP is such that the very short channel segments like road crossings which cause instability are not modeled. Second, the time delay linear reservoir routing method used by SWM-IV does not use the differential equations which require either very short time steps or long channel segments. Although HSP does use the differential equations, the calculation time step is not fixed externally (as is the case with SWMM), but rather varied as needed to maintain solution stability. In any case, the absence of fine scale modeling with HSP would tend to minimize this difficulty.

SWM-IV does not model backwater effects, surcharged flows or reservoir (pond) storage, although the latter could be handled by dividing the watershed such that each pond was at the outlet from a land segment. On the other hand, HSP can model flow regulation, flood stage, reservoir storage, and water diversion from a watershed. Backwater effects are only approximated in the flow calculations; surcharged flow conditions cannot be modeled by HSP, but may be simulated by HSP II.

Calibration (7)

Effective calibration of SWM-IV or HSP depends to a large degree on the familiarity of the user with the model, the watershed, and hydrologic concepts in general. Several factors tend to make calibration less than routine:

1. The number of physical processes represented;
2. The number of mathematical expressions, parameters, and variables used; and
3. The interactions between physical processes, and therefore between parameters and variables, that must be considered.

Overton and Meadows (1976) observe that complex, multi-parameter models are not amenable to programmed optimization because there is an enormous number of possible parameter combinations that would have to be tried to establish the best fit between recorded and simulated series. Furthermore, many combinations might result in the same fit because of model and data errors. Without bounds on feasible or realistic parameter values, it may also be possible to force fit the model but thereby lose its predictive ability.

It is apparent, therefore, that knowledge of legitimate parameter ranges, knowledge of which parameters affect what aspects of the simulation and in what ways, and recognition of the desired application of the model (e.g., flood forecasting or low flow analysis) are indispensible to good calibration.

A programmed parameter optimization method has been developed in conjunction with the NWS version of SWM-IV (Monro, 1971). The optimization process was facilitated by the long (6 hour) time step and internal simplifications used by the NEW model. The NWS model is not appropriate for urban use, however, as discussed earlier.

Parameter optimization has been developed also in conjunction with the KWM. The optimization model is called OPSET, and is reported by Liou (1970), Ross (1970), and James (1970, 1972). Rather than optimizing all model parameters, the program concentrates on those that are difficult to measure directly and to which the flow sequence is sensitive. Based on sensitivity studies an initial list of 18 parameters which were difficult to measure was reduced to 11 to be optimized. These were divided into three categories: those significant in controlling monthly flow distribution; those related to flow volume immediately after major flood peaks; and those relating to timing, peak, and shape of flood hydrographs. The program was then developed to provide efficient simulation and optimization.

Two observations on OPSET are in order. First, because of computer storage and computation time requirements if multi-year sequences are used, OPSET establishes a set of parameter values based on recorded ans simulated flows for one year at a time. The final set of parameters is obtained by averaging a number of yearly results. James (1972) observes that this procedure may cause some bias because over-year effects are not completely represented, but computational considerations necessitated the year-by-year analysis.

Second, OPSET may only be applied for a single flow point for which both recorded and simulated flow sequences exist. In most cases this limits its use to total watershed modeling since data for all desired subareas seldom exist. OPSET has been applied to watersheds ranging 0.67 to 473 square miles (James, 1972). The applications to both rural and urban watersheds have shown that additional programming difficulties may result in any given situation. Although OPSET represents an admirable attempt to apply programmed parameter optimization to a continuous similation model, the need for good hydrologic knowledge and judgment on the part of the user has not been eliminated.

The approach used by OPSET in examining groups of parameters affecting a certain aspect of simulation is also used in subjective calibration (Linsley, et al, 1975; James and Burges, 1978). Annual and monthly totals are checked first, followed by more specific calibration affecting individual hydrographs, recession constants, etc. Model familiarity is a definite advantage. Linsley (1971), for example, states that in all but the most unusual cases only four of the 17 parameters used by HSP in modeling rainfall-runoff response are critical. Similarly, James (1972) states that two KWM parameters have consistently been found to be most important. Mein and Brown (1978), reporting a study of the sensitivity of flow simulation to changes in parameters found by optimization (using the Boughton Model), similarly found that a three parameter subset of a 13-parameter model could account for a great deal of the accuracy of a simulation. Although they observe that greater precision can be obtained by adding parameters to which flow is sensitive, they recommend measurement of as many parameters as possible so calibration can be focussed on the most sensitive.

It is therefore apparent that model calibration, although complex, is feasible and in particular is facilitated by user knowledge. Under no circumstances, however, can user expertise overcome data deficiencies which cause faulty simulation or misleading comparisons between recorded and simulated sequences.

User Comprehension (8)

Fundamental hydrologic concepts like infiltration, surface runoff, or baseflow are easily understood by anyone who has observed rainfall and runoff. What is important is the comprehension by both direct and indirect model users of the capabilities and limitations of a model. The first step toward user familiarity is model documentation.

SWM-IV is well documented, both as to its technical structure and its applications. HSP, being a proprietary model, is documented somewhat less well in the public literature. In compensation, however, Hydrocomp conducts several user workshops each year to discuss the model, and provides professional assistance to users in new applications.

User comprehension is a lesser problem for direct model users (e.g., municipal planners and engineers) because they are more likely to be well grounded in the technical aspects of hydrology or modeling than are public officials. The key to understanding a model on the part of the latter, indirect user group lies in the effectiveness of communication with direct users. Whereas the planners and engineers need to know model details, decision makers need to know what the model says, how well, and at what price. The model documentation can help answer the first two questions. Price is largely governed by the application intended. The flexibility of model output provided by the many SWM variations should facilitate user understanding as well. The decision maker can see how well the model replicates a recorded series, runoff volumes, etc. The concept of altered flow probability with land-use change can be seen in the simulated flow sequences; land-use implications and the effectiveness of alternative management strategies can be shown.

To facilitate user comprehension and to increase overall efficiency of operation Hydrocomp is developing a "Simulation Network" in conjunction with development of HSP II (Crawford, 1978). The basic concept is to concentrate expertise where it can be most efficient. Model users would not actually concern themselves with compiling and debugging the model on their own computer. (This process always consumes a great deal of initial time and money. The Juanita Creek experience (Tang, et al, 1977) with the supposedly well documented SWMM was a good example of this problem.)

Local users will use remote computer terminals to manage data, communicate with other computers, and interface with a large computer. System communication and programming problems will be handled by specialists elsewhere. Computer language differences between data sources, for example, and the main program will be handled by the system rather than by the users.

Seattle is one of the cities identified for local telephone communication with the HSP II network. Complete documentation of the capabilities of the system in general and the modified hydrologic model in particular are not available at this writing, but should be complete by the end of 1978.

In the meantime, there do not appear to be any obstacles to good user comprehension, the key link in the process being effective communication between the direct and indirect users.

Model Components (9)

The primary optional feature of SWM-IV and HSP is the snowmelt routine, discussed previously. In addition, the length of the simulated period may be varied to fit the applications, as may the time step used for simulation (e.g., from five minutes to one day). Channel routing may be "turned off", or used only for hydrographs exceeding some preset flow. Output is very flexible as well, as described earlier. Only the processes controlling rainfall-runoff response must be modeled, and even some of these can be eliminated by setting appropriate parameters (e.g., if the application is not concerned with groundwater loss to other basins).

Another feature of the new HSP II hydrologic model is the extensive use of optional routines. A modeler will have the option of channel routing by time delay/linear reservoir, kinematic, or dynamic methods, for example (R. Johanson, Hydrocomp, 1978; personal communication). This approach will allow even greater flexibility in tailoring the model to user needs and eliminating unwanted parts.

Data Use (10)

Although the desired time increments for precipitation and evapotranspiration data are hourly (or finer) and daily, respectively, all versions of SWM are capable of accepting several increments. For example, daily storage precipitation gage data for two stations, and hourly data for a third may be used.

Wherever possible, however, the shortest time step for which data are available should be used. This is especially important given the typical small size and rapid runoff response of urban watersheds.

Precipitation data since 1948 may be obtained in card format from the National Weather Records Archives. Some records may be available for the period from 1940 or earlier. In addition, hourly precipitation data may be available from recorder charts for years prior to 1940, when those data were first published (Hydrocomp, Inc., 1969).

A useful feature of HSP is a data management module that accepts diverse data records, examines them for missing data, and prints error messages. This capability could provide early warning of potential data problems. The analysis also develops correlations between daily and hourly precipitation and provides error messages if the ratio of storage to hourly precipitation is unusual for any time period. With these aids, deficiencies in the existing data base can be identified before simulation, avoiding the problem of having to identify the cause of inconsistent results during model operation.

