Asit K. Biswas

Systems Approach to Water Management

McGRAW-HILL
BOOK COMPANY
New York
St. Louis
San Francisco
Auckland
Bogota
Düsseldorf
Johannesburg
London
Madrid
Mexico
Montreal
New Delhi
Panama
Paris
São Paulo
Singapore
Sydney
Tokyo
Toronto

Edited by

ASIT K. BISWAS

Director, Environmental Systems Branch
Department of Environment
Ottawa, Canada

Systems Approach to Water Management

This book was set in Times Roman by Textbook Services, Inc.
The editors were Rose Ciofalo and James W. Bradley;
the production supervisor was Milton J. Heiberg.
R. R. Donnelley & Sons Company was printer and binder.

Library of Congress Cataloging in Publication Data
Main entry under title:

Systems approach to water management.

Includes index.
1. Water resources development—Mathematical models. I. Biswas, Asit K.
TC409.S93 333.9'1'00184 76-25968
ISBN 0-07-005480-0

**SYSTEMS
APPROACH
TO WATER
MANAGEMENT**

1 2 3 4 5 6 7 8 9 0 DODO 7 8 3 2 1 0 9 8 7 6

This book is dedicated to

MOSTAFA KAMAL TOLBA
Executive Director, UN Environment Programme

humanist, scientist, and administrator extraordinary

CONTENTS

LIST OF CONTRIBUTORS

ASIT K. BISWAS, Director, Environmental Systems Branch, Department of Environment, Ottawa, Canada; Senior Consultant to the United Nations Agencies on Water

DOMINIC M. DI TORO, Environmental Engineering and Science Program, Manhattan College, Bronx, New York

LUCIEN DUCKSTEIN, Department of Systems and Industrial Engineering, University of Arizona, Tucson

DOUGLAS A. HAITH, Departments of Agricultural Engineering and Environmental Engineering, Cornell University

CHARLES W. HOWE, Department of Economics, University of Colorado

CHESTER C. KISIEL (deceased), Department of Hydrology and Water Resources, University of Arizona, Tucson

RAY K. LINSLEY, Professor Emeritus of Civil Engineering, Stanford University; Chairman, Hydrocomp, Inc.

DANIEL P. LOUCKS, Department of Environmental Engineering, Cornell University

N. C. MATALAS, U.S. Geological Survey, Washington, D.C.

DONALD J. O'CONNOR, Environmental Engineering and Science Program, Manhattan College, Bronx, New York

GERALD T. ORLOB, President, Resource Management Associates, Lafayette, California; Professor of Civil Engineering, University of California, Davis

ROBERT V. THOMANN, Environmental Engineering and Science Program, Manhattan College, Bronx, New York

J. R. WALLIS, IBM Research Center, Yorktown Heights, New York

EDITOR'S INTRODUCTION

In the space of one hundred and seventy-six years the Lower Mississippi has shortened itself 242 miles. That is an average of a trifle over one mile and a third per year. Therefore, any calm person who is not blind or idiotic, can see that in the Old Oolitic Silurian Period, just a million years ago next November, the Lower Mississippi River was upward of one million three hundred thousand miles long. By the same token any person can see that seven hundred and forty-two years from now the Lower Mississippi will be only a mile and three quarters long. There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.

Mark Twain

Science, as Mark Twain suggests, is indeed "fascinating." Scientific methods and techniques, if properly developed and used, can significantly rationalize the planning process and streamline the art of decision-making. In contrast, if scientific facts and procedures are misused, the results could be misleading at best and catastrophic at worst. Therein lies one of the so-called dilemmas of the modern world: so-called because some have recently suggested that man's current predicaments are due to developments in science and technology. Such sentiments seem to be completely oblivious of the facts that scientific developments and technological innovations have given mankind, amongst others, improved standards of living, longer life spans, instant communication, and leisure society. Admittedly, one can argue that such developments have also been responsible for a population explosion that cannot be sustained on a long-term basis at the present growth rate, as well as an intensive resource-consuming society. Many of these adverse effects are to a great extent due to man's failure to evaluate the secondary and tertiary effects of beneficial scientific developments or are due to their misuse. Thus, what is needed is not less science and technology but more—a determined and concerted attempt to use their full potential to solve the complex problems facing mankind, some of which they themselves may have helped to create for one reason or other.

In the area of water-resources management, two new developments in recent decades are becoming increasingly more important. These are the application of systems analysis techniques to improve the planning and decision-making processes, and the need for interdisciplinary teamwork during such analyses. The two are not mutually exclusive: in fact they are closely interlinked. Systems analysis has provided a new dimension to man's analytical capabilities, and improvements in computer technologies have significantly improved man's computational abilities. These two developments, in combination, now enable planners to develop new and effective management strategies for a popular resource like water, the diversity of which and the intensity of demands on which have increased manifold in recent decades and are bound to increase more in the future.

Water-resources planning is not planning for water per se. One of the first questions that has to be asked is, water for what? There are different demands on water, and each of them needs a specific quality and quantity of water. For example, a certain quality of water may be used for irrigation, but it may not be suitable for domestic or industrial purposes. Quality and quantity, however, are closely interrelated, and it really does not make much sense to discuss quantity of water without any reference to its quality, or vice versa. In addition to quality and quantity of water, it is necessary to consider the organisms that live in and around a water body, as well as the land surrounding it. In other words, at the present state of human development, it does not make much sense planning only for water: we must consider water and land as an interacting and interrelated planning unit. This means that planning options and management strategies must be developed on an interdisciplinary basis. Historically, water-resources planning has been primarily the domain of engineers and economists, but with increasing complexities of the planning process it can no longer be so. Participation from other disciplines like biology, chemistry, ecology, sociology, law, mathematics, geography, or political science is not only desirable, it is now essential.

"Systems Approach to Water Management" is an attempt to look at the problems on an interdisciplinary basis by using systems analysis techniques. Up until the nineteenth century it was possible for a brilliant person to know nearly all there was to know about a specific problem area. The information explosion, however, has made that condition impossible in the latter half of the twentieth century. For example, today we are faced with the impossible situation that globally there are some 35,000 journals which publish about 2,000,000 articles each year, written by about 750,000 scientists in some 50 languages. This is in addition to numerous books that are being published in many different languages all over the world. Thus, at the very early stages of planning of this book, it became quite apparent that it was extremely difficult, if not impossible, for any single person to write such a text. Hence, the most effective alternative was to assemble a distinguished group of contributors, each an international authority in his own field, to prepare comprehensive chapters in their own fields of specialization, written within a prescribed overall framework. The present book is the result of this effort.

The first chapter is an introductory one that reviews some of the fundamental aspects of water-resources management. It discusses the reasons which have contributed to making the water-resources management process exceedingly complex at present, and it points out that the process will become increasingly more complex in the future. In spite of increasing complexities, the average planner or decision maker has been provided with a few fundamentally new tools and concepts during the past several decades. One of these new tools is systems analysis. Relevant information on computers, mathematics, and systems analysis has also been provided.

The concept of systems analysis, with direct reference to water, is explained, and so also are the different categories of models. The concept of multiobjective planning, including the difficulties associated with such a process, are discussed. The chapter ends with a description of the present status of social sciences modeling, which has not advanced to the same stage as models developed in physical sciences.

The next nine chapters deal with models in specific areas. The second chapter examines rainfall-runoff models. One of the key hydrological problems has always been to estimate the flow of ungaged streams or to extend the available records of gaged streams. Ray K. Linsley, who pioneered modeling work in this area with his Stanford Watershed Model, reviews some of the early developments which lead to his work—unit hydrographs, determination of infiltration rates and snow melt, the coaxial method, and other developments in the 1950s, including the advent of computers. The structure of a water-balance model is succintly described—including the functions of rainfall, evapotranspiration, interception, impervious area runoff, soil moisture storage, infiltration, interflow, upper zone storage, overland flow, interflow discharge, ground water, and other relevant parameters. These functions are discussed with specific reference to the Hydrocomp Simulation Program, which is the latest and most completely tested model deriving from the original Stanford Watershed Model.

The chapter ends, appropriately enough, with some thoughts on the application as well as the future of simulation. This logically leads to the next chapter: generation of synthetic flow sequences.

Nicholas C. Matalas and J. R. Wallis point out that the design of a water-resource system is dependent, in part, upon the sequences of streamflow that are assumed to be realized over the system's economic life. Unfortunately, the generating mechanism of streamflow is unknown, but this mechanism can be approximated, and an ensemble of "future" flow sequences, referred to as *synthetic flow sequences*, can be generated. Over the past decade, a series of techniques has been developed for generating synthetic flow sequences, most of which have been based on short-memory processes. Recent developments, however, enable planners to introduce long-memory processes to approximate long-term persistence that is evident in many historical flow sequences. Matalas and Wallis review the developments thus far in this area. Special attention is given to some of the operational problems involved in generating synthetic flow sequences on a multisite and multiseason basis, including those which derive from the paucity of streamflow data, as well as those that derive from the operational constraints of model building.

Chapter 4 is a comprehensive analysis of ground-water problems by the late Chester C. Kisiel and by Lucien Duckstein. It is a somewhat more rigorous treatment of the topic than in other chapters. It identifies the current state of modeling, as well as its deficiencies. The focus is on emerging approaches to describing and managing the ground-water system and not on the many theoretical and empirical solutions to regional and specialized ground-water problems. Some examples of specific methodologies are given. Various ground-water models have been summarized, along with some statements about their properties which should enable one to select a suitable methodology. A significant part of this chapter is relevant to problems other than ground water. These are some of the important techniques and considerations, i.e., model choice, multilevel optimization, hybrid computations, adjustment algorithims, multiobjective features, and fundamental problems like uncertainties, error growth, worth of data, and economic losses. It is suggested that planners should know enough about uncertainties to interprete their possible consequences. It is the essence of professionalism to attack such issues in a frontal manner.

The subject changes from ground water to surface-water management in the next two chapters. Daniel P. Loucks, who is one of the world's leading system analysts, examines the status and application of models to the management of surface water. Since the emphasis on surface water in a real world is considerable (it provides the major portion of the world's agricultural, industrial, and domestic water supplies), we decided to treat the problem in two consecutive chapters: the first dealing with the quantity aspect of the problem and the second with the quality aspect. However, it must be remembered that, even though surface water is an important component of the total water-resources management problem, comprehensive analyses of regional water management must consider the conjunctive use of ground and surface waters and the control of water quality as well as quantity.

The first chapter by Loucks, Chapter 5, is concerned with the definition and evaluation of alternatives for controlling the allocation and distribution of surface-water flows within a region. The chapter captures the essence of the procedures available to analyze surface-water management alternatives and at the same time provides additional information on the risks associated with various investment and operating policies. Specifically, the models discussed serve as a means of illustrating how preliminary estimates can be made of the desired amount and reliability of various yields or allocations of water to each comsumptive or nonconsumptive use and the requirements, if any, for over-year, within-year, and flood-control storage capacity in multipurpose reservoirs. Loucks correctly points out that developing models of river basin systems is an art. There is no single best way to do it, although for specific problems some approaches are better than others.

Chapter 6 examines a variety of models for selection of water-quality management policies for surface waters. It reviews recently proposed important models for defining and evaluating combinations of waste-water reduction and treatment, artificial aeration, flow augmentation, and bypass piping alternatives for the management of dissolved oxygen concentrations. It contains a succinct discussion on the prediction and control of water quality, including alternative methods available for water-quality control. It shows how the quality standards and objectives can be incorporated within a modeling framework. River quality control models are analyzed, including waste-water treatment and reduction models, thermal-loading control models, flow augmentation models, artificial aeration models, and waste-water transport models. There is also a brief section on lake and estuarine quality control models.

Details of mathematical modeling of estuarial systems, however, can be found in Chapter 7, written by Gerald T. Orlob, to whom all of us owe a great debt of gratitude for making models more relevant and application-oriented. The estuary is one of the most complex and challenging systems that any water-resources analyst has to deal with. Up until recent years, it was extremely difficult to analyze the complexities of the system's behavior. Physical models have been used with some success, but these were not very successful in dealing with the dimension of quality. Developments in computer technology have made it possible to determine analytical solutions to this formidable class of problems—so much so that mathematical models have become the most useful tools for estuarial water management. The first part of the chapter deals with theoretical considerations, especially advection-effective diffusion, hydrodynamics of tidal motion, and different quality considerations. The second part is a review of some of the major estuarial models developed so far—Delaware Model, Bay-Delta Models, Gulf Coast Models, and a series of other models developed for different areas, having different emphases. There are also sections on model calibration, as well as their potential applications.

Donald J. O'Connor, Robert V. Thomann, and Dominic M. Di Toro consider ecologic models in Chapter 8. Ecologic models, in this context, are considered to be an analytical structure of broad segments of the aquatic ecosystem. Lack of a basic set of laws on biological behavior makes construction of ecologic models somewhat difficult. Nevertheless, ecologic models have been constructed along several lines. For example, a large number of ecologic models have been developed with linear interactions. Some models, like phytoplankton biomass models, have tended to be nonlinear because detailed phytoplankton-zooplankton nutrient interactions can be closely approximated. The main focus of the chapter is on a linear model of nitrification to analyze dissolved oxygen in natural water bodies. The models discussed progress from relatively simple nitrogen equivalent BOD models to more complex ones having feedback effects. A simplified ecologic model, having general application in one-dimensional natural water systems, such as streams and estuaries, is presented. The models are particularly useful in describing the broad outlines of the effects of nitrification on dissolved oxygen.

Chapter 9 is on economic modeling and is written by an eminent economist, Charles W. Howe. Economic modeling is intended to relate uses of other scarce resources (investment and operating inputs in public and private sectors) and to provide criteria for ranking different water development and management policies. It is necessary to model the physical system which influences those dimensions of welfare measured by income, its distribution among subsets of the population, the generation of employment, and physical environmental conditions. The first half of the chapter provides a concise discussion of contemporary issues in the social evaluation of water. The second half reviews the recent economic modeling achievements in the water-resources area. The achievements are divided into seven classes, representing important model types and/or problem areas in which important advances have been made. The seven classes of models are then discussed. Finally, areas which warrant substantial additional research investigations are pointed out.

Specific models by different areas are discussed in the preceeding chapters. Chapter 10, by Douglas A. Haith and Daniel P. Loucks, looks at multiobjective water-resources planning, some fundamental aspects of which are reviewed in the first chapter. In order to deal with the complexities of multiobjective planning, planners usually construct simplified representations or models of their problems that can range from solely conceptual ones to those that have to be solved by high-speed digital computers. General experience indicates that some alternatives are preferable when certain objectives are considered but that these alternatives change when different objectives are examined. As the number of objectives and alternatives being considered increases, the ability of the planners to manage the problem decreases. This is where modeling can play a tremendously important part as an aid to making decisions.

Some of the major topics analyzed are quantification of planning objectives, models for multiobjective planning—including the problems of trade-off and political feasibility, formulation of planning alternatives, and plan selection. It is suggested that what is needed is a methodology that does not require explicit intervention by the political decision makers but makes use of a value judgement that has to be defined by the political decision-making process.