The new HSP II network will have the ability to interface directly with other computer systems, notably those containing weather and streamflow data. Since data handling prior to simulation may comprise as much as one half of the total cost of simulation (Linsley, 1971), this is a significant feature. (Note that the other versions of SWM do not have the data management capabilities of HSP or HSP II, a significant advantage for the latter two models.)

Newly generated data may be incorporated easily by any version of SWM. This will be particularly easy with HSP II. Any updating of simulation using new data requires, however, that the data are coded as they are gathered. Unnecessary delays would result if the data were stored in raw form for an entire year and then coded all in one batch. In addition, deficiencies in the data, inoperative equipment, and other difficulties could go undetected if the data are not systematically reduced for use (Linsley, 1973).

As an example of the way in which the model can be used to direct new data gathering efforts, consider a situation where a significant systematic error exists in the representation of watershed precipitation when the nearest recording rain gage is several miles away. The error may be detected first by several methods, discussed at length by Aitken (1973), Wallis and Todini (1974), and Bates (1976). Errors could be detected by examining the monthly runoff and moisture storage outputs, but this would be a somewhat cumbersome procedure. Visual examination of a simultaneous plot of recorded and simulated flows may also show the error. Another method is to develop a plot showing the cumulative deviations of recorded and simulated flows from the mean recorded flow for a given time period (e.g., for each month). Such a plot is called a residual mass curve. A corresponding statistic, the residual mass curve coefficient, can be calculated as well. (See Aitken (1973) for details).

The existence of a systematic error as detected by one of the methods above could indicate the need for a precipitation record more representative of the watershed. Whereas a recording gage within the basin with long term records is always ideal, future modeling efforts could be considered in selecting the site for a new gage. The new station could be located accordingly, to provide data usable for the current and anticipated future modeling efforts.

To summarize, ability to make use of the existing, or any new data would pose no difficulty. The SWM could be used readily to direct future data collection efforts. A more likely scenario is that available data will be inadequate in quantity or quality for optimal use of the model.

New Data Collection (11)

The need for representative data has been stressed throughout this document. The importance of the data base to urban hydrology was recognized by the Urban Hydrology Research Council of the American Society of Civil Engineers (McPherson, et al, 1969), which assessed the data base in existence in 1969 from a national needs standpoint. Adequate precipitation and streamflow data were found to be virtually nonexistent although methods existed for their collection.

McPherson, et al (1969) and Linsley (1973) provide several suggestions for establishing data networks:

1. Precipitation data - Continuous recording of precipitation is needed for fixed time increments of five minutes for small areas to fifteen minutes for larger areas. (Note that increments of 30 to 60 seconds might be needed for modeling of very small relatively impervious catchments like those examined by Schaake, et al (1969). The longer time intervals noted above would be adequate for subwatershed modeling consistent with user needs and the capabilities of SWM-IV, HSP, etc.). Synchronization between records of precipitation and streamflow is facilitated by using a fixed time interval. Gages should record in intervals of 0.01 inch. A tipping bracket gage is suggested as being capable of this precision. Its limitations are that snow is not measured without heating the bucket (thereby measuring moisture content rather than snow, <u>per se</u>), and accuracy is reduced for rain intensities above 3 inches per hour. Its advantages are in high accuracy at low rainfall intensities and compatibility with remote transmission networks. Since snowfall is relatively unimportant in the urban lowland areas of King and Snohomish Counties and rainfall intensities above 3 inches per hour are rare (Miller, et al, 1973), it appears this type of gage is appropriate.

   Efficiency of data handling can be enhanced if data are telemetered to a central site. This improvemnt comes with increased equipment cost, but these costs may offset manpower costs for data reduction to a large degree. Advantages of a telemetered data network include the ability to translate raw data reduction to a large degree. Advantages of a telemetered data network include the ability to translate raw data directly to the format required by a simulation model, elimination of the need for manual transcription of data and a corresponding reduction in the potential for error, and ease of relating precipitation to runoff at a given time. Linsley (1973) states that a telemetered data network is justified only where a large number of stations is involved or real time information is needed for system operation (e.g., selective control of overflows).

   The rain gage network operated by METRO is telemeterd, principally because it was originally intended to provide data for real time computer control of the storm sewer overflow system. The network is used primarily as a monitoring device rather than an operational tool, however. Monitoring has allowed METRO to activate automatic water quality samplers when precipitation occurs (in addition to allowing overflow control). Data are transmitted continuously for ten minute time steps, and hourly results are tabulated and summarized for further use. Since real time data are not required for continuous simulation planning purposes, it is questionable whether a telemetered system could be justified for King and Snohomish Counties in general.

An alternative method is to have on-site equipment capable of providing computer compatible output. Since data reduction and analysis can represent as much as one-half the total cost of simulation (Linsley, 1971), some means of continually processing data should be considered. Linsley (1973) suggests that an automated system is justified if more than ten stations are involved. (For example, the City of Seattle system of about 20 gages uses on-site magnetic tape recorders. Tapes are translated to provide a computer card record and the cards are processed to provide the desired output for future use.)

The trade off in installation, operation, and maintenance costs between telemetered and on-site recording precipitation stations should be examined in more detail for any comprehensive data gathering program.

It is very important to have more than one rain gage per watershed to ensure that both spatial and temporal distribution are represented correctly. Eagleson (1967) shows that long term mean areal rainfall can be represented adequately by one or two gages per watershed. For good accuracy in representing shorter term phenomena, however, about three gages are needed for any area up to 25 square miles. Similar results reported by Johanson (1971) are cited by Linsley (1973). The locations of gages should be selected to provide good coverage by area (and elevation in larger watersheds) and to minimize interference from trees and buildings.

2. Evaporation data - Linsley (1973) states that records from a U.S. Weather Service Class A evaporation station within 50 to 100 miles of a watershed are acceptable as long as the general meteorological conditions are essentially similar. This being the case, the records for Maple Leaf Reservoir and Puyallup are sufficient. It would be necessary to develop a synthetic record for the period prior to 1941, based on other meteorological data that are readily available (see Linsley, et al, 1975; pp. 160-170). (This was done for the period 1928-1941 during the RIBCO studies, using HSP (METRO and City of Seattle Water Department, 1974), but the results may not be accessible any longer as discussed in Chapter 4.)

3. Streamflow data - Data for three to five years are needed for reliable calibration of a simulation model. Although a shorter sample may be used, the risk that some important hydrologic condition is not represented in the data is increased. An additional

> two to three years of data should be used for verification of the calibration. Thus, a minimum of five years of data is desirable.
>
> The number of stations for which data are needed varies. If stream systems are simple, land-use in all basins is basically the same, and the overall area to be modeled is relatively small only a few stations on the main stem of selected streams would be needed. A mix of rural, suburban, and urban stations would be useful in identifying parameter values for general land-use categories.
>
> On the other hand, if land-use is diverse, the overall area large, and stream systems complex, many more stations are needed, principally because the diversity of the area makes generalization of parameters and channel effects less reliable. Data for each watershed may be needed if sufficient diversity exists.
>
> Many types of streamgages are available; the one best suited to the location and intended application of the data (e.g., precision desired) should be selected. McPherson, et al, (1969), and Linsley (1973) discuss the pros and cons of many types. The following generalizations are pertinent. First, any gage should be calibrated for the site. Precision is more important at high rather than low flows in most applications (Linsley, 1973); this should be considered in both gage selection and calibration. Second, the site and the gage should be selected to minimize potential inaccuracies caused by surcharge from a downstream section (particularly culverts that might block debris), interference from debris, and alteration of flow caused by the gage itself. Third, the record must be continuous for use with SWM-IV, HSP, etc., with sampling intervals of about five minutes for small areas and fifteen minutes for larger areas (Linsley, 1973). Longer time intervals are very likely to miss many important runoff responses in urban watersheds. Finally, simple stage measurements are not adequate for either storm drains or natural channels because of many sources of error inherent in establishing stage-discharge measurements. Accurate flow measurement requires both depth and velocity measurement.