The role of mathematical modeling in water-resources decision-making and its present status are explored in depth in Chapter 11, the final chapter. The primary role of a decision maker is to make right decisions on the basis of available information and within the allowable time and resource constraints. The basic types of models used for decision-making, technocratic and incremental, are discussed, and so are the common criteria of the decision-making process in a real world. Even though modeling can add an important dimension to the decision-making process, surprisingly enough it still lacks credibility with the policy makers. The reasons for this "credibility gap" are analyzed, and some basic rules are suggested as guidelines for realistic model development. The positive and negative aspects of modeling as used for decision-making are reviewed. Appropriate remedies are suggested to improve the image of modeling in the eyes of decision makers, which will reduce the proliferation of unvalidated, untested, and useless models, much of which can be classified somewhere between dilettantism and academic exercises.

During the past two decades considerable progress has been made in the fields of systems analysis and computer technology. For example, in the area of computers, as their speed and capacity have multiplied, their cost per unit of operation has steadily declined. Thus, in 1952, it cost $1.26 to carry out 100,000 multiplications. The unit cost has progressively declined to $0.26 by 1958, to $0.12 by 1964, and $0.05 by 1970. Today the same computations can be carried out for only one cent! Thus, the potential contribution of systems analysis to national water-resources management is enormous: we have only just scratched the surface.

Having worked for more than a decade in the field of natural resources management at both national and international levels, I feel that the state-of-the-art in mathematical modeling has advanced sufficiently to be useful in water-resources management. Admittedly, some of our current models in this field are rather crude and somewhat dependent on the judgement of the analyst, but the issue is very definitely on the side of having a model, even a crude one, against having no model at all.

ASIT K. BISWAS

1

SYSTEMS APPROACH TO WATER MANAGEMENT

Asit K. Biswas

Director, Environmental Systems Branch
Department of Environment
Ottawa, Canada

1-1 INTRODUCTION

"Water," said Pindar, as early as the fifth century B.C., "is the best of all things." This statement is not surprising, especially when it is considered that water has been one of the most precious commodities throughout man's recorded history. Without it, life and civilization, at least as we know it, cannot survive. The Greek philosopher Empedocles of Agrigentum (490–430 B.C.) postulated that there were four primary elements or roots (rhizōmata) from which all the materials of the world were constituted, one of which was water. Even Plato and Aristotle, with only slight modifications, accepted this concept of water as a fundamental element.[1]

The entire history of mankind could be written in terms of our need for water. From the very beginning, man realized that water is essential for survival, and, hence, early civilizations flourished on lands made productive by great rivers—the Tigris and Euphrates in Mesopotamia, the Nile in Egypt, the Indus in India, and the Huang-Ho in China. By 3200 B.C., the Egyptians had already developed intricate water-resources networks, especially irrigation systems. For example, the historian Herodotus mentions that King Menes, the first king of Egypt, dammed the Nile and diverted its course. He also mentioned that during the Middle Kingdom (2160–1788 B.C.) artificial lakes were used to store and control the high flood waters of the Nile. The historian was much impressed by the "artificial" Lake Moeris, which, according to him, had a circumference of 450 miles—almost equal to the entire coastline of Egypt.

Later the Persians used *kanāt* systems extensively to develop their ground-water resources. A *kanāt* is an artificial underground channel that carries water over long distances either from a spring or from water-bearing strata. This remarkable system started in Armenia and quickly spread as far as Northern India. [2] During the Roman civilization, the Romans built magnificent aqueducts to supply their capital city with millions of gallons of water daily, elaborate sewer systems, and a very fine harbor. The truly remarkable aspect of the early water-resources development works is that they were built on very little theoretical knowledge of hydraulics and hydrology. For example, Sextus Julius Frontinus (A.D. 35?–104), the famous commissioner of waterworks of Rome, considered that discharge was equal to the cross-sectional area of a stream, irrespective of its velocity. The Roman engineers were practical, and used empirical methods for construction, without much understanding of the physical principles involved. However, when we consider that not only did these structures admirably serve the purposes for which they were built but that some of them are also still in use, these are undoubtedly very remarkable achievements.[3]

1-2 COMPLEXITY OF RESOURCES MANAGEMENT PROCESS

At the beginning, the magnitude and the complexity of resources management and environmental problems were not complex. During the late Stone Age, man started to grow his own food by raising livestock and by farming. Agricultural communities that formed the early civilizations gradually developed on flat and fertile lands adjacent to major river valleys. The population was small and water was plentiful. If there were prolonged droughts, man simply migrated until he found a better location. Right from the beginning, man has generally treated water as gift from God—a "free" resource—and his birthright to use and squander as he saw fit. This freewheeling concept, until fairly recent times, did not pose any serious management problems.

Circumstances changed very quickly with the passage of time and the advent of the Industrial Revolution. Workers from agricultural sectors were attracted to the burgeoning industries. Thus, the great migration from the rural areas to the cities began, and this trend has continued ever since. One of its undesirable direct effects was the development of centers of dense population. As recently as 1800, the population of Berlin was 170,000 and that of New York City no more than 75,000. As the industries in the cities developed, they attracted more migration from the rural areas, in turn attracting more industries, thus creating a somewhat vicious circle. Unfortunately, industries were often established in close proximity to rivers because of the ease with which the waste products could be discharged into the flowing waters at no economic cost. In addition to the industrial effluents, the municipalities discharged their sewage into the river without much treatment, thus compounding the problem. This resulted in gross water pollution near and around centers of dense population. In medieval Paris, the streets were often like open sewers, but the River Seine was clean, and one could see fish swimming in the clear water. Times have now changed. Today the streets of Paris are clean, but the Seine is murky and gray, and one would indeed be fortunate to see any fish!

It is true that world scenarios have never been static. For example, population has been increasing ever since man appeared on earth. But the problem is not so much that everything in this world has been dynamic since time immemorial as it is the rate and/or magnitude of the changes that have taken place in the twentieth century. Let us consider the scale of the changes we are witnessing or have witnessed in the present century:

1 It took nearly a million years for the first billion people to appear on earth, but the next billion is due in only another 15 years.

2 From the beginning of our civilization to the end of the Second World War all the world's industry totaled less than the new industrialized capacity that has been produced within the last 3 years.

3 The United States alone used more resources in one decade, 1959 to 1968, than did the whole world in all previous history.

4 A century ago, the production of crude petroleum was negligible. By 1966, the production amounted to 1,641 million metric tons per year, having increased sixfold over the preceding 30 years.

5 The world will consume more metals during the next 35 years than it has in the last 2,000.

As our need for more and more energy and other resources has increased, so have our waste discharges into the environment. With ever-increasing industrial production rates and rapid technological developments, discharge of waste products to the environment has gone up as well. Had all these activities been uniformly distributed over the entire world, the resulting environmental pollution problem would not have been so bad. But since human activities are being increasingly concentrated in a few urban regions, it means that the environment in those select areas has to assimilate a variety of waste products in ever-increasing quantities. In many cases, we discharge more residuals to the environment than it can be reasonably expected to assimilate, and this creates problems.

In addition to the increases in discharge of residuals to our rivers and streams, we have also to consider society's continuing demand for a better quality of life and a better environment in which to live. However, environmental consequences of water-resources development and management can be described as a relative newcomer as an area of major national concern. Before the present era of environmental awareness, our society as a whole placed an overriding priority on the first-order effects of technology and economic growth. Consequently, if there was a conflict between having more water-resources development projects or increasing industrial production and the necessity of minimizing environmental pollution, it would have been resolved in favor of the former in practically all cases almost as a routine procedure. The secondary effects such as environmental pollution would have been taken in stride. To the extent that environmental deterioration was discussed or thought about, it was considered to be the "price of progress."

But times are changing. Societal values and norms are shifting significantly from an automatic acceptance of economic growth for its own sake toward a deep concern and better understanding of its environmental and social consequences. In the field of water-resources development, within a few years, societal concern with the protection of the quality of the environment has grown significantly in terms of public awareness, policy implications, and the urgency and complexity of the research problems posed. Thus our "environmental crisis" with relation to water-resources management is due partly to increasing levels of pollution and partly to our increasing perception of the pollution that has resulted from society's need or demand for a better quality of life, which, in turn, is a by-product of our increasing levels of affluence and education. This shift in value toward a better environment has begun to permeate the political process and is gradually being reflected in national policies and international concerns.

These developments have created a difficult dichotomy on the part of planners and policy makers. Because of the increase in population, per capita use of resources, and technological and industrial developments, our discharge of residuals into the environment (and thus to our water bodies) is increasing at the same time that society is demanding a better quality of life and environment. Consideration of these types of new societal attitudes, along with more traditional objectives of water-resources development such as those of economic efficiency or regional income redistribution, has made the natural-resources planning and management processes much more complex than ever before.

Thus, even though our water-resources planning process has become exceedingly complex at present, and will become more so in the future, it is becoming increasingly apparent that the average planner and decision maker has been provided with few fundamentally new tools and concepts in the past several decades. One of these few new tools is systems analysis; it is being used quite extensively in the operational phases, but the planners have so far used only a fraction of its total potential.

1-3 COMPUTERS, MATHEMATICS, AND SYSTEMS ANALYSIS

Even though the application of sophisticated systems analysis techniques to the planning, management, and operations of water-resources systems is of comparatively recent origin, the study and use of models probably antedates recorded history. Man has always used models to make decisions. Consciously or subconsciously, when one is faced with a situation requiring a decision, one uses a mental image or a model to quickly determine the benefits and costs of a specific individual course of action or to decide on an "optimal" solution by quickly considering several alternatives. These mental images or models are simple, but they are based on the same fundamental principles as the most complex mathematical models. For example, like the computer models, we use concepts and parameter relationships to make decisions. The only major difference is that computers can handle much more complex concepts and parameter relationships than a human brain. Thus, the question is not *whether* we should use models for decision-making, but *what type of models* should we be using to obtain the best possible results.

There are two major differences between mental and computer models. First, computers can store a fantastic amount of information in their memory, a feat that cannot be duplicated by the human brain. For example, the current generation of computers can recall hundreds of thousands of numbers instantly. With a somewhat longer delay, they can have access to a hundred million numbers in their memories. The modern computer can store all the information available in the *Encyclopedia Britannica* and can retrieve the information from any specific page within a fraction of a second. Also it can analyze and manipulate the numbers instantly (much faster than the human brain) and can carry out several billion calculations a day without making a mistake. As a very rough rule of thumb, a computer can carry out computations a million times faster than the human brain, increasing our computational ability by six orders of magnitude.

Even though the computers have incredible speed and memory, they cannot, by themselves, solve anything. In human terms, it would be true to say that a computer has an IQ of zero and probably is the most patient and obedient servant that man has ever found to carry out instructions without asking any embarrassing questions. Therein, however, lies one of the major problems: a computer will carry out instructions even if they are totally erroneous and nonsensical. Computers carry out our instructions accurately, and very often they perform precisely what they are programmed to do, which may not be exactly what the scientists or programmers meant them to do!

Computers have become indispensable to water-resources planners and designers during the last three decades, but the use of mathematics has always been indispensable.[4] Much of the mathematical sophistication that is available at present was available during the precomputer era, but the necessary computational capability was not. Even during the precomputer era, mathematical relationships were used to describe natural processes; the computations were then carried out laboriously on slide rules or adding machines. It was a time-consuming process, and because of the physical limitations it was impossible to analyze many alternatives or even one solution in great detail.

As computer technology has advanced, it has given a great impetus to mathematicians to further broaden their horizons by developing new methods and refining existing techniques. Developments in one area have spurred developments in another, and this has turned out to be a rather constructive cycle of events.

Development of computers and advancement of mathematics have created a new field of analysis: mathematical model building. Prior to the pre-1950 period, the use of models in the field of environmental and resources management was quite limited. Since the Second World War, however, there has been a tremendous increase in the use of modeling as a policy-making and problem-solving technique, especially in the defense and aerospace-oriented industries, under such labels as "systems analysis," "operations research," "linear, dynamic, or integer programming," "management science," "simulation techniques," etc. The relative successes of these types of analyses in such highly complex areas of defense and aerospace industries have not gone unnoticed, and, hence, there is an increasingly healthy sign that planners and decision makers are attempting to develop models to formulate more rational policies in several areas of national interest, including environmental and resources management.

1-4 SYSTEMS ANALYSIS

Systems analysis may be defined as an analytical study that helps a decision maker to identify and select a preferred course of action among several feasible alternatives. It is a logical and systematic approach wherein assumptions, objectives, and criteria are clearly defined and specified. It can significantly aid a decision maker to arrive at better decisions by broadening his information base, by providing a better understanding of the system and interlinkages of the various subsystems, by predicting the consequences of several alternative courses of action, or by selecting a suitable course of action that will accomplish a prescribed result. Systems analysis has added a totally new dimension to the science of policy-planning and decision-making.

Quantitative methods are preferred in systems analysis, but qualitative analyses can also be incorporated in the process. Computers are not essential, but they are almost mandatory if the system to be modeled is complex and multidimensional. In addition, model development needs expert intuition and judgment. This means that systems analysis cannot replace experience—in fact, it augments it.

Systems analysis provides the answers by methods and techniques that are available to everyone for critical analysis and examination. These are not unique in the sense that anyone who has the necessary expertise and experience can exactly duplicate the analysis. The models developed can be constantly updated as more information becomes available. In contrast to other available decision-making tools that have the same limitations, systems analysis uses all the relevant information available and extracts the best components from different scientific methods from different disciplines on which the analyses are based. Thus, virtues of systems analysis are also virtues of the methods and techniques on which it is based.

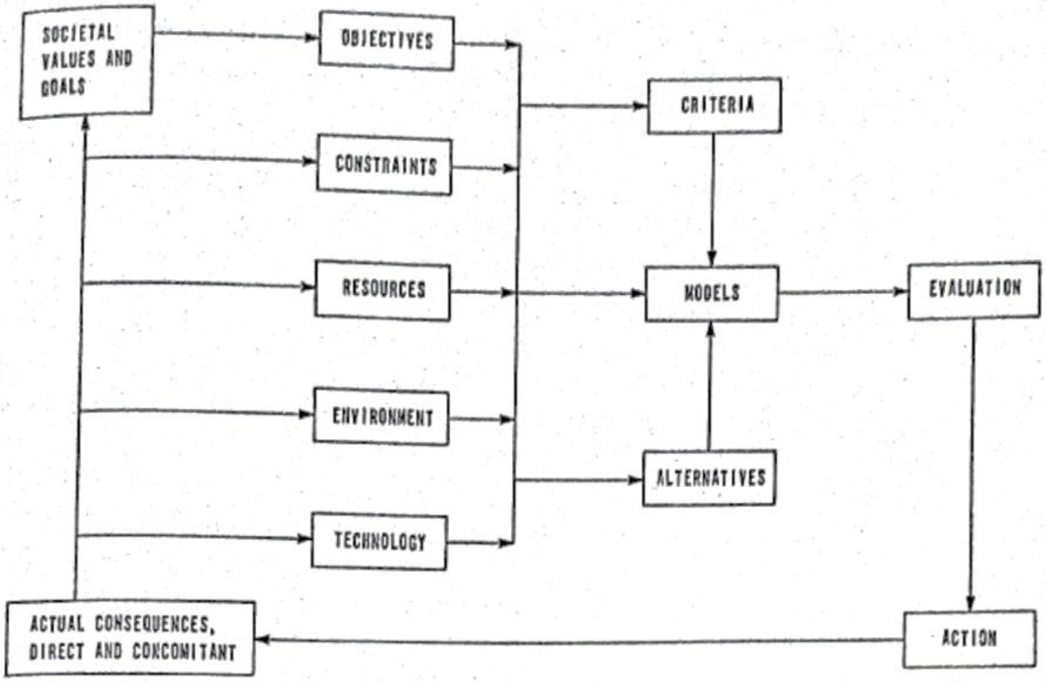

FIGURE 1-1
The role of models in the planning process.

Basically, systems analysis is a problem-solving technique wherein attempts are made to build a replica of a real-world system or situation, with the objective of experimenting with the replica to gain some insight into the real-world problem. The system is represented by a series of mathematical expressions in such a way that the resulting relationships describe the phenomenon. The parameters that affect the system are included, as well as the factors that influence the parameters. Thus, in a real sense, it is implied that a good mathematical model of a system needs a thorough knowledge and understanding of that system. However, since in most cases of water-resources planning and management, all the factors affecting the system are not known, or, if known, often cannot be evaluated and quantified, the resulting model does not exactly describe the real-world situation, but may be fairly close to it for all practical purposes.

Broadly speaking, the analysis of a water-resource system goes through five related stages:

1 Identification and explicit statement of objectives

2 Translation of objectives into measurable criteria

3 Identification of alternative courses of action which will satisfy the criteria

4 Determination of consequences that follow from each alternative

5 Comparative evaluation of the consequences of the alternatives in terms of the criteria

Figure 1-1 shows the general steps involved in water-resources planning process. The starting point is the definition of national goals and values from which specific water-resources development objectives should be derived so that the programs when completed will help to achieve those goals. The objectives then are translated into measurable criteria which can be used to appraise the degree to which the objectives are satisfied. The next stage is to develop a model of the system that will examine and evaluate the alternatives. The criteria used by the model will relate the alternatives to the objectives. During the process of development of the criteria, model, and alternative plans, due consideration should be given to the resources available, constraints to the system, and technological and environmental factors. There should be a good understanding of the interface between the system and the environment that it serves or alters and by which it is altered or constrained.

Finally, systems analysis can not only help planners and decision makers as an aid to prediction and planning processes, but it can also be used as a gaming or teaching tool. These types of models are generally less complex and are used to test assumptions, to explore consequences of different policies, and sometimes to get a "feel" of the system by varying different parameters or parameter relationships. The model permits the players to test management policies by experimenting with *what if* games such as: if estimates of . . . are correct, . . . might happen to . . . if . . . were to occur. The player receives an immediate output, often visual, which evaluates the consequences of his decisions. Thus, one develops an appreciation of planning and decision-making situations by substituting gaming in a simulated environment for experience in a real-world situation.

1-5 PROGRAMMING AND DESCRIPTIVE MODELS

In general, models can be divided into two categories—programming and descriptive—depending on the relationship of the model to problem-solving. Programming models, for a given objective function, attempt to derive the optimal policy. Descriptive models, on the other hand, attempt to predict possible future consequences due to a set of assumed exogenous variables and policy alternatives.

Theoretically, water-resources managers should find programming models more relevant as an aid to decision-making, since they are geared to obtain optimal policies, directly or indirectly. However, programming models are valid for rather simplified systems which can assume linearity of functional relationships. Also, often it is not possible to define objective functions, especially in the field of water-resources systems management, because of the many conceptual and empirical issues associated in constructing a truly comprehensive social welfare function. Examples of this type of modeling efforts are several linear programming models in the water-quality-management field,[5] the interregional linear programming models of Henderson[6] and Stevens,[7] and the interregional linear investment model of Rahman.[8]

Objective functions need not be defined for predictive models since they are not directly related to objectives. These types of models predict the values of endogenous variables for a given set of exogenous variables. Exogenous variables can be chosen by the model builder or the decision maker and are often called *policy* or *control variables*. If it is assumed that the future consequences are functions of policy variables, the decision maker can select an "optimal" policy by changing the policy variables, which will give conditional predictions of future states.

Mera[9] has pointed out the advantages and disadvantages of this type of modeling efforts quite succinctly:

> The predictive model is inferior in the sense that each alternative examined must be chosen subjectively by the persons constructing the model and, therefore, the chance of missing a significant alternative cannot be eliminated. However, it is superior in many senses: the future state can be described in far more detail, the future state can be evaluated differently for different preferences, and the model can be used to test the sensitivity of response to any particular policy variable.

Milliman[10] and Hamilton et al.[11] have presented two excellent reviews of these types of models to forecast regional economic activities.

1-6 MULTIOBJECTIVE PLANNING

The objectives of water-resources planning and management, or of any other type of natural-resources planning and management for that matter, have drastically changed over the years. Broadly speaking, this can be attributed to our increasing awareness and understanding of our social needs and goals. Historically, the main objective of water-resources development in North America has been economic efficiency, and the technique used for its evaluation has been benefit-cost analysis. For example, the 1902 U.S. Federal Reclamation Act required economic analysis of projects, and the 1936 U.S. Flood Control Act stipulated that benefits to whomsoever they may accrue should exceed costs. Gradually, to this single objective of economic efficiency, other objectives have been added. These, in order of their emergence, are regional income redistribution, environmental quality, and social well-being. The addition of these three objectives has undoubtedly broadened the decision-making framework and is an improvement over the past practice, which was pretty much limited to economic efficiency analyses. The endeavor of the planners to simultaneously achieve these multiobjectives within the planning framework stems, to a great extent, from the needs and desires of the society; hence, if the planning analyses are properly conducted, they would presumably expedite social and political acceptance of the plans.

The multiobjectives, however, have given rise to multifarious problems and have made the planning process much more complex than ever before. The dimensions of the complexities can be realized by the facts that, currently, relatively few methodologies exist for quantification of social and community goals and objectives and that, even for the single objective of economic efficiency, we do not have ideal analytical tools. For example, Pollard and Moore,[12] in their discussion on community planning, stated:

> Development of community goals and survey of public attitude are areas in which the state of the art is not far advanced. There is a current theory to the effect that there is no such thing as "Community Goals." Certainly no adequate method has thus been found for measuring them or determining what they should be.

For the analyses of economic efficiency objectives, the identification and measurement of benefits "to whomsoever they accrue" and "all costs" are difficult tasks even in the best of circumstances. Often, adequate and compatible data are not available. In addition, there are many methodological problems associated with the evaluation of secondary and intangible benefits and costs. The dimensions of the latter problems are further heightened by the addition of another objective in the planning process: environmental quality. Traditional economic analyses cannot evaluate intangible benefits and costs, except in a rather subjective fashion. (For a critical review of the techniques currently available for evaluation of environmental intangibles and some of the methodological problems associated with these processes, see Biswas and Coomber.[13]) And yet, in this age of environmental awareness and conservation, the quality of life, which is reflected somewhat in the social implications of planning, is a very important criterion. Inclusion of environmental quality as an objective of water-resources development recognizes the fact that the welfare of the society has other dimensions besides economics, and, hence, the real question is not whether environmental quality should be considered as a planning objective, but rather how it should be considered objectively within the planning framework. Another question might be whether an environmental-quality objective can really be separated from a social well-being objective.

Addition of environmental quality and social well-being to the other two traditionally accepted objectives of water-resources development—economic efficiency and regional income redistribution—poses a major problem for the planners: how should benefit-and-loss functions be constructed for all the objectives individually and collectively. The use of economic efficiency criteria as a decision-making tool is a matter of expediency, since they primarily deal with tangible and quantifiable factors, and, hence, they can be analyzed objectively. In contrast, the social-political elements of the objectives are intangible and nonquantifiable, and, hence, would have to be treated rather subjectively. Moreover, the objectives constituting the multidimensional functions are not mutually exclusive—in fact, they are often conflicting. Therefore, contributions to one can only be made at the expense of the other. This gives rise to two important questions: First, how should the different objectives be traded off against each other, and on what basis, especially when the subjectivity of some of the parameters is realized? Second, who should make a decision on the final mix of alternatives—planners, politicians, the public, or some mixture of the three?

The analyses of trade-offs between the various objectives can be quantitative, qualitative, or, as is usually the case, both. A system can be designed to perform optimally in terms of one objective, subject to a specified level of performance of the other, which in effect becomes a constraint. If the environmental-quality objective is known, some contributions to achieving it can be measured in terms of economic efficiency by considering consumer or producer willingness-to-pay. If this is not possible, such contributions can be treated as constraints that have to be met by the planning process. For example, the levels of dissolved oxygen in a stream or an estuary can be treated as a constraint rather than as a value to be maximized by arguing that, from an ecological point of view, a dissolved oxygen level of, say, 5 ppm is quite adequate and that any improvement on that level would be primarily of an aesthetic nature and is difficult to measure in terms of economic efficiency.[14] Thus, the level of dissolved oxygen, which may form one part of the overall environmental-quality criterion, is decided on ecological and aesthetic considerations (or any others for that matter), and then economic efficiency is maximized subject to this constraint. Alternately, environmental-quality objectives can be maximized subject to the constraint of economic efficiency. In other words, if both economic-efficiency and environmental-quality objectives are to be considered for planning analyses, one can be included in the objective function and the other can be treated as a constraint.

However, there are several aspects of environmental quality that can neither be measured in terms of economic efficiency nor quantified meaningfully for evaluation and comparison of alternate plans. The environmental-quality objective is a composite of diverse elements, and some of these are rather abstract from an analytical viewpoint. Even for the clearcut cases of air or water pollution, the losses and damages are difficult to measure, and, hence, for a subtler form of environmental pollution, evaluation of these estimates will be extremely subjective and will differ greatly from planner to planner, depending on their perception of the problem. In other words, inclusion of environmental quality as an objective of water-resources development has made the planning process less susceptible to objective criteria and more dependent on the perceptions and subjective analyses of the planner. Thus, intangible social disbenefits, in terms of environmental degradation, may provide sufficient justification for rejecting a development project, irrespective of economic-efficiency objectives. Inclusion of the environmental-quality objective in our planning process has made the process more complex, but it has undoubtedly made the planner's task much more important and rewarding than ever.

On the question of the selection of the final plan, it often is very much of a political process. The planners do not make the final decision, nor do they pass legislative actions which directly or indirectly effect planning. They do, however, where possible, point out the cost-effectiveness of the various alternative courses of action as well as their social, environmental, and technical feasibilities, and this information assists the decision makers to reach responsible decisions. Thus, the real decision-making lies with the politicians. In fact, water-resources planning, project authorization, and level of funding are all essentially political processes. Hence, *the planners decide the feasibility of the project, and politics decide the implementation of the plan.* As Ogden[15] has pointed out:

> No matter how sound a project may be physically, no matter how profitable it will be economically, it will come about only if effective political leaders can champion its cause in the right way at the right time.

The story of the Grand Coulee Dam will illustrate the point. The dam was proposed in 1918 by Rufus Wood, and yet the decision to build it was not made until the spring of 1933 because of the personal interest of Senator Clarence C. Dill of Washington, who had been a preconvention Roosevelt Democrat in 1932. President Roosevelt promised a dam to Senator McNary, Republican Minority Leader, to reduce unemployment in Oregon. Senator Dill, not to be put off, demanded a dam too. Roosevelt, according to Dill, initially offered him $40 million. Dill protested vigorously: "We can't even put concrete across the river for that!" Roosevelt increased the offer to $50 million and Dill again objected. "Sixty million, Clarence, and that's as far as I will go!" said Roosevelt. And so the final decision to build the Grand Coulee was made—initially as a low dam and a work-making project. Later, plans for the original dam were reinstituted by Harold Ickes.[14]

1-7 SOCIAL SCIENCES MODELING

During the last decade or so, tremendous progress has been made on the development of physical models for water-resources planning and management, but commensurate progress on social sciences modeling is sadly lacking. Within the social sciences area, several models currently exist that consider some economic and demographic parameters, but very few, if any, include sociological and institutional factors. Biswas and Reynolds[16] have recently presented a comprehensive review of the current status of socioeconomic modeling in water management, and Biswas[17] has further discussed some of the possible uses of these types of modeling to improve the decision-making process.

Since modeling is a scientific method used for analyses of known parameter relationships and observed data to understand and explain different phenomena and is a predictive tool, its role in social sciences should be similar to that in physical sciences.[18] Social scientists are becoming increasingly aware of the potential of the mathematical models to analyze social phenomena. Rex,[19] for example, categorically states that the "important question for the sociologist is not whether he should interpret observed human behaviour in terms of models, but what sort of models he should apply."

It is often argued that social phenomena cannot be modeled since it involves consideration of human behavior, which is often random and unpredictable. This argument is not really valid. One can possibly compare the unpredictability of human behavior to the uncertainty associated with weather forecasting. Our existing knowledge for predicting human behavior is probably at a similar stage as that of meteorological forecasting a hundred years ago. Through the establishment of new meteorological theories, weather forecasting has now become a science rather than an art. Admittedly, these forecasts are not always totally accurate, but they do serve a useful purpose. Similarly, the potential for meaningful analysis and prediction of social phenomena are there; it has only to be developed. And it can only be developed by realizing the tremendous contributions that the social scientists can make to the planning process and by making special efforts to get the social scientists really involved as equal partners in that process. Without a concerted effort by social and physical scientists, it is difficult to visualize how this potential can be exploited.

There is also another important aspect of the interdisciplinary considerations of water-resources planning and management. In the initial stages of analysis and planning, it is often difficult, if not impossible, to predict which disciplinary viewpoints will turn out to be the most important. In other words, we do not know a priori what the major issues and problems are going to be and who will be the most appropriate people to analyze and solve them.[20] A study by James, Bower, and Matalas[21] considered four variables associated with water-resources planning decisions, characterized by hydrology, modeling of dissolved oxygen behavior in an estuary, projection of economic development, and water-quality objectives. These were tested for sensitivity in evaluating the system performance, and it was found that, for the system under consideration, the relative importance of the variables in descending order is (1) economic development projection, (2) water-quality objectives, (3) dissolved oxygen modeling, and (4) hydrology. This does not imply that the relative order of importance of the same four variables are going to be identical for all other systems: they could very well be different. In order to forestall such problems, it is desirable that the members of a planning team should have different disciplinary backgrounds and should at least be familiar with the techniques and goals of other disciplines. The planners should not only be able to understand the technical terms commonly used in other disciplines but should also be familiar with their methodologies and techniques. This will ensure effective and meaningful communication among the team.