With these guidelines in mind more specific observations may be made. First, the experience of METRO and the authors indicates clearly that an improved rain gage network is required for extensive watershed modeling. A minimum of one centrally located recording gage and one or more daily gages should be installed in each watershed. Translated into number of stations this means that at least 52, and probably 78 or more, gages would be needed to instrument fully the 26 transitional watersheds in King County (see Chapter 2); there are also 30 completely rural watersheds, some of which will become transitional in the next few years). This includes the six inter-county watersheds. Twenty or more additional stations would be necessary to cover the Puget Sound and Snohomish River drainages in Everett and Snohomish County, including the Quilceda Creek basin. Such an extensive data gathering program clearly indicates that automated tape recording stations like those used by the City of Seattle would be in order, and perhaps that telemetry could be justified. If for example, 26 recording and 52 daily stations were operated by King County, manual transcription of 15-minute and daily data for one month would involve over 76,000 observations (counting periods with no precipitation). The computer is obviously better adapted to this situation than are manual data reduction methods. Linsley (1973) stresses the need for prompt data processing for several reasons:

1. Faulty operation and maintenance of equipment may go undetected for long periods;
2. Inadequacies in the data network may go undetected;
3. Data may actually be lost; and
4. Accumulation of a large backlog of data may result in indefinite postponement of data reduction (i.e., the data may never be processed).

The extensive network described above represents an almost ideal data situation. It is unlikely, however, that such a network would be feasible. The issue then is the extent to which the network can be scaled down without sacrificing drastically its representativeness. The type, number and location of existing and new stations must be considered.

Representative hourly data are most important. Because the record for any new station will be short, it will be used principally for calibration. Long term simulation will still necessarily rely on the longer, more distant records. The local data could be used to identify approximate scaling factors with which to correct the more distant data for systematic errors. Data specific to an individual watershed are always desirable, but data for nearby sites may be useful as well.

For example, perhaps two recording gages would be adequate to represent five of the six inter-county basins (a separate gage would be used for Evans/Big Bear Creek). A daily gage in each watershed would be beneficial as well. Some random error would still exist for each watershed, but systematic error that would have resulted if only a distant record were available should be reduced significantly. Since the bulk of the data described above for a month were from the recording stations, data handling would be reduced. System cost would also be reduced in proportion to the number of stations eliminated from the ideal network.

Another approach to station siting revolves around the idea of official planning priorities. A proposed standard method of systematically establishing planning priorities for King County was mentioned in Chapter 2 (T. Nesbitt, King County Planning, 1978; internal memorandum and personal communication). This system recognizes that a limited number of comprehensive plans (probably no more than two or three, even assuming an increase in personnel) could be prepared in any year. It also recognizes the fundamental fact that comprehensive planning is for the most part preventive planning rather than remedial action. Consequently, it is recognized that watersheds in which runoff related problems are now apparent, but for which land-use conditions are not expected to change, are not good candidates for comprehensive planning. The logical argument is that options available for remedial action are very limited and that watersheds of this type can be dealt with effectively through public works and safety programs. In addition, given the two plans per year limitation, analysis of the worst basins first could conceivably lead to analysis of all watersheds only after they had become critical.

The proposed system therefore concentrates on transitional watersheds. The complete list of King County watersheds would be screened from more than seventy (including many completely rural basins) down to about thirty based on easily identified criteria, e.g., percent of stream in the natural state, percent transitional area, etc. The thirty basins would be screened a second time using more subjective criteria (e.g., frequency of citizen complaints, favorable conditions for combined drainage/park land-use planning, political sensitivity, etc.). About ten watersheds would reach this second list, and two of these would be selected each year for comprehensive planning.

The data gathering network could be coordinated with this process at the second screening level by adding a criterion evaluating the representativeness of the watershed of other nearby basins. All basins which passed the second screening could be instrumented completely. Since a delay of several years could occur from the time a basin first reached the short list to the time it was selected for comprehensive planning, a reasonable data base could be developed for simulation during planning. In this way, data specific to planning needs could be gathered in anticipation of those needs and data network costs could be reduced.

Watershed specific streamflow data are also important. At an installation cost of approximately $10,000 per gage for stations like those installed by

U.S.G.S. on Juanita Creek (continuous recording depth-velocity-discharge stations; G. Farris, METRO, 1978; personal communication), the costs mount quickly. Such stations are needed at least on the mainstem of streams. Small tributary streams may, depending on their physical size, drainage area, and expected flows, be gaged using a manufactured control section (e.g., a flume). The latter approach was used on a tributary to Juanita Creek, at an installation cost of about $2,500 (G. Farris, METRO, 1978; personal communication). Both gages can provide continuous records at a cost of about $2,500 to $3,000 per year per gage. Cost components include periodic inspection and maintenance, replacement of gage charts, and transcription of data to coded form.

As discussed earlier regarding precipitation stations, an ideal network of streamgages is probably not feasible. The opportunity for transferring data from one watershed to another is much lower in the latter case, however, because of the watershed land-use, soil, and topography variation that is present. Nonetheless, the basin priority system may aid in identifying priorities for stream gages as well.

Consideration should be given to establishing at least a main stream, mouth-of-the-watershed gage for the basins surviving an initial screening process. Additional gages should be established on major tributaries and at other main stream locations as needed to identify satisfactorily the runoff characteristics of the watersheds surviving a second screening. Finally, it may be beneficial to locate new gages at the sites occupied formerly by discontinued U.S.G.S. gages so that maximum use could be made of the prior record. Land-use conditions at the time the station was discontinued should be documented, if possible, and any changes that occurred in the ensuing period identified. Subsequent land-use modifications during the period of record should always be noted. After comprehensive planning was completed for a watershed it would be desirable to maintain at least the main stream station(s) until ten to fifteen years data were collected for three reasons:

1. To check the original modeling against a longer record as a hedge against problems inherent in short record calibration;

2. To provide a basis for assessing the effectiveness of implemented control measures and for future updating of the comprehensive plan; and

3. To provide information useful in identifying the hydrologic effects of the specific land-use changes that took place during the period of record.

In sum, methods are available for obtaining the data needed by SWM-IV, HSP, etc. The cost of doing so will vary with the degree to which the ideal data network is approximated. The process of identifying watershed planning priorities has the potential to offer considerable assistance to the identification of station sites. The delay likely to be encountered between initial identification of a watershed for planning and planning itself provides some leeway in establishing data stations and developing the data needed for simulation.

Whether the costs of a nonideal, scaled down data system are reasonable depends on one's perception; this topic is not addressed in detail here. A simple example will put the issue in perspective, however. Suppose a comprehensive plan is developedusing a continuous simulation model, but incomplete precipitation and streamflow records are available. The selected management option involves $2 million in public funds for channel stabilization, acquisition of pond sites, etc. (Although this figure may seem high, it is typical of the costs involved. Estimates for pond site and wetland acquisition, easements, and channel stabilization for Juanita Creek total $1.6 million (T. Nesbitt, King County Planning, 1978; personal communication). RIBCO preliminary plans for North Creek, which has a drainage area about 3.5 times that of Juanita Creek had costs ranging from $2.9 million for a "nonstructural" alternative (excluding land costs) to $9.1 million for an all structural solution (both figures in 1973 dollars). See U.S. Army Corps of Engineers, 1974B). If one recording and one daily precipitation gage, and two additional streamgages were added and operated for three years before planning, the extra cost would be about $50,000. This represents just three percent of the public costs cited above, yet the accuracy of simulation could easily be improved to an extent that would result in savings of more than three percent (i.e., $50,000) in over or under design. The costs associated with over design are obvious, e.g., excess land acquired or structural components installed. The cost of under design is represented by flood damage not eliminated, erosion not prevented, etc. Whereas the savings provided by adequate data might not be sufficient to offset costs for a single watershed, the benefits of the added data, particularly precipitation data, are potentially enormous when veiwed from a regional perspective.

Expressed another way, Linsley (1973) states that storm drainage costs add about $1,050 per acre to the cost of urban land (1969 dollars; that figure needs to be doubled for current prices). Adding another $100 (1978 dollars) for a good data network would add less than 5 percent to the drainage cost per acre. As an example, nearly $45,000 dollars would be available via this mechanism for Juanita Creek, and the improved simulations and resulting decision making could easily recoup that amount.

It is probably, therefore, that a vastly improved precipitation and streamgage network, particularly in conjunction with the improved simulation accuracy and flexibility of SWM-IV or HSP, could easily pay its own way on a regional basis through improved accuracy of modeling, design, and decision making.

SUMMARY

In this chapter many hydrologic models with continuous simulation capability have been screened and the characteristics of the family of models derived from the Stanford Watershed Model discussed in the context of the evaluative criteria developed in Chapter 4. Each of the eleven evaluations is summarized below:

1. Areal Representation - Detail of representation is limited only by data availability, not by model structure. All versions of the SWM provide several outputs that can be used to test the reliability of the representation.

2. Land-Use Representation - Land-use is not an explicity input. If the premise is accepted that no model can portray very small scale land-use effects on runoff with reliability (see Chapters 3 and 4), however, aggregated land-use changes can be modeled at the subwatershed level by SWM. Development of typical parameter values from nearby, small areas of uniform land-use can provide some guidance, but is not a substitute for local data.

3. Flow Representation - There is no limit to the number of channel flow points that may be simulated. Reliability of simulation depends on data for model calibration. HSP allows representation of nonlinear routing, and HSP II provides even greater flexibility (linear routing, simple continuity, or full continuity and momentum representations may be used). See number 6, below.

4. Output Displays - Many standard and optional displays of flows and storage components for land segments and channel flow points are available for any potential applications. HSP and HSP II can provide relatively more information because more flow points can be modeled in greater detail. The flexibility of HSP II is apparently very good in this regard.

5. Physical Process Accounting - Continuous accounting of the important physical processes is the central concept of SWM. Snowmelt may be

modeled, but probably is not necessary for this locale, the possible exception being the upper reaches of Issaquah Creek.

6. Channel System Representation - The land segment and flow point representations of SWM are compatible with reality for subwatershed scale simulation. SWM-IV uses a channel time delay/linear reservoir function, whereas, HSP employes hydraulic routing equations to represent nonlinearities. It is believed that HSP II offers both options in addition to full equations of continuity and momentum (compelte documentation is not available). Solution instability as experienced in the use of SWMM and SNODOB will not be a problem in the applications anticipated for continuous simulation models. SWM-IV does not model backwater effects, surcharged flow, or pond storage; HSP cannot model surcharged flow, and backwater is only approximated. HSP II is capable of representing all pertinent hydraulic features.

7. Calibration - Calibration is greatly facilitated by knowledge of the model and the watershed. Although calibration of SWM-IV or HSP is not simple, it is facilitated by the output obtained from the models, examination of parameter subsets affecting specific aspects of the simulation, and knowledge of model sensitivity to given parameters and of the watershed itself. Attempts to date to develop reliable relationships between measurable watershed characteristics and model parameter values have been only partially successful. Calibration using programmed optimization criteria is of limited usefulness as well.

8. User Comprehension - SWM-IV is well documented; the HSP models are less well documented, but user workshops are held periodically by Hydrocomp, Incorporated. The important phase in user comprehension relies on effective communication between direct model users (e.g., planners and engineers) and indirect users (policy makers). The flexible model output should aid this situation. The Simulation Network being developed by Hydrocomp should also enhance user understanding by removing many of the technical functions from the list of responsibilities of the local user, allowing more attention to be directed toward problem solving.

9. Model Components - The primary optional component is the snowmelt routine (see number 5, above). Considerable flexibility is allowed in other parts of the models as well. Time steps can be changed, for example, or channel routing used only for major floods. The extensive use of subroutines in HSP II allows even greater flexibility in selecting the modeled processes and the detail level to be used.

10. Data Use - Flexibility is provided in accepting data of somewhat different resolutions (e.g., daily and hourly precipitation). HSP includes a data management package that converts all data to compatible formats, analyzes them for correlations, and flags missing data or unusual values for correction before simulation. The new HSP II network will have the ability to interact directly with data storage systems and other computer facilities in addition to an advanced data management package. Outputs from all

versions of SWM can be used to identify data errors (e.g., systematic error) and deficiencies (e.g., another rain gage is needed in a certain location).

11. Data Collection - The need for continuous precipitation and flow data, preferably for each watershed and subarea has been stressed continually in this work. Precipitation and data deficiencies may be reduced somewhat by proper selection of station type and location. Coordination of the station selection and basin priority processes offers significant potential to limit data network cost without affecting drastically the utility of the data. It is probable that the increased modeling precision, improved decision making and reduced over and under design allowed by better data would more than offset the cost of the data collection network.

It is concluded that there are no significant deficiencies in the Stanford Watershed Model or its derivatives relative to the evaluative criteria developed here. The single largest potential limitation to the application of such models is the lack of adequate data. In particular, of the models listed here, the Hydrocomp Simulation Package II (HSP II) offers the greatest flexibility, modeling detail (if desired), and data management capability.

CHAPTER 6

CONCLUSIONS, SUMMARY FINDINGS, AND RECOMMENDATIONS

CONCLUSIONS

The preceding chapters have shown that the family of continuous simulation hydrologic models derived from the Stanford Watershed Model - Version IV (SWM-IV) is more capable of meeting the desires and needs of the potential model users identified in Chapter 2 than are the analytical methods presently in use. There are limitations, however:

1. Aggregate (e.g., subwatershed) land-use representation must be acceptable for comprehensive drainage planning;
2. Less than perfect reproduction of an historical flow record must be acceptable if the physical meaning of model components and model predictive reliability are to be maintained;
3. Reliability of results of subarea simulation, specific land-use representation, and predictive application are dependent on the existence of data adequate to define the values of model parameters; and
4. Success in implementation is dependent on availability of data and funds for planning, and on the abilities and skills of direct model users (planners and engineers) to communicate their convictions of the need and justification for continuous simulation modeling to the municipal officials charged ultimately with the implementation decision.

It is further concluded that the Hydrocomp Simulation Package II (HSP II) offers the greatest flexibility, precision in modeling component processes if desired, and data handling capacity of the many versions of SWM-IV examined in this work.

The remainder of this chapter provides supporting summary findings, and makes recommendations for further study and implementation.

SUMMARY FINDINGS

1. Analytical methods currently used for runoff estimation, notably the Rational Method, are inadequate in the context of community goals for preservation of natural stream systems and mitigation of downstream impacts. Designs based on the flows estimated by these methods may lead to excessive drainage control costs caused by overestimation of flows, and are incompatible with comprehensive planning. "Design storms" are selected based on judgment rather

than on evaluation of economic or environmental benefits and costs associated with different flows.

2. Computer simulation models used in the past in King and Snohomish Counties, the EPA Storm Water Management Model (SWMM) and WASH-USE-1/SNODOB, have been partially satisfactory for comprehensive planning. Internal model characteristics contribute to this situation, but of more fundamental importance are the general limitations associated with event models.

3. Event models in general cannot be used reliably in a predictive mode because of the importance of representing antecedent conditions properly, the absence of a true design storm in the data record against which to calibrate the model and the absence of a linear relationship between rainfall probability and runoff probability. Furthermore, the calibration process used with event models provides a false sense of the predictive ability of a model because close replication of two or three historical events does not necessarily mean that: (a) any other recorded events will be well represented; (b) any nonrecorded events will be represented for existing watershed conditions; or (c) that any events will be represented for any alternative watershed conditions. Event models therefore provide no reliable information on runoff flow probability.

4. All hydrologic models require spatial and temporal aggregation because of imprecise knowledge of the physical processes involved and incomplete data to provide the necessary definition of relationships for small areas and time steps. Availability of data for model calibration dictates the lower limit of areal application that is appropriate in any situation. No single model is appropriate for use in both development planning (areas as small as two acres) and watershed planning (up to 60 square miles). There is therefore a need to develop a model appropriate for development planning that will yield results compatible with comprehensive planning.

5. The Soil Conservation Service Curve Number (CN) rainfall-runoff model provides reasonable representation of time delay caused by precipitation abstractions and appears suitable for modeling pre- and post-development pervious area runoff. Impervious area can only be modeled by increasing the selected CN to decrease abstraction and runoff response time, whereby the pervious area representation is altered. Rather than make such a change, it may be preferable to represent impervious area using the British Road Research Laboratory (RRL) model (Terstriep and Stall, 1969). Another approach to drainage system design

using continuous simulation results is suggested by Crawford and Linsley (1966); details of the method are not clearly documented, however. It is possible, in addition, that the continuous simulation approach cannot consider adequately the wide variation in soil runoff characteristics experienced locally.

6. Application of a model to conditions outside the range of data available for calibration requires that care be exercised during calibration to maintain the physical meaning of, and relationships between, model parameters. It is also important to represent in an appropriate way all important physical processes so that antecedent conditions and nonlinear rainfall-runoff relationships are adequately simulated. SWM-IV and its variations provide many outputs that enable a modeler to monitor the parameters, moisture storages, and runoff components for reasonableness. Calibration is also facilitated by knowledge of both watershed and model.

7. Reliable relationships between values of model parameters and measurable characteristics have not yet been developed. Results obtained in other locales are useful only as guidelines, and values derived by obtaining data for small areas typical of a specific land-use (e.g., single family residential) may not be valid in another nearby location, given the diversity of rainfall-runoff response that exists.