Individuals trained in different disciplines could also look at a common problem to be analyzed and solved in totally different fashions, depending on their education, background, and experience. The point can be best illustrated by the following story. The manager of an old building once received complaints from his tenants regarding the long waiting time for elevators. The manager called in his engineers and asked for possible solutions. The engineers suggested three alternatives: add extra elevators, replace old elevators with more efficient new ones, or use a banking system. The manager rejected the first two because they were too expensive for an old building and the third because it reduced the waiting time only marginally. The manager, however, had a friend who was a psychologist and who heard of this dilemma. The psychologist offered a simple solution: install mirrors in the elevator lobbies. This surprisingly enough stopped all the complaints. The mirror gave the ladies waiting for the elevator an opportunity to do some adjustments, and the men could look at the ladies in the mirror without any embarrassment.

Whether the story is true or not is really unimportant: what is important is the fact that the psychologist saw the same problem that was facing the engineers in an entirely different light. The engineers attempted to reduce the actual waiting time by technological means, but that solution did not occur to the psychologist. His solution was not to reduce the waiting time but to make it look like it had been reduced, and this happened to be an acceptable solution. The point we are trying to make is that we should have an interdisciplinary group for water-resources planning and management because different disciplines could perceive the same problem in different lights as a result of their training and background.

Thus, unless we make a determined effort to develop a truly interdisciplinary planning team, water-resources policies and programs that are developed are highly unlikely to be the best possible decision for society as a whole.

REFERENCES

1. BISWAS, A. K., "History of Hydrology," 2d ed., North-Holland Publishing Company, Amsterdam, 1972.
2. BISWAS, A. K., Hydrologic Engineering Prior to 600 B.C., *J. Hydraul. Div., Am. Soc. Civ. Eng.*, vol. 93, pp. 115–135, 1967.
3. BISWAS, A. K., A Short History of Hydrology, in A. K. Biswas (ed.), "Selected Works in Water Resources," pp. 57–79, International Water Resources Association, Champaign, Illinois, 1974.
4. BISWAS, A. K., The Role of Mathematics and Computers in Resources and Environmental Management, in A. Utton (ed.), "Interdisciplinary Environmental Approaches," pp. 154–166, Educational Media Press, Costa Mesa, California, 1974.
5. LOUCKS, D. P., and W. R. LYNN, A Review of the Literature on Waste Water and Water Pollution Control: Systems Analysis, *J. Water Pollut. Control Fed.*, vol. 36, no. 7, July 1964; vol. 37, no. 7, July 1965; vol. 38, no. 7, July 1966; vol. 39, no. 7, July 1967; vol. 40, no. 6, June 1968; vol. 41, no. 6, June 1969; vol. 42, no. 6, June 1970.
6. HENDERSON, J. W., "The Efficiency of Coal Industry," Harvard University Press, Cambridge, Mass., 1958.
7. STEVENS, B. H., An Interregional Linear Programming Model, *J. Reg. Sci.*, vol. 1, pp. 60–98, 1958.
8. RAHMAN, M. A., Regional Allocation of Investment, *Q. J. Econ.*, vol. 77, 1963.
9. MERA, K., "Survey of Model Building for Regional Economics," Discussion Paper

No. 55, Program on Regional and Urban Economics, Harvard University, Cambridge, Mass., 1969.

10. MILLIMAN, J. W., "Large-Scale Models for Forecasting Regional Economic Activity: A Survey," School of Business, Indiana University, Bloomington, 1968.
11. HAMILTON, H. R., S. W. GOLDSTONE, J. W. MILLIMAN, A. L. PUGH, E. B. ROBERTS, and A. ZELLNER, "Systems Simulation for Regional Analysis: An Application to River Basin Planning," The M. I. T. Press, Cambridge, Mass., 1969.
12. POLLARD, W. S., and D. W. MOORE, The State of the Art Planning, *J. Urban Plann. Develop. Div., Am. Soc. Civil Engrs.*, pp. 27–42, April 1969.
13. BISWAS, A. K., and N. COOMBER, "Evaluation of Environmental Intangibles," Genera Press, New York, 1973.
14. BISWAS, A. K., Socio-Economic Considerations in Water Resources Planning, *Water Resour. Bull.*, vol. 9, no. 4, pp. 746–754, August 1973.
15. OGDEN, G. M., Politics of Water Resources Development, in "Social and Ecological Aspects of Irrigation and Drainage," pp. 353–375, American Society of Civil Engineers, New York, 1970.
16. BISWAS, A. K., and P. J. REYNOLDS, Socio-Economic Simulation in Water Resources Systems Planning, vol. 1, pp. 75–82, Proceedings of the International Association for Hydraulic Research, Kyoto, Japan, 1969.
17. BISWAS, A. K., Mathematical Models and Their Use in Water Resources Decision-Making, vol. 5, pp. 241–248, Proceedings of the 14th Congress, International Association for Hydraulic Research, Paris, France, 1971.
18. BISWAS, A. K., Mathematical Models for the Planning and Management of the Saint John River Systems, vol. 3, pp. 415–428, Proceedings of the International Symposium on River Mechanics, Bangkok, Thailand, 1973.
19. REX, J., "Key Problems in Sociological Theory," p. 60, Routledge & Kegan Paul, Ltd., London, 1961.
20. BISWAS, A. K., P. J. REYNOLDS, and R. W. DURIE, Water Resources System Planning, pp. S.117–S.134, Proceedings of the Symposium on Water Resources Systems Planning, Varna, Bulgaria, International Commission on Irrigation and Drainage, New Delhi, India, 1972.
21. JAMES, I. C., B. T. BOWER, and N. C. MATALAS, Relative Importance of Variables in Water Resources Planning, *Water Resour. Res.*, vol. 5, no. 6. pp. 1165–1173, 1969. Reprinted in A. K. Biswas (ed.), "Selected Works in Water Resources," pp. 221–230, International Water Resources Association, Champaign, Illinois, 1974.

2

RAINFALL-RUNOFF MODELS

Ray K. Linsley

Professor Emeritus of Civil Engineering
Stanford University

Chairman, Hydrocomp, Inc.

One of the key problems of the hydrologist has always been that of estimating the flow of ungaged streams or of extending the records on gaged streams. He has needed to know flow volumes for estimating reservoir size; peak rates for design of spillways, levees, and conveyance channels; and low flow rates for estimating yield of diversions and navigation channels and for dealing with stream pollution. He has sought to estimate what nature had done or might do—in short, he has attempted to simulate the natural processes.

At first, he had no more than his intuition, possibly aided by such physical evidence as he could see, i.e., the size of the natural channel. This was apparently far from being uniformly successful. Biswas[1] describes Sadd El-Kafara Dam in Egypt—one of the earliest known dams built about 2800 B.C. The evidence indicates that this dam failed in its first year because no provision was made for a spillway.

The development of the science of hydraulics in the eighteenth century was a significant aid to the hydrologist because it gave a basis for some quantitative estimates of flow rate in streams—a far better guide to judgment than merely the visible cross-sectional area. The success of the European canal system of the eighteenth and nineteenth centuries was no doubt largely dependent on the significant aid provided by the recently discovered laws of hydraulics.

2-1 EARLY MODELS

The first published method for estimating flood peaks was that of Mulvaney,[2] and it is known as the *rational formula*. It was, however, the development of methods of stream gaging during the latter part of the nineteenth century which led to an accumulation of data on streamflow that made possible the science of hydrology as we know it today. With data on streamflow in relative abundance, it was possible to devise various relations by correlation, providing the hydrologist with a basis for estimating yield or flood peaks. Until well into the twentieth century, however, success in planning hydraulic works may have resulted more from the fact that the demand imposed on streams was a relatively small fraction of the mean flow, together with the use of liberal factors of safety in the design of spillways and conveyance works. Even so, hydraulic development was not without its failures—reservoirs which did not produce expected yields and dams which failed because of inadequate spillways.

Estimates of annual runoff volume as a function of rainfall were made in the late nineteenth century,[3] but the first development that deserves the title of "rainfall-runoff model" was that of Meyer.[4] Meyer's procedure appears to have been the first serious attempt to use a water balance calculated from precipitation, evapotranspiration, and soil storage to estimate monthly and annual flow volume. It is described by Mead as "quite involved and depends upon such a complete knowledge of physical conditions of the drainage area that apparently it is applicable only when more knowledge is possessed than is common in the majority of such problems."[5] The discussion of flood flows by Mead is largely descriptive of historic floods coupled with relations between observed peak flows and drainage area.

2-2 THE UNIT HYDROGRAPH

The first approach to a short-term rainfall-runoff model derived from the combined work of Sherman[6] and Horton[7] in the early 1930s. Sherman observed that the hydrographs of floods from a given basin were remarkably similar in shape when caused by rainfall of similar durations and that, if the hydrographs were reduced to a unit volume, they tended to be approximately identical. This concept, called the *unit hydrograph*, was the first expression of the linear system approach in flow simulation. The unit hydrograph concept not only provided a workable basis for estimating the shape of the hydrograph to be expected from a specified volume of runoff in a given time period, but as a linear system it permitted the application of the principle of superposition. It thus became possible to talk of runoff amounts in specific time intervals, i.e., 6 or 12 hours, rather than in terms of storms of varying duration. Complex storms made up of several periods of rainfall and often exhibiting multiple hydrograph peaks could be subdivided into single events. Utilization of this advantage was considerably restricted by the fact that rainfall observations were generally available only from nonrecording, daily-read rain gages. The unit hydrograph concept rapidly became the basic tool of the professional hydrologist. Snyder[8] presented a procedure for developing synthetic unit hydrographs when the necessary flow data were not available. Not long thereafter, Clark[9] demonstrated the equivalence of the linear routing procedure known as the Muskingum[10] method and showed that a unit hydrograph could be constructed by routing of the time-area diagram of the basin converted to flow units. Many other persons—too numerous to mention here—contributed to the general development of the unit hydrograph concept in the three decades following its presentation by Sherman.

2-3 INFILTRATION

Horton's outline of the infiltration process proved less immediately useful than the unit hydrograph concept, but, nevertheless, it marks an important milestone in modern hydrology. His presentation offered for the first time* a quantitative basis for considering the process by which rainfall is converted to runoff that feeds the streams. The existence of a limiting rate at which water can enter the soil, forcing rainfall occurring at higher intensities to become surface runoff, provided a basis for defining components of streamflow on the basis of their route to the stream. Demonstration that this capacity was time-variable explained why different storms with similar rainfalls produced differing volumes of runoff, and why storms with similar rainfall but varying duration also yielded different amounts of runoff. Quantitative application of the concept proved difficult. The absence of recording rain gages which could produce records of short-interval intensities was a major problem.

Experimental determination of infiltration rates on a large scale began soon after Horton's paper appeared. The Soil Conservation Service lead the way, since it seemed that its mission of controlling erosion and runoff might be best achieved through the control of infiltration. If infiltration capacity could be increased, there would be less surface runoff and less erosion. It seemed that experimental determination of infiltration before and after land treatment should indicate quite directly the effect of the treatment measures.

The search proved somewhat illusory. Techniques for measuring infiltration were not really adequate. Infiltration rates proved to be highly variable over a watershed. The initial infiltration capacity, a key parameter in Horton's equation, proved to be variable with antecedent moisture. In some watersheds,

---

*Infiltration as a problem in fluid flow or soil physics had been studied for many years, but Horton first presented the process as a hydrologic concept.

interflow, part of the infiltrated water, contributed a large and variable component of flow to storm runoff. Treatment of infiltration as a function of time did not properly account for changes in the infiltration capacity when rainfall intensities were less than capacity. These difficulties led to the simplification of the infiltration approach to infiltration indices which merely expressed an average loss rate.[11]

2-4 STATISTICAL RELATIONS

Paralleling the infiltration development, there had been an effort to deal with the runoff problem on a statistical basis. A variety of statistical procedures were developed, probably the most successful being the coaxial method[12] which was initially developed as a multivariable graphical relationship. Betson[13] subsequently demonstrated that the same type of relationship could be developed analytically. The coaxial relation did not perfectly explain the variability of storm runoff, but it was far superior to the use of infiltration indices.

The coaxial approach utilized an antecedent precipitation index which assumed an exponential decline in the effectiveness of antecedent rainfall as a function of time. This index gave an approximation to the initial soil moisture. The recession rate was assumed constant throughout the year, and the effect of varying evapotranspiration rates was approximated by utilizing calendar dates (expressed as weeks of the year) as a variable in the correlation.

2-5 THE DILEMMA OF DESIGN

The history of early runoff relations points up a dilemma which has plagued the development of hydrology from its inception. The primary use of hydrologic techniques was for the design of water control works—dams, reservoirs, channels, etc. The designer was required to estimate a "design flow" which might be expected with some specified (and relatively low) frequency. Once the structure was built, no clearcut indication of the accuracy of the design estimate was forthcoming. Usually the designer did not take time to look back at his earlier designs to see how they had performed. If the structure was damaged or destroyed by a flood, this was to be expected. After all, the selection of a design frequency meant that a calculated risk of failure was taken! If the structure never failed from the result of excessive flow, it was not obvious whether the design flow had simply not occurred (as was to be expected) or whether the structure was indeed grossly overdesigned.

On the other hand, the flood forecaster issued an estimate of an expected flow and time of occurrence, and within a relatively short time it was quite clear whether he had been accurate in his prediction or had missed badly. The forecaster, therefore, quickly learned that methods which were widely accepted for design purposes were simply not reliable enough for forecasting. The research hydrologists of the U.S. Weather Bureau conducted a continuing program of methodology development following quite different lines than those involved in design. Indeed, design methods tend to persist in use for many decades after their validity has been disproved and better methods are available.

2-6 SNOWMELT

Substantial volumes of precipitation occur as snow, which may remain on the ground in the solid state for days or weeks after falling. Any system for dealing with the problem of runoff must, therefore, be able to predict the melting of snow and its contribution to streamflow. The snowmelt process is a thermodynamic one, and snowmelting rates are primarily governed by the availability of the heat required to convert ice to water. Once liquid, the meltwater must move downward through a granular medium that has properties similar to soil (e.g., the infiltration process) but has the unusual characteristic that the melting process itself involves a metamorphsis of the snow, and, hence, the change in these properties.

The basic thermodynamic processes of snowmelt were understood at an early date (e.g., see Sverdrup, 1934[14]) and were summarized by Wilson in 1941.[15] To utilize these concepts, however, required data on solar radiation, wind speed, dewpoint, and other parameters which were not generally available. If they had been available, the relatively tedious computations of melting rates caused by condensation, convection, radiation, heat of rainfall, and ground heat might well have precluded their use for most tasks. Instead a relatively simple concept, the melt per degree-day, was the most widely used method[16,17,18] for dealing with short-term snowmelt. The daily temperature excess above 0°C became a proxy for all heat sources, and a degree-day factor defined as the daily runoff volume divided by the number of degree-days was developed from historic data to be applied to future conditions. Since snowmelt alone was rarely responsible for floods, this approximate method served reasonably well.