8. Any level of detail in flow routing can be attained with any hydrologic model that provides a complete hydrograph. Detail of simulation must be treaded against computation cost, however. For most applications, particularly in watershed planning, less precise routing approaches are appropriate and are consistent with the precision available in land segment modeling. Precision obtained by using the full one dimensional hydraulic equations for unsteady, nonuniform flow cannot compensate for uncertainty in representing the land phase of the hydrologic cycle. General watershed response to different subarea land-use configurations and control measures can be analyzed with the less precise methods (e.g., the time delay/linear reservoir function used by SWM-IV); subsections of the conveyance system can then be analyzed in greater detail for design purposes once a general runoff management strategy and land-use configuration for the watershed are selected. Conveyance system features within modeled areas would be modeled similarly. HSP II offers the full range of routing options.

9. Adequate data are critical to the validity of model application, particularly where prediction is required. Precipitation data truly

representative of the watershed are most important. A data base adequate for all intended comprehensive planning model applications in King and Snohomish Counties does not now exist. Instrumentation of all watersheds for which planning is contemplated would be desirable, but is not feasible. By considering similarities between watersheds, patterns of storm direction, and topography in the process of establishing planning priorities, a data network that is both feasible and representative may be defined, while providing data needed for immediate planning as well. It is argued intuitively that on a county-wide scale even the ideal, extensive data network would more than pay for itself by reducing over and under design, allowing better risk analysis, and providing better information for decision making. The cost of handling data and updating records may account for as much as 50 percent of the total cost of model application. HSP and particularly HSP II have extensive capabilities for efficient data management.

10. Direct model users identified in this work are municipal planners and engineers. Indirect users will be the municipal decision makers. Communication between these two user groups as to the capabilities and limitations of continuous simulation models will be critical to eventual success of a modeling program. There is no significant lack of expertise on the part of the direct users, relative to an ability to interpret model output, but personnel with hydrologic modeling experience will probably be needed to provide technical assistance. The major factor preventing acquisition of experienced staff or hiring of consultants for an extensive watershed modeling and comprehensive planning program is the lack of funds designated specifically for drainage work. Options are being investigated for funding of planning at this time but have not been decided upon. When a stable source of planning monies is developed, there will be just one further institutional or financial limitation on development of a comprehensive planning program using a continuous simulation model: the need for close interjurisdictional coordination, including agreements specifying planning, funding, construction, and other responsibilities in a given watershed.

11. Continuous simulation models like SWM-IV and HSP are useful for many applications other than urban drainage modeling, e.g., flood frequency analysis for large watersheds like the Snohomish River Basin. Consequently, a decision to implement a continuous simulation hydrologic model for urban drainage planning and design in the two Counties could have added benefits by familiarizing people

with the model and its application to other problems. The data network developed for urban drainage modeling would also be useful in other applications provided some stations were operated for a sufficiently long time.

RECOMMENDATIONS

Recommendations resulting from this work are presented in two sections: those relating to further research that is needed; and those relating to implementation of a continuous simulation modeling program using HSP II.

Further Research

The following areas for further research are suggested by the findings and conclusions of this work:

1. A rainfall-runoff model suitable for development planning for small areas, yet compatible with comprehensive planning concepts, should be developed, documented, and applied. It is suggested that a combination of SCS Curve Number and RRL methods may be appropriate, with the former simulating pervious area and the latter impervious area runoff. Another approach of possible merit is that suggested by Crawford and Linsley (1966) using continuous simulation results. Other possible models should be investigated as well. Compatibility with the assumptions of and recommendations from comprehensive watershed plans should be stressed in such an evaluation.

2. Locally specific investigation is needed on the sensitivity of simulated flows to the parameters and variables in HSP II. The sensitivity of models to precipitation inputs has been cited earlier. Considerable information useful for initial data gathering and parameter value setting, and for subsequent calibration could be obtained through sensitivity studies (see, for example, James, 1970). For example, the sensitivity of the model to parameters describing the interflow component of runoff could direct the amount of effort that would be useful in gathering data to define those parameters as compared to parameters describing some other process like baseflow or surface runoff. (It should be noted that field observation indicates that interflow may be the dominant runoff component for undeveloped land in this geographical area, and may also be important for most developed conditions. This situation results from the predominance of relatively permeable surface soils underlain at depths of just one to three feet by hardpan clays or bedrock. Sensitivity analysis using local data could benefit any future model application by helping substantiate the relative importance of the parameters defining interflow. This issue is being

investigated at this writing at the University of Washington (D. Garen, Department of Civil Engineering, 1978; unfinished M.S. Thesis). Results of this work may be available in timely fashion for implementation of HSP II.

3. Investigation is needed to establish better relationships between model parameters and measurable watershed characteristics. Sensitivity analysis, as suggested above, can assist this evaluation by providing information useful in screening parameters for which great precision is not critical to model success. Ross (1979), James (1972), Shanholtz, et al, (1972), and Magette, et al, (1976) have documented such investigations in other geographical areas. It was observed in Chapter 5 that such results are probably useful only as guidelines. Consequently, development of relationships based on local data would be of significant benefit to a comprehensive watershed modeling program.

4. Investigation is needed to determine the feasibility of the "Runoff File" approach to continuous simulation in the urban setting, as reported by Lumb and James (1976). Appendix A discusses the basic principles of this modeling technique, which is based on identification of typical flood hydrographs from a continuous simulation record for the important land-uses in an area. In the application cited above, just four land-use/hydrologic types were determined to be adequate. Typical hydrographs corresponding to several return period flows were selected for unit areas and stored in files. Analysis of land-use and management strategy alternatives is accomplished by using the appropriate combination of unit-area runoff files to represent land-use in conjunction with a routing program. This approach has considerable intuitive appeal, since it could eliminate the need for costly and time consuming calibration of the model for every watershed. It is possible, however, that the extreme variability in soil types, runoff response, and topography encountered in the King and Snohomish County urban areas could make a Runoff File approach infeasible because of the large number of files (and corresponding calculations) that would be needed, and the lack of adequate data to support the simulation for many files. The possible advantages of this approach nevertheless suggest that a thorough investigation should be made. It is further recommended, therefore, that personnel from Hydrocomp, Incorporated in Palo Alto, California, be engaged to evaluate the feasibility of Runoff Files for this geographic area.

Implementation

The following steps should be taken by METRO, the City of Everett, and

King and Snohomish Counties to implement the recommendation of this work that the HSP II modeling system be applied for future urban drainage planning and design in King and Snohomish Counties:

1. Contact Hydrocomp, Incorporated in Palo Alto, California, to obtain detailed information about the simulation network being established at this time (Crawford, 1978).

2. Obtain complete documentation of the FORTRAN version of HSP being developed for the Environmental Protection Agency and scheduled for release sometime after November 1, 1978. Possible advantages of using this version locally, rather than the Hydrocomp Simulation Network, should be evaluated. (Note that the latter system offers significant data handling advantages and reduced requirements for local modeling expertise; these factors will offset any direct cost savings that might be perceived for local model maintenance and operation).

3. Reassess the retrievability of the precipitation and streamgage data that were coded and stored during RIBCO planning in the context of anticipated watershed modeling in both Counties. (A corresponding data base was not developed for the Snohomish River Basin planning, since a continuous simulation model was not used). The cost of correcting the problems encountered by the City of Seattle and METRO in attempting to access the data should be evaluated against the cost of recreating the data files. The data management capabilities of HSP II may allow efficient, inexpensive regeneration of the RIBCO data, particularly since more recent data need to be incorporated as well, in which case the RIBCO data would not have to be saved any longer.

4. Institute immediately a comprehensive data gathering program designed for compatibility with continuous simulation. Selection of precipitation and streamgage stations should be coordinated with any process establishing planning priorities (e.g., the proposed King County system described in Chapter 5). Stations should be selected based on: (a) the probability of near term comprehensive modeling for the watershed; (b) the representativeness of proposed stations of other watersheds (or subareas) of lower planning priority; and (c) The representativeness of the proposed stations of watershed land-use, soils, etc., not depicted in the existing data record.

A minimum of one recording (fixed time interval) rain gage per watershed is needed; two or more are desirable. One recording and two daily gages would be adequate as well. Such a rain gage network should be established at least for those watersheds selected for planning over the next 5 years (e.g., about 10 basins in King County); additional stations should be established as needed to complete the representation of precipitation distribution.

Streamgage stations should be selected based on similar criteria. At least one main stream station should be established for the same watersheds identified for near term planning above. Additional main stream and tributary stations should be established as necessary to represent the major subareas or significant hydrologic differences in each watershed. All gages should be calibrated carefully to ensure the best possible streamflow record.

5. Develop and implement specific interjurisdiction agreements for the watersheds identified for near future planning, establishing the funding responsibilities, personnel requirements, and planning responsibilities of each municipality involved. A timetable for participation and assurances of compliance with comprehensive plan provisions should also be included.