In the mountainous regions of the Western United States, the main interest in snow was in its value as a reservoir to store the winter precipitation until spring and early summer. Church, in 1909, devised the Mt. Rose snow sampler—a tube which could be driven into a deep snow pack to retrieve a core of snow from which the water equivalent of the snow on the ground could be determined. Using samples taken about April 1, it was possible to estimate the total water equivalent of the snow pack and to predict the volume of streamflow to be expected between the survey date and the end of summer.[19] A simple graphical plot of snow-water equivalent versus runoff volume sufficed to give quite accurate forecasts for many watersheds.

Subsequently, it was demonstrated that forecasts of equal accuracy could be obtained by correlating winter precipitation (usually observed at stations near and below the snow line) with annual runoff.[20] This was followed by the development of numerous more complicated correlations using either water equivalent or precipitation and sometimes a combination of the two measurements.

2-7 THE 1950s

The decade of the 1950s found hydrologists involved with flood problems usually employing fairly sophisticated rainfall-runoff correlations to estimate runoff volume and the unit hydrograph or some related linear process to transform the runoff volume to a streamflow hydrograph. If snowmelt were involved, its magnitudes were usually estimated by applying a degree-day factor to the degree-days above freezing and adding the estimated quantities of snowmelt to the precipitation before entering the rainfall-runoff relation. For the many flood-flow estimates for highway culvert design and urban storm drainage, very simple procedures were the rule, with the rational formula by far the most popular method. In terms of completed cost, far more project design was based on simplified methods than on the more sophisticated rainfall-runoff correlation and unit hydrograph method.

Forecasting of seasonal runoff from mountain snow packs was done on the basis of first-of-month snow surveys and a correlation relating these data to future runoff or, alternatively, from a correlation using the accumulated seasonal precipitation.

Reservoir design involving an analysis of long-period flows was usually accomplished by selecting a "critical period" from the record and employing a simple continuity calculation to determine the required reservoir size. If the record was very short, a relatively simple relation between monthly rainfall and monthly runoff might be used to estimate flows for a period of low rainfall which was more "critical."

The concept of probability in hydrology had been introduced by Hazen[21] in 1914 and was subsequently developed by many others. However, flow records were short, and there was little opportunity to employ other than the "critical-period" technique for reservoir design, even though it yielded no information on the probability of the proposed reservoir being able to satisfy its intended function. Flood-frequency analysis was employed in many instances, but, for what was probably the vast majority of projects, flow records were too short or nonexistent and a "design-event" approach was used. Where flow records were available, the largest flood of record was sometimes used as the basis for design. Where no flow records were available, a "design storm" was often selected. The design storm might also have been the largest recorded storm in the region or it might have been a station rainfall value of specified duration and return period. In either case, the design storm was transformed to streamflow by whatever method was in favor, and commonly, the erroneous assumption was made that the probability of the estimated streamflow peak was identical with that of the storm.

Two major factors determined the status of hydrologic procedures in the 1950s. The first factor was the limitation of data. Records were relatively short, and in the case of precipitation, most of the longer records were from nonrecording gages which reported only daily increments of rainfall. These data limitations determined the way in which hydrologic estimates were made—the design-storm and critical-period approach. The data limitations also, in part, determined the kind of methodology employed. A technique such as the infiltration approach was not practical if only daily rainfall data were available.

Limitation of data, however, clearly was not the controlling factor. Some recording precipitation gages had been in operation for many years and a fairly extensive network had been initiated in the early 1940s. The second and controlling factor was clearly the limitations of manual computation. The runoff process was fairly well-understood.[22] Reasonably detailed computational procedures had been described in the literature.[23,24] It had even been demonstrated that these procedures could be used to extend flow records and thus augment the data base for frequency analysis.[25] All these procedures, however, involved tedious computation which consumed many man-hours and risked numerous errors. Thus, it was the computational difficulties which stood in the path of progress. Hydrology may well have advanced nearly as far as it could with the constraint of manual calculation with slide rules and desk calculators. The time was right for a new computing tool!

2-8 THE ADVENT OF COMPUTERS

The digital computer had been in use since the 1930s, but it was not until the mid 1950s that digital computers became available in sufficient numbers so that they could be widely used in hydrologic research and application. Since they were first viewed largely as a new and larger slide rule, it was natural that their early applications in hydrology employed available hydrologic methodology. Computers were widely used to explore rainfall-runoff correlations, to derive unit hydrographs from complex storm sequences by successive iteration, to perform reservoir operation studies, and for flood routing.

The reservoir operation study (reservoir system simulation) proved to be an ideal application and rapidly developed into the complex systems analysis techniques discussed elsewhere in this volume. Flood routing proved to be effective for flood-forecasting operations, and elaborate programs for this purpose were developed.[26] Unit hydrograph analysis also expanded into "linear hydrograph analysis," but this perpetuates the limitations of the linear assumptions in the unit hydrograph concept and shows little prospect of developing into a useful hydrologic technique. Multiple correlation studies of the rainfall-runoff process also proved rather fruitless. The rainfall-runoff process is a complex one and is not easily represented by an equation involving a linear sum of terms or by any simple nonlinear expression.

Some researchers soon realized the potential of the digital computer for a totally different approach to hydrologic analysis. This new approach has come to be called *hydrologic simulation*. It seeks to describe the rainfall-runoff process by a series of mathematical functions, each describing a particular portion of the process and in combination simulating the whole natural process. The simulation programming is designed to accept rainfall as its primary input and to output streamflow—thus providing a tool which could transform historic rainfall data into streamflow, demonstrate the effect of land and channel changes on the streamflow regime, and perhaps enhance our understanding of the hydrologic cycle. It is now clear that digital computer simulation will be an important hydrologic tool of the future, and the balance of this chapter will be devoted to simulation methods and applications.

2-9 SIMULATION METHODS

Since the first simulation model was announced in 1960,[27] a large number of models have been described in the literature. It is neither necessary nor practical to discuss each one here, and an attempt will be made to classify the various models and discuss their general characteristics before discussing simulation in general.

Linear models Linear models consist of a scheme to decompose an observed hydrograph to determine the parameters of an impulse function (unit hydrograph). The parameters are usually a time function (lag) and a flow function (peak). These models do not include functions to calculate the quantity of runoff and, hence, simply provide a means of estimating the hydrograph, given a volume of rainfall excess. They are, therefore, not rainfall-runoff models and will not be discussed further.

Routing models Routing[28] models employ a flow-routing process to convert rainfall excess to hydrograph form. Like the linear models, they do not include a procedure for estimating runoff volume. If the routing process employed is linear, the routing model is essentially equivalent to the linear model.

Sugawara[29] has proposed a model consisting of a complex cascade of linear storages for simulating the entire runoff process from rainfall to streamflow. He does not, however, relate the various storages to features of the natural process, and hence, his model can be fitted to a real watershed only by a very lengthy trial-and-error process.

Event models Many models are designed to deal with the runoff process on a storm-by-storm basis.[30,31] Such models employ some type of loss function to estimate runoff from rainfall and a routing procedure to convert the computed rainfall excess to flow. Such models differ very little from the routing models except for the addition of a simple loss function. This approach fails to utilize the biggest advantage of the computer—its ability to carry through long, continuous calculations—and does not really get at the heart of the rainfall-runoff process.

Continuous water-balance models The continuous models employ a continuity calculation to maintain a continuous accounting of the water in storage in the watershed and relate the loss functions for rainfall to the current condition of the watershed. Such models are capable of continuous simulation of flow for long periods of time and can be considered as most closely meeting the ideal of hydrologic simulation. The discussion which follows will focus on water-balance models.

2-10 SPACE VARIABILITY IN SIMULATION

A fundamental problem in hydrology is the spatial variability of the governing hydrologic factors. It is relatively simple to cope with time variability of precipitation by making calculations using short time increments (assuming the availability of the required data). If the model contains the correct functions, the time variability in secondary factors such as soil-moisture storage will be automatically accounted for. Spatial variability is quite a different problem. The rainfall surface over a watershed is almost always a complex warped surface. Since the runoff process is nonlinear, error is introduced if the areal average rainfall is substituted for the detailed pattern. On the other hand, if the watershed is divided into a large number of subareas to account for the variation of precipitation, the computation time required increases greatly. Nearly all simulation models must perform the same computations for each subarea, and total run time increases almost linearly with the number of subareas. In addition, since only a few rain gages will be available, precipitation amounts must be interpolated in some way for each subarea. Superimposed on the variability of the precipitation is the variability of watershed characteristics—soil, vegetation, slope, land-use, etc.—and of the secondary effects—soil-moisture storage and infiltration as controlled by soil moisture.

It is a practical necessity to employ *lumped parameter models*, in which parameters are required to define average characteristics for a finite area. While it is theoretically possible to discuss *distributed parameter models*, they are practically unattainable at present. The issue is, therefore, the degree of "lumpiness" that will be tolerated. The practical solution is to divide the watershed into *segments* and calculate the runoff from each segment independently. As a minimum, there should generally be one segment for each rain gage which provides independent data; i.e., gages so close together that they record virtually the same precipitation would not be treated separately. In addition, segment boundaries may be drawn to reflect differences—in soil, vegetation, topography, or land-use—large enough to seriously affect the computed runoff. Each segment is then subject to simulation independently for the calculation of the runoff volume, and the runoff from the several segments is combined to calculate the total hydrograph. As suggested earlier, there is a trade-off between accuracy of the simulated flows and cost of the simulation which must be resolved.

A study by Johanson[32] indicates that if too few segments are used, the variance of the simulated flows will be too high, but the mean will be reasonably correct. This is intuitively apparent if one considers a single rain gage in a catchment which is relatively flat. The gage will on occasion receive the maximum rainfall within the catchment, and since the gage catch is assumed to be the catchment average, simulated flows will be too high. On other occasions, the gage will receive the minimum rainfall in the storm and will simulate too low. Thus, the range of simulated flows will be too great and the variance correspondingly large. In the long run, however, the gage catch will approximate the watershed mean, and consequently the simulated mean flow should be close to the correct value. Studying only rainfall variability, Johanson concluded that the errors decreased rapidly as the *number* of gages increased. He found that in even the smallest watershed, a minimum of three gages was desirable, but that the required number of gages does not increase linearly with catchment area. For a watershed of several thousand square kilometers, 10 rain gages might prove adequate. Johanson's study is difficult to generalize, because he studied conditions only in Illinois. However, it seems to clearly demonstrate that the concept of gage density (i.e., area per gage) is not a correct concept and that, after a reasonable minimum of gages are included, the increase in accuracy gained by adding an additional gage is relatively small.

2-11 STRUCTURE OF A WATER-BALANCE MODEL

The earliest water-balance model was the Stanford Watershed Model (SWM) I.[27] This model was improved and enlarged several times[33,34] and finally culminated in version IV.[35] A flow diagram of SWM IV is shown in Fig. 2-1. Many other models have been built on essentially the same basic concepts as SWM IV.[36,37,38] The flow diagram follows the concept of the hydrologic cycle as described in Linsley, Kohler, and Paulhus.[24] In the following discussion, the functions of the Hydrocomp Simulation Program (HSP)[38] will be described, since it is the latest and most completely tested model deriving from the original SWM.

Input data Inputs required for the HSP are rainfall and potential evapotranspiration. Rainfall data are usually input as hourly amounts. The model can utilize time increments from 5 minutes to 6 hours. Regardless of the time increment, the subsequent computations are essentially identical. Potential

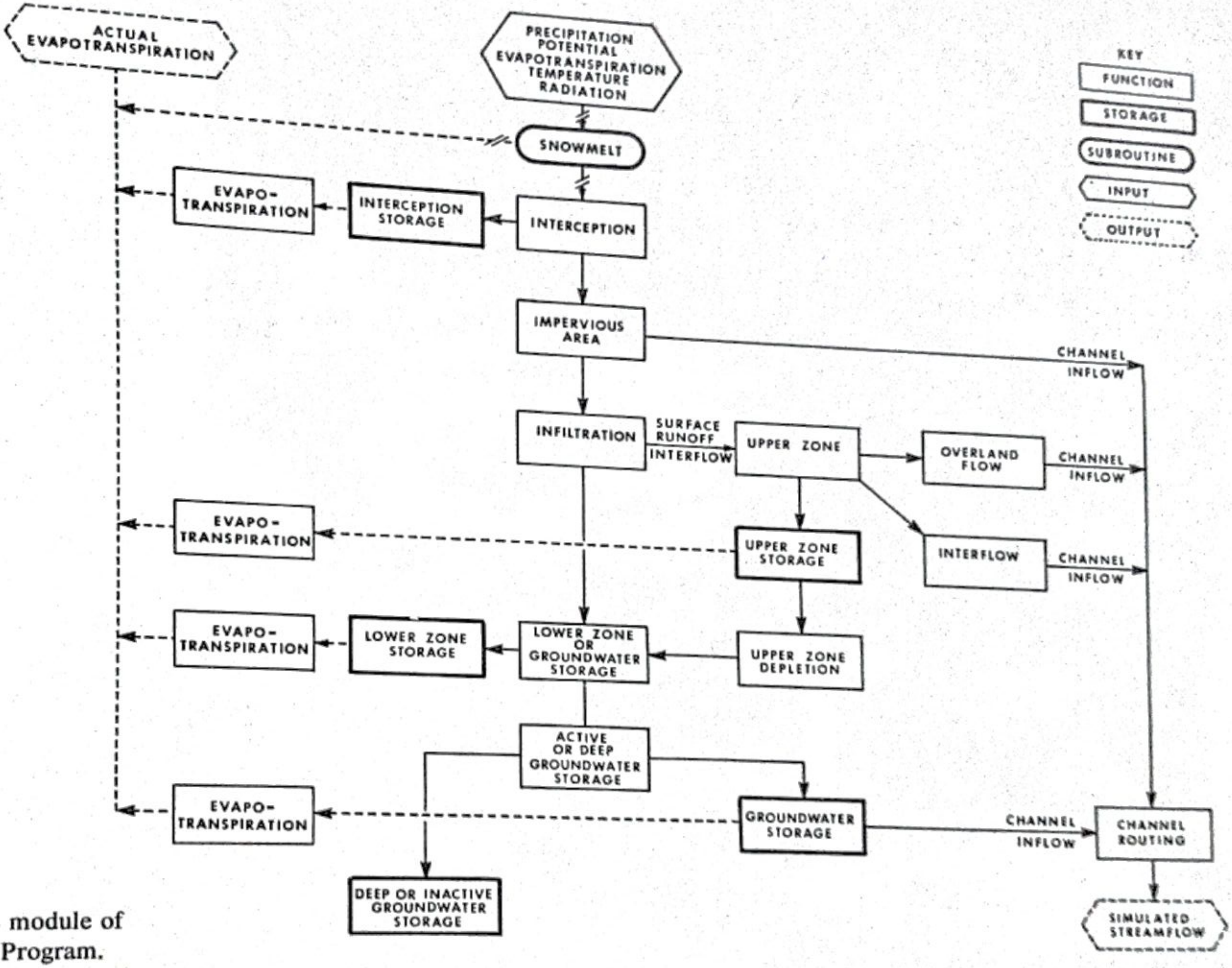

FIGURE 2-1
Flow chart for the LANDS module of the Hydrocomp Simulation Program.

evapotranspiration (PET) may be input as daily values or as semimonthly averages, i.e., the rate is assumed constant for a 15-day period. Estimates of potential evapotranspiration may be made on the basis of pan evaporation data or may be calculated from meteorological data. At first glance, it might seem that the values of PET employed would be very critical since, on the average, about two-thirds of the precipitation is returned to the atmosphere by this route. Actually, in watersheds where the precipitation is less than PET, the precipitation becomes the limiting factor and PET need not be defined precisely. Where precipitation greatly exceeds PET, the actual evapotranspiration (AET) will nearly equal PET. The calculated runoff volume is dependent on the PET, and any error in PET will be reflected in an equal error with opposite sign for the calculated runoff.

Rainfall adjustment Rainfall reported at a gage may not be equal to the average rainfall over the segment of the basin the gage is supposed to represent. If the measured amount is consistently low or high, the resulting bias can be corrected by multiplying the measured precipitation by a constant factor (K_1). This correction assures that the rainfall used in subsequent computations has approximately the correct mean, but it does not assure the correct variance. Thus, the water-balance computations will be nearly correct but individual storm events may still be in error.

Interception Interception loss is simulated with an input parameter $EPXM$ which represents the maximum volume of interception storage on the segment expressed in millimeter depth. Any rain occurring when the quality of water in interception storage is less than this maximum goes into the interception storage. When the interception storage is full, no loss occurs. Water in interception storage is depleted at the potential evapotranspiration rate until the quantity in storage is reduced to zero. The limiting interception storage capacity is usually small—in the vicinity of 2 or 3 mm. Thus, the influence of interception on a major storm is negligible, but over the period of a year it may be a significant factor in the water balance.

Impervious area runoff Most watersheds contain some impervious area from which runoff may be expected from any rain heavy enough to satisfy interception losses. The impervious area factor A represents the percentage of such impervious area. It may consist of roads, rock outcrops, buildings, impervious soils, and exposed water surfaces of streams, ponds, and swamps. In all cases, any area assigned to the impervious fraction should be *directly connected* to the stream system. Any impervious area from which runoff will flow over pervious soil should not be counted, since this runoff will be subject to infiltration. For most watersheds, the impervious area will be small—usually less than 3 percent of the total catchment area. However, in watersheds with substantial areas of lakes or swamps, the percentage will be much higher. In urban areas, A may be quite large.

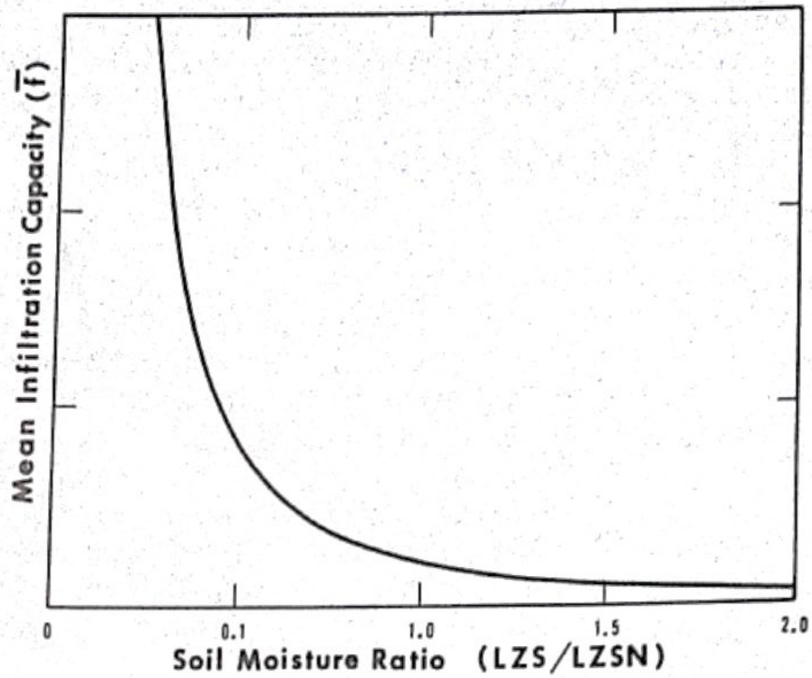

FIGURE 2-2
Graph of the function defining variation of average infiltration capacity with soil moisture.

Since the impervious area is small on most watersheds, this parameter will be of little significance in floods. It does, however, fix the minimum runoff at an amount equal to A × (rainfall − interception). The impervious area function is useful in explaining small runoff events occurring when soils are relatively dry. It is, of course, essential in simulating urban watersheds.

Within the model, a quantity of water equal to A times the precipitation minus the interception is directed to channel inflow or land surface runoff (LSRO) where it enters the channel routing process.

Soil moisture storage Soil moisture storage is the heart of a water-balance model. If this storage capacity is defined in terms of an absolute capacity which cannot be exceeded, then when this capacity is reached during simulation a sudden and dramatic change in segment runoff characteristics must occur. Such occurrences are not observed in nature. Consequently in HSP, the soil moisture or lower zone storage is defined by a nominal capacity $LZSN$. For most watersheds, $LZSN$ is usually between 200 and 400 mm. It is perhaps best defined as the moisture storage when one-half of any infiltrating water passes through to the ground water (Fig. 2-8). Actual lower zone storage (LZS) can exceed $LZSN$ by a factor of 2 or more, but this will happen infrequently since many processes in the model are controlled by the ratio $LZS/LZSN$. For example, when this ratio reaches 2, infiltration becomes very small (Fig. 2-2).

The lower zone is assumed to represent storage in the zone of aeration from near the soil surface to the bottom of the root zone. Moisture stored in the zone of aeration below the root zone cannot enter the hydrologic processes in significant amount since there is no mechanism to remove it from the soil. Therefore, it need not be considered in simulation. At the immediate soil surface, there is a thin layer of soil from which moisture may be removed by evaporation and transpiration at the potential rate. To distinguish this zone, an upper zone storage (*UZS*) is also simulated. The nominal capacity of this upper zone (*UZSN*) is treated in the same fashion as *LZSN*. It is a nominal capacity which can be exceeded, but as the ratio *UZS*/*UZSN* rises above 1 the fraction of new water reaching this zone which is retained drops rapidly (Fig. 2-6). The upper zone storage is assumed to simulate moisture storage in the very surface soil exposed to potential evapotranspiration rates and surface storage in the form of puddles (surface detention). Values of *UZSN* are usually much smaller than *LZSN* and commonly range between 10 and 50 mm. The upper zone storage is not large, but it is depleted rapidly by evapotranspiration and thus is effective in absorbing much of the rainfall of small storms and early increments of large storms.

Infiltration The infiltration function is probably the most important single function in the HSP. It is assumed that the infiltration capacity is controlled by the current moisture storage in the soil (*LZS*). Philip's equation[39] for infiltration capacity f at any time is

$$f = \frac{st^{-1/2}}{2} + a \tag{2-1}$$

where t is time and a and s are constants. The cumulative infiltration F at time t is

$$F = st^{1/2} + at \tag{2-2}$$

Assuming that a can be ignored,

$$fF = \frac{s^2}{2} = \text{constant} \tag{2-3}$$

Equations (2-1) and (2-2) are based on theoretical considerations and assume, among other things, homogeneous soil properties with depth. Since decreasing permeability is more usual with depth, Eq. (2-2) has been modified to

$$fF^b = \text{constant} \tag{2-4}$$

where b is an exponent greater than 1. In HSP $b = 2$; the ratio *LZS*/*LZSN* is used to indicate the current level of f. Figure 2-2 shows the basic infiltration function used for all watersheds. This function must be adjusted in level to represent the variations in infiltration capacity between watersheds. This is done by an input parameter *INFILTRATION* which is equal to f when

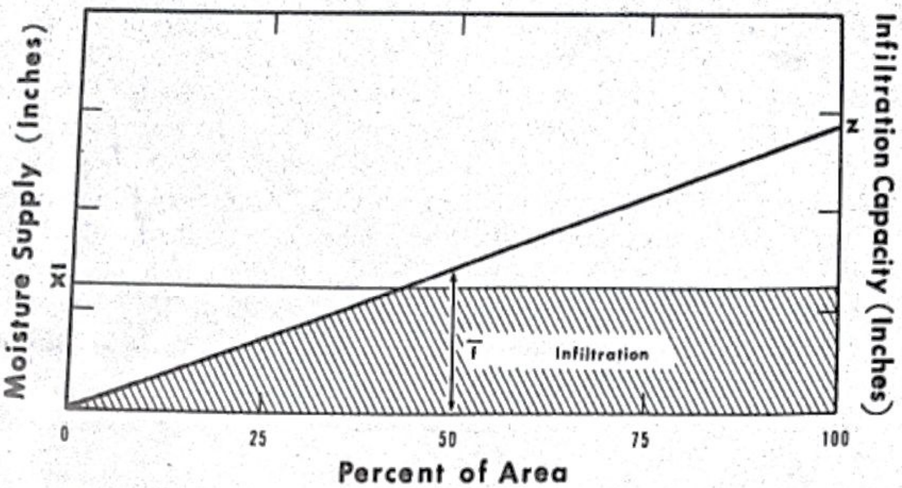

FIGURE 2-3
Variation of infiltration capacity with a watershed segment, showing method of computing actual infiltration.

$LZS/LZSN = 1$. The basic equation is thus

$$f = \frac{INFILTRATION}{(LZS/LZSN)^2} \tag{2-5}$$

Infiltration capacity at any instant is a variable over a watershed segment. Only extensive field testing could define the nature of this variation, but limited field data suggest that it may be very nearly a uniform distribution. A unique feature of SWM which has been retained in HSP is the assumption that infiltration capacity at any time varies linearly over the watershed from zero to a maximum (Fig. 2-3). If the supply rate to the infiltration function is x, the infiltration for a time increment is the area defined by the shaded trapezoid in Fig. 2-3. The infiltration thus varies with average rainfall intensity until $x > z$, when the infiltration becomes constant. Figure 2-3 may also be interpreted as defining the fraction of the watershed over which runoff occurs at a particular rainfall intensity.

Figure 2-3 is related to Fig. 2-2 in that the average infiltration rate for the segment (f, Fig. 2-3) is the current capacity defined by Fig. 2-2 and the ratio $LZS/LZSN$. Thus, the position of the line on Fig. 2-3 varies from time increment to time increment as the antecedent moisture conditions change. The straight-line assumption in Fig. 2-3 has obvious computational advantages. Experience suggests that it is a satisfactory approximation, even though a flat curve might be more realistic.

Interflow Interflow is that water which infiltrates the soil and then flows laterally through the soil for at least part of its course to the stream. In HSP, the infiltration determined as described above is *net* infiltration, i.e., that water which remains as soil moisture or percolates to ground water. The runoff vol-

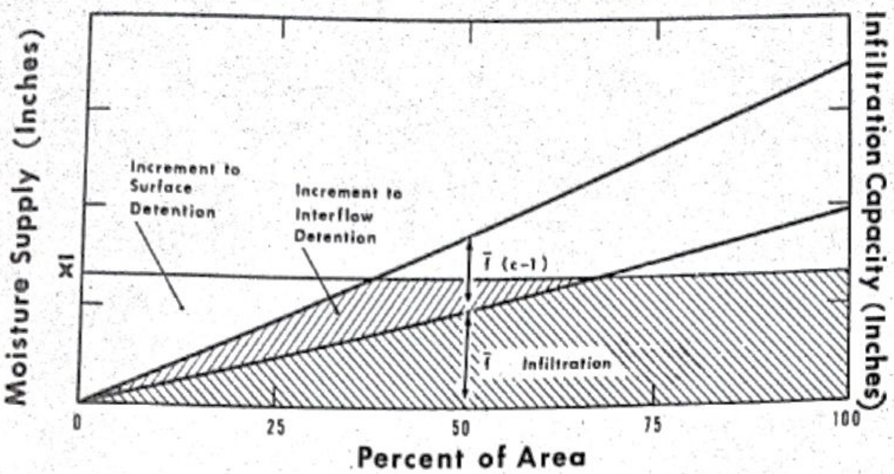

FIGURE 2-4
Graph of the function defining the position of the interflow line on Fig. 2-5.

ume, therefore, includes surface runoff and interflow. The fraction of interflow will be larger when soil moisture is high and lower when soil moisture is low. The interflow function (Fig. 2-4) is a function of the lower zone moisture ratio. As in the case of infiltration, the level of this function is adjusted by an input parameter *INTERFLOW*. Figure 2-4 defines a variable c which fixes the position of the upper sloping line of Fig. 2-5 at a mean rate of fc. As an equation:

$$c = INTERFLOW \cdot 2^{(LZS/LZSN)} \qquad (2\text{-}6)$$

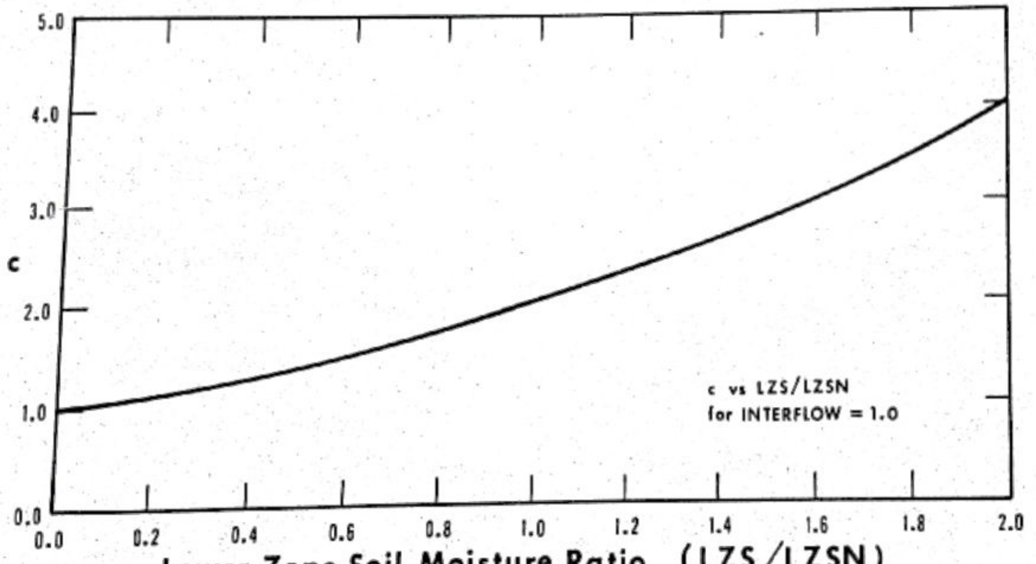

FIGURE 2-5
Variation of interflow and infiltration over a watershed, showing method of estimating interflow and surface runoff.