6. Establish a general fund, under a separate intergovernment agreement, form which monies for maintenance and operation of the two-County data network may be drawn. This would prevent any single jurisdiction from having to assume too large a share of the data development responsibility. Since all jurisdictions would benefit from a better data base even for watersheds wholly within a given municipality, cost sharing is completely equitable.

7. Develop a source of revenue that will be reliable and adequate for development of comprehensive drainage plans, possibly using a property value - property use approach (URS Company, 1977c). Utility assessments might also be used to generate revenue for future plans.

8. Assess existing staff numbers and expertise in the context of an extensive watershed modeling and data gathering program. Because data are so important for such a program, personnel assigned data management tasks such as inspecting gages for proper operation, changing recording charts and tapes, and preparing data for computer use must be properly trained. It is not crucial for a single person to have all data responsibilities, but a standard data handling procedure should be established to provide continuity between stations and time periods. Data should be coded into computer compatible form immediately after they are obtained so data gaps, inoperative gages, and other important problems in data gathering can be identified and corrected. Technical staff requirements are for persons in both planning and public works who are familiar with hydrologic models and who have an understanding of comprehensive

watershed modeling. As above, it should not be critical for an individual to be charged with comprehensive planning responsibilities throughout a County-wide program. It is more important for there to be a standard planning approach. Any new person beginning work with the model should first become thoroughly familiar with it. Periodic refresher courses would be in order. Finally, start up costs of such a system might be reduced somewhat by hiring a hydrologic modeling expert to assist in defining needed data and required management procedures. Periodic reassessment of all staff needs should be done as well.

9. Update completed comprehensive plans (e.g., Juanita Creek and May Creek), using HSP II when it is implemented.

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APPENDIX A

DISCUSSION OF INTERVIEWS WITH KING COUNTY, SNOHOMISH COUNTY, METRO, AND CITY OF EVERETT PLANNING AND ENGINEERING PERSONNEL RESPONSIBLE FOR DRAINAGE PLANNING AND DESIGN

The following represents a more complete discussion of the interviews conducted with municipal officials than was presented in Chapter 2. The questionnaire used as the basis for the interviews is reproduced as Table A.1. [Comment] denotes analysis, comments, or clarifications. References are those listed in the bibliography.

Runoff Prediction Methods (Questions 1, 4)

The Rational Method continues to be used for virtually all drainage planning by developers, despite its well known limitations. It is not considered adequate by the interviewees because it does not provide an entire hydrograph, leads to overdesign based on high estimates of peak runoff rate, and is not compatible with policy to maintain natural stream systems.

It is recognized that the SCS Curve Number method would be more appropriate for all but the smallest parcels; nonetheless, its use has not been required by drainage plan reviewers. Lack of familiarity with the SCS method (or any other alternatives) on the part of developers, their engineers, and municipal public works officials was cited as the reason. In King County the problem has been compounded by effectively making the Rational Method "official" in the Hydraulics Division Procedures Manual which is distributed to developers (King County Hydraulics Division, 1977).

In Snohomish County the WASH-USE-1/SNODOB computer model has been available but has not been applied for drainage plan review. A suggestion of the SNOMET 208 Urban Task Force, that a fee system could be established whereby developers could have the computer model calculate runoff, has not been implemented.

Developing Areas (Question 2)

Most developments (e.g., 80 percent in King County) with which the municipalities must deal are 40 acres in area or smaller. Larger developments of up to 300 acres were mentioned as well; virtually all developments are smaller than this, however.

Predevelopment land-use usually is either the second growth forest typical

TABLE A.1

RUNOFF MANAGEMENT QUESTIONNAIRE

1. What rainfall-runoff prediction method is currently endorsed and/or used by your personnel for drainage planning?

   ______ Rational Method ______SCS Curve Number Method ______Other (Specify)

   Do you consider the method to be adequate? ______ If not, why? Why is the method being used now?

2. What is the average size of development proposals (acres) with which you deal? What is the usual pre-development land use?

3. Have you identified drainage basins which need overall drainage planning (comprehensive planning)? How many? What sizes? (Names and locations, if possible.) Are any of these basins shared with other municipalities? If so, which ones?

4. Do you currently have methods for satisfactorily determining both magnitude and timing of flows from development, sub-watersheds, and entire drainage basins? If so, what methods? What consititutes "satisfactory" for your purposes?

5. Are you familiar with any computer models which could be used for drainage planning? Which model(s)?

   Have you used any models for this purpose? Which one(s)? What level of areal resolution do you perceive necessary to use such models? (Watershed only, sub-watershed, 40 acres, 10 acres, etc.)

6. Based upon your experience with or understanding of computer models, what would you like a model to do and how accurately?

   Determine overland flow rates and volumes?
   Determine channel flow rates and volumes?
   Assist in pipe or channel design?
   Optimize pipe/channel/retention area design?
   Other?

7. Would it be valuable to your planning efforts to know the probability of occurrence of a given flow in a stream? If so, what typical probability levels (recurrence intervals) are of interest?

8. Which of the following represent the major issues that a comprehensive plan must address? (Identify others, if necessary)

   (a) Identify areas which, now or in the future, will be subject to:

      (i) flooding.
      (ii) erosion of streambanks and channels
      (iii) sedimentation of stream channels and ponds
      (iv) erosion of land surfaces

   (b) Identify the runoff changes and impacts which would result from a given land use change in a specific area (i.e., proposed development in a specified location)?

   (c) Evaluate optimal land use patterns?

   (d) Evaluate optimal drainage control measures and locations?

   Do you feel that a computer model could be useful in these efforts? What other kinds of models are useful; e.g., judgment and experience?

9. (a) Who would be the user(s) of a model if applied to drainage work by your municipality? What is their expertise?

   (b) If no one currently on your staff would be available to use or has expertise for the use of a model, would you hire someone specifically for this purpose? Would the need to hire an additional person prevent you from using a model altogether?

   (c) Do you see any advantages in having County or regional agency (e.g., METRO) personnel actually operate the computer, subject to the inputs and outputs from your personnel? Would you be more likely to use a model under such circumstances?

10. What issues have we missed that you think are important? Please elaborate during the interview.

of the area (mixed alder, maple, and fir with extensive understory growth) or grassy meadows or pastureland. It was observed that it is probable that surface runoff rarely, if ever, occurs, particularly in the former case. The urbanization of the land, therefore, constitutes a drastic alteration of the hydrologic response of a parcel (see Savini and Kammerer, 1961; Leopold, 1968, for descriptions of the hydrologic effects of urbanization).

In addition, it was observed that many sites which are now being developed are marginally suited for development. Reasons given include excessive slope, instability, erosion hazard, and very poor drainage.

> [Comment] It is interesting to note that these are precisely the conditions which should be identified during comprehensive planning so that development in such areas can be prohibited or modified to the extent necessary to mitigate the problems (URS Company, 1977).

If development does occur in these areas, both King County Ordinance 2812 and the SNOMET Model Ordinance would impose more stringent runoff controls than for more suitable sites.

Identifying Basins for Comprehensive Planning (Question 3)

King County has identified 41 drainage basins which are in various stages of urbanization. Of these, 26 include at least 10 percent land that is in a transitional state, where "transitional" is defined as : 10 to 30 percent of land built up; low overall density but rapid growth. The remaining 15 basins are completely urban or suburban (King County Division of Planning, 1977). No timetable for the ultimate development of any of the basins has been established. The County Planning Division desires to focus its comprehensive planning effort on the 26 transitional basins. Juanita Creek, May Creek, and the White Center area are all in this category. Since funds and manpower are not available for all comprehensive plans simultaneously, priorities must be established. METRO is helping to identify priorities based upon present and probable future water quality and public health conditions. King County is also considering rate of development, status of land-use planning, severity of existing problems, and other factors. Preliminary priorities based on these criteria were suggested during the 208 planning but have not been adopted officially (D. Tracy, King County Planning, memorandum to I. Berteig, 1976; D. Tracy, personal communication, 1978). A standard method for establishing planning priorities is being developed at this writing (August 1978) but has not been adopted officially (T. Nesbitt, King County Planning, internal memorandum, 1978; personal communication, 1978).

The two top priorities were Swamp Creek and North Creek, both of which straddle the county lines (see Figure 2.3). The next priority was May Creek, between Bellevue and Renton, because of the opportunity for concurrent development of the drainage plan and the Newcastle Community Plan. The remaining intercounty basins (Lyon Creek, McAleer Creek, Bear Creek, and Evans/Big Bear Creek) were also nominated for high priority. These six intercounty basins involve land within as many as six separate municipalities (e.g., Swamp Creek: Everett, Lynnwood, Mountlake Terrace, Brier, Snohomish County, King County). Comprehensive planning for the shared basins is considered to be very important by all jurisdictions involved as exemplified by a Memorandum of Understanding for Coordinated Surface Water Planning, drafted April 12, 1978 and signed by seven out of nine municipalities at this writing. This memorandum states a general philosophy and approach to such planning and may serve as a basis for more specific agreements for individual watersheds in the future.