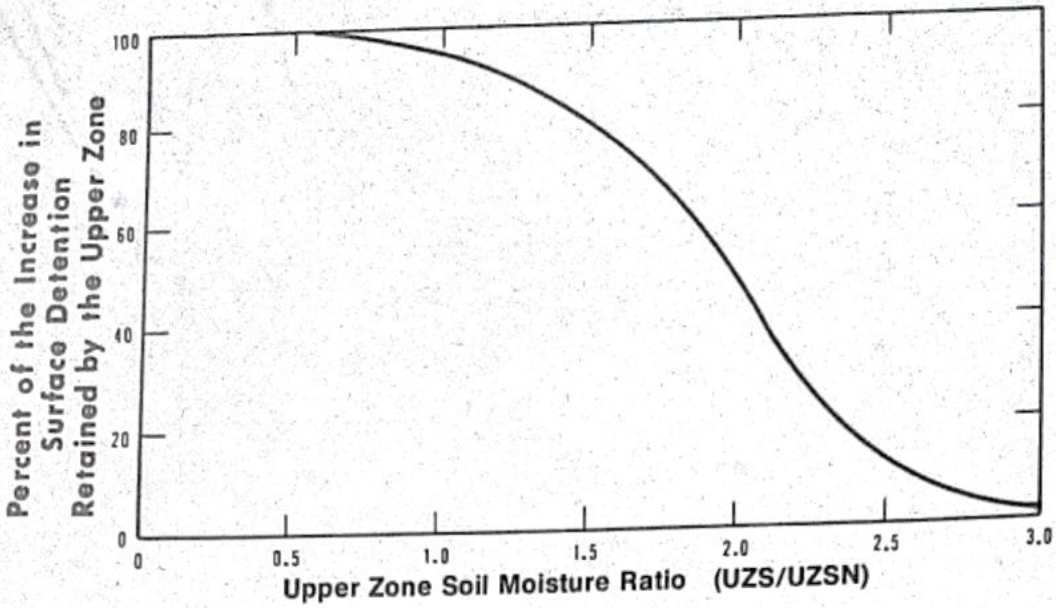

FIGURE 2-6
Graph of function defining the fraction of new water retained in the upper zone storage.

This divides the surface detention triangle into two portions—surface runoff detention and interflow detention.

Since the interflow function does not alter the volume of direct runoff, its role in simulation is primarily through its effect on the shape of the hydrograph.

Upper zone storage The infiltration-interflow function defined a quantity of interflow and surface runoff detention. The detention volume must move over the surface soil enroute to the stream, and while so moving it is subject to retention in the upper zone. Figure 2-6 defines the percentage of this detention which is retained in the upper zone as a function of the upper zone storage ratio ($UZS/UZSN$). As would be expected, the fraction retained is high when the ratio is low and approaches 0 as this ratio rises to about 3. This function thus represents delayed infiltration from the water as it moves to the stream, including infiltration from water retained in puddles and depressions.

Overland flow The portion of the overland flow detention which escapes the upper zone enters the overland flow process. Overland flow simulates the time delay incurred as the surface runoff moves over the ground surface to the stream. It also permits the occurrence of additional infiltration during the time of overland flow. Two computations are involved. The first is merely a continuity calculation of the quantity in detention D (cubic meters) at the end of a time increment:

$$D_2 = D_1 + \Delta D - \bar{Q}\,\Delta t \tag{2-7}$$

where the subscripts refer to the beginning and end of the interval, ΔD is the

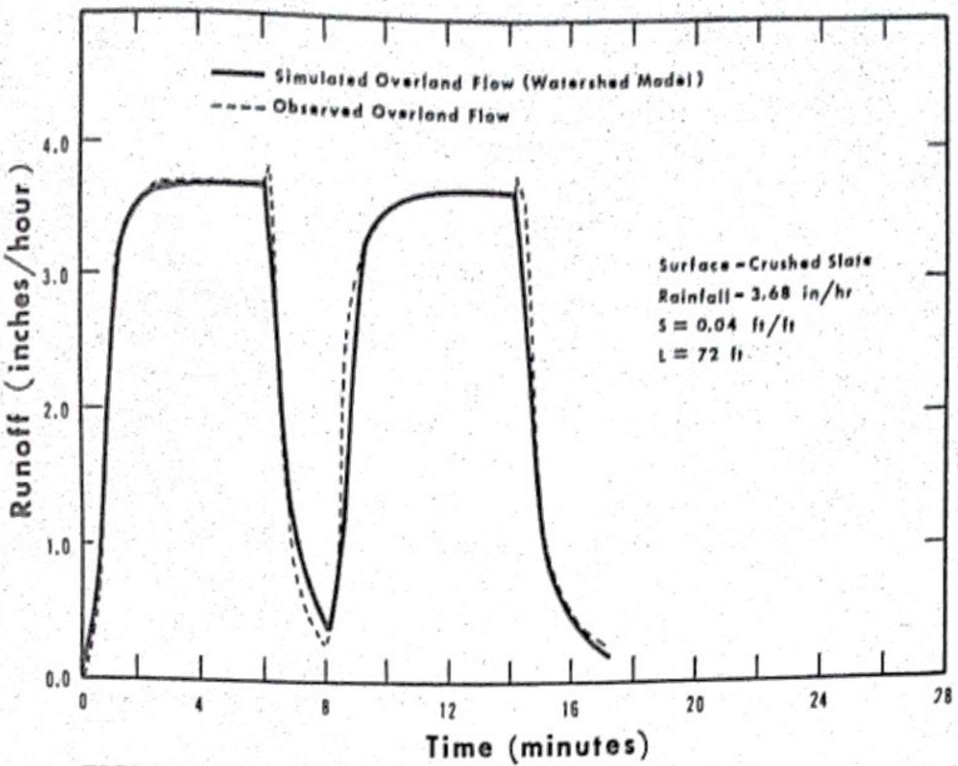

FIGURE 2-7
Comparison of simulated and observed overland flow based on experimental data by Izzard.

increment of detention added during the interval, and $\bar{Q}$ is the average outflow rate (cubic meters per second) during the interval Δt. The second computation is the determination of the outflow rate $\bar{Q}$. This is accomplished by starting with the Chezy-Manning equation:

$$Q = \frac{y^{5/3} S^{1/2}}{n} \tag{2-8}$$

where the depth y (meters) is defined by the empirical expression

$$y = 1{,}000 d \left[1.0 + 0.6 \left(\frac{d}{d_e} \right)^3 \right] \tag{2-9}$$

where d is the detention depth (millimeters) and d_e is the detention depth at equilibrium given by

$$d_e = \frac{0.00405 \; i^{0.6} \; n^{0.6} \; L^{1.6}}{S^{0.3}} \tag{2-10}$$

where i is the supply rate in millimeters per hour and n is Manning's friction factor.

Substituting Eq. (2-9) in Eq. (2-8) provides the outflow equation when values of d_e from Eq. (2-10) are used. Although Eq. (2-9) is an empirical expression, the procedure reproduces experimental overland flow results quite accurately (Fig. 2-7). Because the flow rate at the beginning of a period is used in

Eq. (2-7), an approximation is involved but the error is small if the interval Δt is short. To achieve this, the calculations are actually performed on a 15-minute interval when the input precipitation data are on an hourly basis. One-fourth of the hourly precipitation is assumed for each 15-minute interval.

To effect the overland flow calculation, the average length of overland flow L (meters), average slope S, and average roughness NN as indexed by Manning's n must be input. Obtaining these values accurately is quite difficult. Available maps are rarely adequate to define the slope of the ground and the distance to the nearest channel at a point within the watershed. In addition, these values may vary widely within a segment. Selection of proper average values is, therefore, quite subjective. Fortunately, the overland flow computation deals with a process generally of secondary importance. Its first role in simulation is to account for the time delay which takes place in overland flow. On large watersheds, this is negligible compared to the delays in channel flow, but on small watersheds the overland flow delay may be greater than the channel delay. Hence, inclusion of an overland flow function permits the model to be applied to watersheds of all sizes. However, in dealing with very small watersheds, it is important to provide the best possible estimates of the overland flow dimensions.

The second role of the overland flow computation is to simulate the delayed infiltration occurring during the overland flow process. This is accomplished in HSP by adding the detention volume at the end of any time interval to the rainfall increment for the next interval *before* the infiltration function. Thus, any water remaining in detention at the end of an interval is subject to infiltration and assignment to interflow. Delayed infiltration is an important part of the infiltration process and cannot be effectively treated simply by use of the direct infiltration process at the time the rain reaches the ground. Thus, although definition of the physical dimensions of the overland flow process is difficult, its inclusion in the simulation provides for adjustments to runoff volume and timing which are in the right direction and, as between two watersheds with greatly different characteristics, in the correct relative magnitude.

Outflow from the overland flow process Q is stored for later computations in the channel routing process.

Interflow discharge Water assigned to interflow enters interflow storage. Outflow from interflow storage to the stream ($INTF$) takes place in accordance with a linear function of storage defined by the equation

$$INTF = \alpha \cdot SRGX \tag{2-11}$$

where $SRGX$ is the current volume of water in interflow storage. If a 15-minute interval is being used:

$$\alpha = 1 - (IRC)^{1/96} \tag{2-12}$$

where IRC is the conventional recession constant, the ratio of interflow rate at any time to the interflow rate 24 hours earlier.

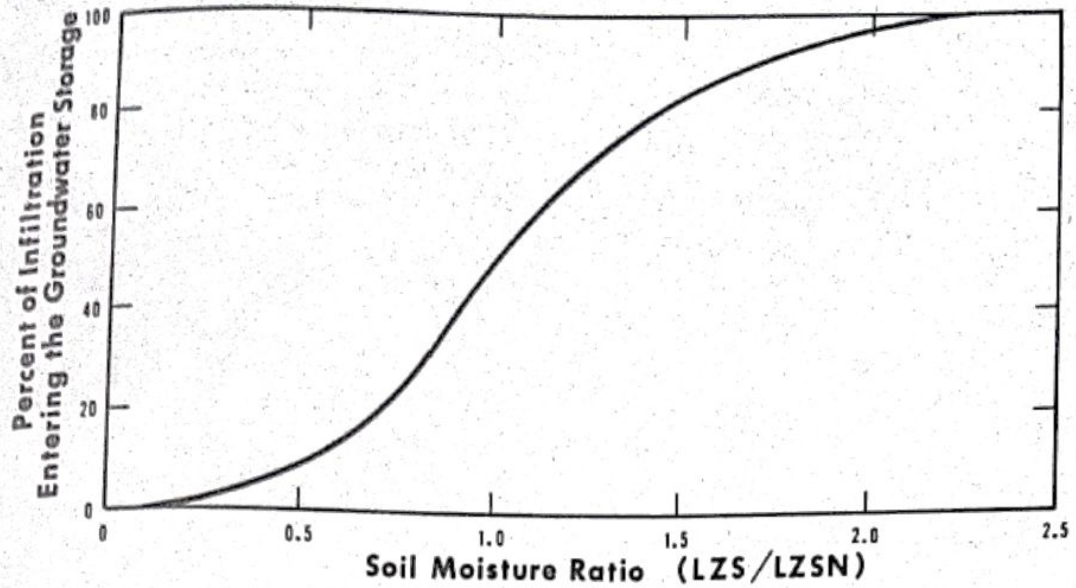

FIGURE 2-8
Graph of the function defining the fraction of infiltrated water entering the ground-water storage as a function of lower zone soil moisture.

Upper zone depletion Water temporarily retained in the upper zone may move downward into the lower zone by infiltration from puddles and depressions and by downward movement out of the surface soil. One may suppose that this rate is a function of the relative wetness of the upper and lower zones. The amount of down seepage (*PERC*) is

$$PERC = 0.003 \cdot INFILTRATION \cdot UZSN \left(\frac{UZS}{UZSN} - \frac{LZS}{LZSN}\right)^3 \quad (2\text{-}13)$$

where *INFILTRATION* is the infiltration level parameter. Percolation from the upper zone occurs only when $UZS/UZSN > LZS/LZSN$. When the term in parenthesis is negative, no movement takes place.

Lower zone function The lower zone function receives the increment of infiltration and the percolation from the upper zone in each interval and divides this incoming water between lower zone storage and ground-water storage. Figure 2-8 is the graph of the function employed. When the ratio *LZS/LZSN* is very low, nearly all of the incoming water is retained in the lower zone. As the ratio rises to unity, incoming water is divided evenly between the two storages and when the ratio is above 1.0, the larger portion moves directly to ground water.

Ground water Accretion to ground water through the lower zone function goes to the ground-water function. In some watersheds, it can be determined that some ground water percolates below the lowest point in the stream channel and never reappears in the channel as ground-water flow. If this is believed to occur, a fixed percentage of each increment of accretion is diverted to deep or inactive ground-water storage, and the balance moves to the active ground-water storage (SGW). The water going to deep storage is lost from the system. Since the model is for surface water, only water which may eventually appear as streamflow is of interest. The diversion to deep storage is used solely to maintain the water balance. Conceivably, however, the amounts diverted to deep storage could be useful information for a study concerned with ground-water recharge.

Water in active ground-water storage is released to the stream by depletion of the storage. The equation is

$$GWF = \beta\,(1 + KV \cdot GWS) \cdot SGW \qquad (2\text{-}14)$$

where GWF is the increment of ground-water flow, SGW is the current quantity of ground-water storage, and β a depletion constant related to the ordinary ground-water recession constant by

$$\beta = 1.0 - (K_{24})^{1/(24/\Delta t)} \qquad (2\text{-}15)$$

where K_{24} is the ratio of the ground-water flow at any time to that 24 hours earlier and Δt is the time increment of the computation in hours. It is frequently observed that the ground water seems to recede somewhat more rapidly immediately after a significant runoff event. The term $KV \cdot GWS$ in Eq. (2-14) allows for this by making the ground-water depletion rate a function of a ground-water storage index (GWS) which is defined as

$$GWS_t = 0.97\ (GWS_{t-1} + \Delta SGW) \qquad (2\text{-}16)$$

A value of KV can be selected so that the depletion rate will gradually shift from a higher initial value to β as GWS decreases between storms when there is no accretion to ground water.

Evapotranspiration Evapotranspiration proceeds continuously from the several storages, subject to the limitation of the current PET. The hierarchy of evapotranspiration is as follows:

1 Interception storage at the potential rate
2 Upper zone storage at the potential rate
3 Shallow ground water at the potential rate
4 Lower zone storage at a rate dependent on $LZS/LZSN$

Evapotranspiration from shallow ground water occurs when an input parameter $K_{24}\,EL$ is assigned a nonzero value. This value is the fraction of the segment area with water table sufficiently close to the surface for transpiration by vegetation.