Snohomish County has not performed a detailed analysis of basin needs comparable to that of King County. The six shared basins are recognized as being in need of planning. However, the growth rate in other areas of Snohomish County has not been rapid enough to accentuate drainage problems; indeed, the major drainage problem is caused by periodic flooding in the Snohomish River Valley. After the shared basins, Quilceda Creek will probably be the next priority, since it includes the City of Marysville and is already experiencing some growth.

Everett encompasses a number of small watersheds that drain to Puget Sound including Pigeon Creek No. 1. Everett also has land in the shared basins as well as area that drains to the Snohomish River (Wood Creek, for example). The Puget Sound drainages will probably be developed for each basin in order, progressing south from Pigeon Creek No. 1.

The watersheds identified in both counties range in size from about 500 acres (0.78 square mile; Pigeon Creek No. 2, south Everett) to 57.7 square miles (Issaquah Creek, King County). The largest intercounty basin is Evans/Big Bear Creek (47.2 square miles). [References are: C. Olivers, City of Everett, personal communication, 1978; King County Division of Planning, 1977; CH2M-Hill, 1974; respectively.]

Computer Models (Questions 5, 6)

The models which have been applied for urban drainage planning were mentioned previously. Personnel at METRO mentioned that the RIBCO study considered using the Hydrocomp Simulation Program (HSP; Hydrocomp Inc., 1969, 1972); it was used as an overall water quality rather than urban drainage planning tool (METRO and City of Seattle Water Department, 1974; CH2M-Hill, 1974). HSP was operated for approximately two years after which time its use was discontinued. Reasons given were that the cost of maintaining the data base and the higher than average expertise required for its operation (and higher salaries as a result) were judged too high to justify its continued use (J. Buffo, METRO; personal communication, 1978). Apparently at no point was the use of HSP as an urban drainage planning tool considered after the RIBCO work was complete.

It would be desirable to have a computer model which could be used for developments as small as 2 acres or less, according to the interviews. A gap is perceived, however, between small site models like the Rational Method and watershed/subwatershed models. Application of SWMM and WASH-USE-1/SNODOB to the latter category has revealed several problems:

SWMM

1. Modeling of land-use change is cumbersome because of the need to designate subwatershed areas of uniform land-use, which is in turn caused by the way in which impervious area in a subwatershed is modeled. The model makes no allowance for the location or distribution of impervious area but assumes that all such area is located at the subarea outlet point.

2. Natural channel system modeling is difficult using either of the available routing packages (RUNOFF, which uses Manning's Equation and considers only continuity; or EXTRAN, which uses the Saint Venant shallow water equations for gradually varied, unsteady flow and considers both continuity and momentum). RUNOFF is not able to portray adequately the effects of natural channels on hydrograph timing, shape, and peak. It is also unable to simulate such important conditions as backwater effects, surcharged pipe flow, or natural pond storage (Huber, et al, 1975, 1976). EXTRAN is able to model these conditions, but solution instability results unless very short time steps or artificially long channel segments are used. The latter requirement results in loss of desired analytical detail for short channel segments such as road crossings. The need for very short time steps (ten seconds for Juanita Creek) results in excessive computer time and cost.

3. Rainfall-runoff nonlinearities are not well represented. The infiltration function is the principal nonlinear function in the model. The results of the model were found, however, to be insensitive to function changes for the calibration event (Tang, et al, 1977).

SNODOB

1. The routing program is similar to the SWMM-RUNOFF routine, considering continuity only, and has the same shortcomings. In addition, Everett's applications indicated solution instability at time steps of one hour. The use of shorter time steps to eliminate this problem increases computer cost, but is compatible with urban runoff modeling because of rapid rainfall-runoff response.

2. Nonlinear rainfall-runoff relationships are not well represented. The SCS method in SNODOB uses one of three preselected antecedent conditions and area land-use to determine the Curve Number, which in turn fixes initial abstraction. Linear unit hydrograph theory is combined with the nonlinear SCS runoff equation to generate the storm hydrograph at any point. (See Chapter 3 for additional discussion of nonlinearities). The SCS rainfall excess function cannot be varied except by changing the selected Curve Number.

Model calibration in both cases required considerable modification of parameters from initial values obtained from the literature or through physical measurement. In SWMM, percent imperviousness was altered from a measured value, and the storage factor for impervious area was modified from the literature value. This was in part necessitated by use of a small storm for calibration, during which the infiltration rate for pervious area was always greater than rainfall rate and was therefore ineffective for calibration, and for which the impervious area flow resistance factor was found to be ineffective in modifying the simulated runoff.

In SNODOB, the basic Curve Numbers for each land-use/soil group combination were modified substantially from values presented by SCS (1972, 1975) primarily to account for rapid observed response from impervious area, despite the fact that doing so, drastically altered the pervious area representation.

> [Comment]: This artificial calibration suggests that the basic assumptions of the models regarding the physical processes may not be appropriate in this geographical area, and that the final calibration of both models was not representative of conditions other than those upon which the calibration was based. See Chapter 3 for an extended discussion of calibration.

In summary, the major drawbacks of SWMM were inflexibility in dealing with land-use changes and variation in the location of impervious areas; inability of RUNOFF to represent accurately channel routing effects, instability of solutions using EXTRAN at desired time steps and segment lengths, and corresponding high costs for each run; inability to represent nonlinearities of response adequately; and the lack of a justifiable physical basis for parameter selection.

The major faults of SNODOB were its inadequate routing routine, solution instability at one-hour time steps, inability to deal with system nonlinearities, and difficulty of calibration.

On the other hand, the ease with which alternative land-use scenarios could be analyzed with SNODOB was applauded. Unfortunately, the other shortcomings of the model may offset this advantage.

Models used for drainage planning and design should be able to provide overland and channel flow rates and volumes at numerous locations in a watershed, according to the interviewees. Additional capabilities should include the ability to aide in pipe or channel design and to aid in water quality evaluation. (Water quality estimation will be discussed in a later section of this Appendix). The ability to optimize system design (e.g., minimize the cost of all aspects of a given management plan including land acquisition, structural costs, etc.) was not perceived as a necessary attribute.

The desire was expressed that accuracies on the order of 10 percent or better should be attained for estimates of peak flow and runoff volume for overland and channel components.

> [Comment]: Although it would certainly be desirable from a planning or design standpoint to know flows with virtual certainty, this is seldom possible. Such a desire may represent a fundamental misconception of the abilities of computer models. Whereas it might be possible (though improbable) to calibrate a model to within ten percent of observed conditions for a particular event, such calibration drastically reduces the applicability of the model to any other set of conditions which may be of interest (see James, 1965; James and Burges, 1978). Different land-use patterns, increased development densities, larger storm events, or different antecedent conditions are all factors that could invalidate the close calibration.

Finally, it was observed that providing a very accurate representation of basin hydrology does little to solve associated problems of political inaction (e.g., lack of agreements for planning between municipalities), lack of funding, etc. An accurate model therefore does not make better decisions, it merely aids in making them. The manner in which a model can aid the decision process is an important attribute.

Probability of Event Occurrence (Question 7)

It was recognized by the interviewees that the use of a rainfall event having a given return period does not imply that the runoff generated by an event model has the same return period. Policy currently in effect, however, still presumes such a relationship. Procedures for drainage design used in King County require that a 25 year storm be used for either of two conditions:

1. Tributary area is larger than 50 acres; or
2. Runoff flow estimated using a 10-year storm is greater than 20 cubic feet per second.

The 10-year storm is specified for all smaller developments. The use of both rainfall events is arbitrary and does not reflect any consideration of the consequences of providing or not providing drainage facilities based on these criteria.

> [Comment]: Since the Rational Method is still used, "storm" translates to "peak rainfall intensity for the time of concentration expected for the development". The peak flow thus estimated has virtually no relationship to a complete storm hyetograph, nor does the peak intensity probability relate to total storm probability. The flood estimation portion of SNODOB estimates a 100-year flow assuming that virtually 100 percent of the storm precipitation becomes runoff. Such an assumption is not badly in error for extreme events, during which a very wet natural watershed may respond in much the same manner as urban impervious areas (James, 1965; Overton and Meadows, 1976). SNODOB does not provide for lesser event frequencies, however.

The interviewees recognized that the practice of using a single design storm is inadequate for an additional reason, as well. The SNOMET Model Ordinance and King County Ordinance 2812 require on-site detention of surface runoff so that the peak flow rate after development does not exceed the flow for the undeveloped condition. From a comprehensive planning standpoint, however, it may be better to provide regional detention facilities, to provide detention only for some parts of the watershed, or to provide no detention at all. This choice would depend on the goals and objectives for the watershed and on the characteristics of the runoff event as determined by watershed development and precipitation patterns.

Several interviewees mentioned that it would be desirable to evaluate the runoff response of a watershed to a range of events, thereby providing a reasonable basis for selecting a worst case for design. That is, a range of event durations and return periods (e.g., 10-year, 6-hour; 25-year, 6-hour; 25-year, 12-hour) would be analyzed as to problems and possible solutions. A determination would then be made of the costs required versus the benefit gained by providing for each resulting flow, and a "worst case" would be selected for subsequent design.

> [Comment]: This "worst case" is not necessarily the maximum flood, but is rather the worst event for which management measures can be justified. The lack of reliable flow frequency information provided by event models places severe limitations on this sort of alternatives analysis.

Issues in Comprehensive Planning (Question 8)

The objectives of a comprehensive plan should include identification of problem areas (flooding, erosion, etc.), evaluation of the effects of alternative land-use scenarios, and evaluation of alternative runoff control measures and locations. These are the fundamental concepts of comprehensive planning.

Implied in the above is the close relationship between land-use planning and drainage planning. The two counties expressed particular concern that the planning and public works departments should work together closely on the plans. METRO personnel commented that there is a gap in technical expertise between the engineers and planners regarding models.

> [Comment]: This may be true as regards the technical details of models; it seems, however, that the planners have a much better understanding of the potential usefulness of models as planning tools. The engineers are principally concerned with day to day drainage plan review and permit authorization and often proceed without evaluating plans in the larger context. In fairness it should be noted that this is frequently a result of an overload of permit and site plans which does not leave time or personnel for long range planning. Nevertheless, comprehensive plans would provide the engineers with the information needed to evaluate development proposals in a total watershed context.

Although it would be desirable to be able to evaluate the runoff impacts resulting from specific land-use changes in particular locations (e.g., a shopping center located at various points in a watershed), the interviewees felt that it may not be feasible. This refers to the possible gap in capabilities between the small site (e.g., 5 acres or smaller) models and watershed models which was mentioned earlier. The ability to bridge this gap could be one of the evaluative criteria for any potentially useful model.

"Engineering judgment" was cited as the basis for much of the past effort in runoff management. Its shortcoming relative to issues like event frequency, use of the Rational Method, and comprehensive planning have already been mentioned. There will always be a place for judgment in any decision making process, but an informed decision in today's complex society requires a maximum of information presented in a manner that is comprehensible, as well as the ability to analyze such data. Models are one tool for providing such information.

Model Use/Users (Question 9)

The direct users of any models for drainage planning or design would be the planning and public works staff of the various municipalities. METRO personnel have stated that the Agency would like to maintain water quality and oversight functions and leave the technical aspects of modeling and planning to King County. Although both Counties and Everett have staff engineers, systems analysts, and planners who are familiar to some extent with modeling, it is likely that additional personnel will be required as drainage planning and design receive more attention in the future.

It is possible that the need to hire additional staff with modeling expertise would prevent implementation. The controlling factor is development of a reliable source of revenue specifically for drainage work. Several methods are being considered and it is probable that funding will not be a limiting factor much longer, although there is a difference of opinion on this point. Personnel for both Counties expressed optimism despite the lack of success to date; METRO personnel were skeptical, citing the longstanding lack of funding even though drainage problems have received considerable attention since 1974. Nevertheless, when funding is secured, the municipalities will either hire additional staff with the necessary expertise or contract with consulting engineers for the technical work.

There is also a distinction to be made between planning monies and funds for design, construction, operation, and maintenance of public facilities. The Counties must prepare a Comprehensive Plan for an area before a utility can be established and assessments levied to fund the remaining actions listed. It is, therefore, planning funds which create the bottleneck in the overall process.

Some advantages of designating the Counties or a regional agency as the technical leader were observed. The interviewees felt that this would be beneficial primarily for two reasons. First, the smaller communities do not have the technical staff needed to apply computer models on their own, and would be unlikely to hire more persons for their limited amounts of drainage planning and design. Removal of the technical aspects of model application from their list of responsibilities would encourage use of the models.

Second, the problems associated with planning in basins which involve more than one jurisdiction could be alleviated. The RIBCO reports recommended that the municipality with the largest area in a watershed should be the lead agency. In many basins either King County or Snohomish County already have the largest area. If the Counties were to assume the lead in any basin in which they were involved, this issue would be resolved. Finally, by assuming the technical leadership role, the Counties would facilitate planning in multi-jurisdictional basins in which they had no direct stake.

This arrangement would probably result in greater model use, and has been incorporated in the Memorandum of Understanding previously cited [Section 2 (Content of Comprehensive Drainage Plans), subsection E], which designated either King or Snohomish County as lead agency for each of the intercounty watersheds.

Other Issues (Question 10)

Several persons expressed the strong desire that drainage planning and land-use planning should proceed concurrently for the maximum effectiveness of both. The current problems of funding for drainage work do not always allow this to occur, however. Funding is a major issue which must be resolved in the ongoing development of drainage plans.

Additional concern was expressed over the present policy that requires on-site detention of runoff from all new developments throughout all watersheds. The concerns are four-fold:

1. The policy overlooks potential harmful effects of the uniform detention requirement (see Hardt and Burges, 1976) which could be alleviated by the use of regional detention facilities or by selective use of detention in a basin;
2. Economies of scale are overlooked and therefore the total social cost of the present policy is not optimal; increases in total costs caused by the need to provide improved conveyance systems and easements from upstream parcels to regional ponds to prevent damage to intervening areas are overlooked as well;
3. The analytical methods currently used (primarily the Rational Method) are not compatible with good detention design because artificially high predevelopment runoff rates are indicated; the postdevelopment runoff rate which is allowed is therefore high as well;
4. The design event presently used is not the same for all parts of a watershed, nor is it reflective of any worst case conditions in the watershed as described earlier (varying, rather, from one development to another depending on the size of each).

Comprehensive planning for any watershed should deal with these issues. Regional detention sites as well as selective application of the detention requirement could be analyzed along with any other desired alternatives. Such an approach should alleviate the economies of scale problem as well. As for the design event, increased accuracy in modeling of the various component processes of the rainfall-runoff cycle should result in better estimates of pre and postdevelopment runoff. Finally, a comprehensive plan could analyze a range of design events to determine a worst case for design, and the selected event could be specified for use throughout the watershed.

Water quality modeling was the major additional issue raised. The questionnaire did not specify whether quality would be considered in evaluating continuous simulation models; water quality is, however, a major concern of both the public and municipalities. The PL 92-500 Section 208 plans were based on the goal of water quality improvement. However, it was the experience of the author in modeling quality with SWMM for Juanita Creek that the state of the art in water quality modeling leaves much to be desired.

> [Comment]: Many of the parameters of greatest concern in the aquatic ecosystem, such as heavy metals and pesticides, generally are not modeled at all. The pollutants build-up or wash-off functions which are used cannot be generalized from the literature but rather require locally specific data. As METRO personnel observed, wash-off functions integrated over entire storms have been developed locally, but an accurate representation of instantaneous water quality cannot be obtained for conditions other than those for which the functions were developed originally.
>
> The emphasis of the event models currently in use has been toward estimation of runoff "pollutographs", i.e., continuous representation of pollutant concentration throughout the runoff event. Not only does this application run counter to METRO's caution expressed above, but it also fails to account for two other extremely important water quality phenomena.
>
> First, although acutely harmful pollutant levels may be reached during a storm, single event estimates do not account for possible chronic effects of the total annual pollutant load. Whereas chronic effects may be represented by modeling quality in conjunction with a continuous simulation hydrologic model, the representation is no better than the wash-off functions in any case.
>
> Second, perhaps the worst cases of acute environmental impact occur when toxic materials are spilled into the receiving water. Spills occur both by accident (e.g., a drum of industrial solvent is knocked over by a forklift) and by design (the same drum is rinsed out over a storm drain). In neither case can the occurrence be predicted nor modeled.
>
> It is the assumption in this study that a more accurate representation of the hydrology in the urban and suburban setting will also result in a better model of water quality. The same quality functions are currently used for both event and continuous models; as the quality functions are improved the continuous model will continue to provide the better water quality representation.