Evapotranspiration from the lower zone is estimated on the basis of an evaporation opportunity assumed to vary linearly over the watershed (Fig. 2-9). It is assumed that some point in the watershed will have no water available for evapotranspiration and that some other point will have a maximum r with a linear variation in between. The position of the line is determined by the

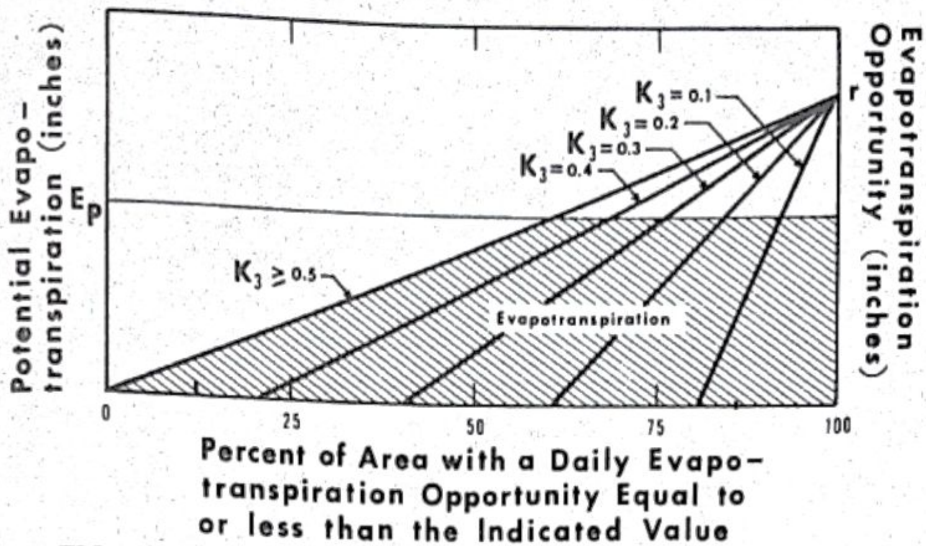

FIGURE 2-9
Graph illustrating assumed variation of evapotranspiration opportunity in a watershed segment and illustrating the method of calculating actual evapotranspiration.

value of r, which is given by

$$r = \left(\frac{0.25}{1 - K_3}\right)\left(\frac{LZS}{LZSN}\right) \tag{2-17}$$

and from trigonometry, the actual evapotranspiration rate is

$$E = E_p^* - \frac{E_p^{*2}}{r} \tag{2-18}$$

where E_p^* is the current potential evapotranspiration reduced by any portion utilized for evapotranspiration from the interception or upper zone. K_3 is an input parameter reflecting the fraction of the watershed with deep-rooted vegetation. If $K_3 < 0.5$, then a fraction of the segment given by $(1 - 2K_3)$ is assumed to have zero-evapotranspiration opportunity from the lower zone.

Hourly potential evapotranspiration is determined from the input daily values by assuming a fixed diurnal distribution. Since the effect of evapotranspiration is an accumulative one, minor errors in the diurnal distribution or in the assumption of a constant daily rate for a 15-day period are of little consequence.

2-12 CHANNEL FLOW SIMULATION

The calculations just described determine a channel inflow or land surface runoff which is the sum of impervious area runoff, overland flow, interflow, and ground-water runoff. The Stanford Watershed Model (and most variants of it) employed a modified Muskingum routing procedure.[10] This required that a channel time-delay histogram be input. The histogram is constructed by drawing isochrones of equal delay time from the outlet on a map of the watershed and determining the fraction of the area between successive isochrones. The runoff for the appropriate segment is multiplied by the percentage of the watershed area within the band and assigned to a time interval appropriately delayed after the occurrence of rain. The result is a hydrograph expressed in millimeter depth over the watershed and translated to the outlet of the watershed. Multiplying by watershed area converts to flow rate in cubic meters per second. The translated flows can then be routed through a hypothetical reservoir with storage equivalent to that of the channel system. The routing equation of the SWM is

$$O_2 = \bar{I} - k\,(\bar{I} - O_1) \tag{2-19}$$

where O_1 and O_2 are outflows at the beginning and end of an interval, $\bar{I}$ is the average inflow rate for the interval from the translated flows, and k is a routing coefficient determined from the usual Muskingum K by

$$k = \frac{1/K - \Delta t/2}{1/K + \Delta t/2} \tag{2-20}$$

where Δt is the routing interval.

The Muskingum routing procedure is simple and fast, but it suffers from the assumption of linear storage on which it is based. This can be overcome by making k a function of flowrate, but the fact that k is an empirical routing constant remains, and no very solid basis for its selection exists. The value of k is quite dependent on the flow velocities assumed for the construction of the time-delay histogram. While a satisfactory combination of routing parameters can be determined by trial, the appropriate values to be used to simulate a change in the channel or for an ungaged watershed are difficult to estimate.

The kinematic routing method[40] has been demonstrated to be reliable as long as the Froude number of the flow is less than 2, a condition usually satisfied in hydrologic studies. Use of the kinematic assumption complicates the programming and increases computer run time. Nevertheless, it offers many advantages for simulation. Kinematic routing employs a continuity equation:

$$(\bar{I} - \bar{O})\,\Delta t = \Delta s \tag{2-21}$$

where $\bar{I}$ and $\bar{O}$ are the average rates of inflow and outflow for the interval Δt, and Δs is the change in storage. The second equation must relate flow velocity to stream characteristics (cross-section slope and roughness) and to the stage. The Chezy-Manning equation is convenient for this purpose.

The algorithms for kinematic routing may be formulated in a number of ways. In essence, given a set of initial conditions in the reach and the inflow to the reach during a routing period, a stage at the end of the period must be found which is consistent with the quantity of storage from continuity and the required outflow rate from the flow equation. The kinematic method has been discussed by several writers[41,42] and will not be discussed in great detail here.

If the kinematic procedure is adopted, the channel system of the watershed must be divided into reaches of appropriate length. The dimensions of the cross section at the lower end of each reach and the length and slope of the channel must be input. Inflow to a reach is the outflow of the upstream reach plus local inflow calculated from the simulated land surface runoff of the appropriate segment and the size of the contributing local area. The routing is performed successively reach by reach through the system to the outlet of the basin.

Use of the kinematic routing permits output of flow and stage data at the end of each reach. Stage data cannot be obtained directly with the Muskingum method, and it would be very awkward to obtain flow data at many points. With the kinematic approach, a reach can be replaced by a reservoir, and diversions into or out of any reach can be simulated. This would be possible only with difficulty using Muskingum routing on a small basin. Since the cross sections of the stream are input, the dimensions of the flood plain can be included, and overbank flow is simulated reach by reach as appropriate. This is more logical than attempting to simulate it with a variable routing constant in the Muskingum approach. Finally, the kinematic routing can be utilized in circular conduits for simulation of urban storm-drainage systems.

2-13 PARAMETERS AND CALIBRATION

Any simulation model requires a substantial number of input parameters. The parameter descriptions for HSP are shown in Table 2-1. While the number of parameters might be reduced somewhat by omitting some of the functions within the model, this can only be done at the expense of losing the generality of the model and quite possibly with some loss of accuracy. Most of the less important functions are quite simple, and little, if any, computer time would be saved by their omission. Thus, the current parameter list may represent a practical minimum. In fact, it would not be surprising that future simulation models operating on larger computers will attempt to employ more parameters. For example, the lower zone may be subdivided into two (or more) zones for better moisture accounting.

Fortunately, most of the parameters utilized in HSP can be determined from maps or other data before simulation. Only four parameters cannot be so determined: the upper and lower zone nominal capacities ($UZSN$ and $LZSN$), the infiltration level parameter ($INFILTRATION$), and the interflow parameter ($INTERFLOW$). It is reasonable to hope that these parameters can be defined by correlation with soil characteristics so that reasonably accurate first estimates will be possible. This will require determination of these parameters by trial on a large number of watersheds for which the necessary information on soil characteristics is available. Until that time, these parameters are determined by *calibration*.

The calibration process involves an initial assumption of parameter val-

Table 2-1 **PARAMETERS OF THE HYDROCOMP SIMULATION PROGRAM**

Lands	
K_1	Ratio of average segment rainfall to average station rainfall
A	Fraction of watershed that is impervious
EPXM	Maximum value of interception storage
UZSN	Nominal capacity of upper zone storage
LZSN	Nominal capacity of lower zone storage
K_3	Evapotranspiration rate parameter
$K_{24}L$	Fraction of ground-water accretion which percolates to deep ground water
$K_{24}EL$	Fraction of area with shallow water tables subject to direct evapotranspiration
INFILTRATION	Relative infiltration index
INTERFLOW	Interflow index
L	Length of overland flow (meters)
SS	Slope of overland flow (meter per meter)
NN	Manning's *n* for overland flow
IRC	Daily interflow recession constant
KK_{24}	Daily ground-water recession constant
KV	Factor to permit variable ground-water recession
Snowmelt	
RADCON	Factor to adjust radiation melt calculated by theoretical equation; should be near 1.00
CONDS CONV	Factor to adjust convection-condensation melt calculated with theoretical equation; should be near 1.00
SCF	Factor to correct precipitation gage catch to allow for snowfall
ELDIF	Difference in elevation between temperature station and mean elevation of segment (meters)
IDNS	Initial density of new snow
F	Fraction of area with forest cover
DGM	Daily groundmelt (millimeters)
WC	Maximum permissible water content of snowpack by weight
MPACK	Water equivalent of the snowpack at the time when the segment is completely snow covered
EVAPSNOW	Factor which adjusts calculations from the theoretical snow evaporation relations; values near 1.00 are expected
MELEV	Mean elevation of segment (meters)
Channel	
RCH	Reach number
TYPE	Rectangular, circular, or reservoir
TRIB-TO	Next reach downstream
SEGMT	Segment number controlling runoff for this reach
LENGTH	Reach length (kilometers)
TRIB-AREA	Area tributary to reach (square kilometers)
EL-UP	Elevation at upstream end of reach
EL-DOWN	Elevation at downstream end of reach
W_1	Bottom width (meters)
W_2	Bankful width (meters)
H	Channel depth (meters)
S-FP	Transverse slope of the flood plain
N-CH	Manning's *n* for channel
N-FP	Manning's *n* for flood plain
DIA	Diameter of circular channel (meters)
NN-CH	Manning's *n* for circular channel
DAM	Dam number
MAX-ELEV	Maximum pool elevation (meters)
SPILLWAY-CREST	Elevation of spillway crest (meters)
MIN-POOL	Elevation at minimum pool (meters)
STORAGE-MAX	Maximum storage (cubic meters)
STORAGE-NOW	Current storage
CONTROLLED	Maximum turbine discharge
SURFACE-AREA	Surface area at full pool (square kilometers)
RULES	Number of rule curves to be entered
USE-RULE (*,*)	Number of rule curves to be used for specified day or month

ues, a trial simulation on a test period, a comparison of observed and simulated flows for the calibration period, and an adjustment of parameters to yield a more correct simulation. The process may be manual or computerized. That is, the evaluation of the results and selection of new parameters may be a matter for the operator's judgment, or an objective function may be programmed and the computer instructed to iterate through parameter values in search of an optimum set of values. The choice is one of economics and practicality. It appears quite impractical to perform an automatic optimization on a multisegment basin with 1975 computers. Optimization of parameters for a single segment basin has been demonstrated,[43,44,45] but the problem becomes vastly larger when there are two or more segments on which the iteration must be performed.

On a single-segment watershed, the questions are (1) can a meaningful objective function be found and (2) is computerized optimization less costly than manual optimization? An appropriate objective function is by no means simple to design. The sum of squares of departures between computed and observed flows, the correlation coefficient between observed and simulated mean daily flow, and other more sophisticated measures have been tried. None has been entirely successful. Errors may be expected both in flow and time. An objective function based on simultaneous flow values may give misleading results where timing errors occur. Moreover, some errors result from input data errors, and with a very good simulation model, these errors may be larger than the errors resulting from defects in the simulation algorithms. Such errors may occur where a major peak flow exceeding the highest meter measurement must be estimated by indirect methods or during the occasional storm where the rainfall input is not representative of the basin rainfall. If a squared error function is used, these large errors may far outweigh other errors and force parameters which are not really representative of the watershed. These are not necessarily arguments against automatic optimization, but they suggest that care must be taken in developing such a procedure.

Automatic optimization requires repeated iteration of the calculations to identify the "best" parameters. The more detailed and sophisticated the basic model, the more costly the optimization. Thus, a very simple model or one operating on a relatively large time increment can be optimized relatively inexpensively. The temptation will also exist to use a relatively short sample—1 or 2 years—in calibration to minimize cost. Experience has shown that parameters derived from a single year of record may be quite far from optimal. The alternative is, of course, to allow the operator to adjust parameters between operations on the basis of his judgment on the required corrections. If his judgment is good, fewer iterations will be required. The operator must, however, be intimately familiar with both the model and the parameters employed. In batch operation, operator optimization will take much longer because of the increased delay between iterations. However, if a model is set up in a time-sharing mode and a graphic terminal is employed to display both observed and calculated hydrographs, the process can be quite fast.

With the HSP, it has been found most effective to first calibrate the functions for land surface runoff until monthly and annual flow volumes are as close to the observed flows as possible. Only when the volume calibration is correct is an attempt made to adjust for hydrograph shape using the channel routing module. This process minimizes computer time and reduces the number of parameters to be considered in each phase of the calibration. If the volume parameters are not correct, very little is gained by attempting to adjust the parameters controlling hydrograph shape. Automatic optimization of volume parameters could be relatively simple because timing errors will not seriously affect the objective function.

2-14 ACCURACY OF SIMULATION

A discussion of rainfall-runoff models would not be complete without some discussion of accuracy, but it is extremely difficult to generalize on this topic. Errors in simulation are caused by deficiencies in the model, by errors and inadequacies in the input data, and by the improper selection of parameters. A program which appears to give excellent results on one watershed may be quite poor on another, either because the input data for the second watershed are poor or because the model is not sufficiently general to cope equally well with two differing hydrologic regimes.

What seems quite clear is that simulation with a good water-balance model is substantially more accurate than older hydrologic methods and, if properly calibrated and with adequate input data, can yield results within the limits of accuracy of the data used for verification (Fig. 2-10). On the other hand, accuracy of simulated flows will deteriorate rapidly if the calibration is poorly done or if the input data are seriously inadequate. However, even with poor data, simulation will usually give better results than conventional methods because it utilizes all the data and is not dependent on a few values.

Errors in simulation are most critical during the calibration phase. If rainfall data are not representative of the storm events over a watershed, calibration of a model will be difficult; i.e., it will be hard to get agreement between observed and simulated flows on a specific date. This condition is frequently encountered on a small watershed subject to thunderstorm rainfall, particularly if the rain gage is outside the watershed. On the other hand, if a long period of record is simulated under these conditions and if the calibration is free from bias, the errors will usually be random, and the frequency curve of flood peaks or the flow duration curve will be simulated quite accurately. This may be stated in another way; namely, if the input precipitation data has the same frequency characteristics as those experienced on the watershed, the probability characteristics of the flow may be simulated accurately, although the peak-by-peak or day-by-day agreement is relatively poor. For application in water-project design, the probability characteristics of the flow are of primary

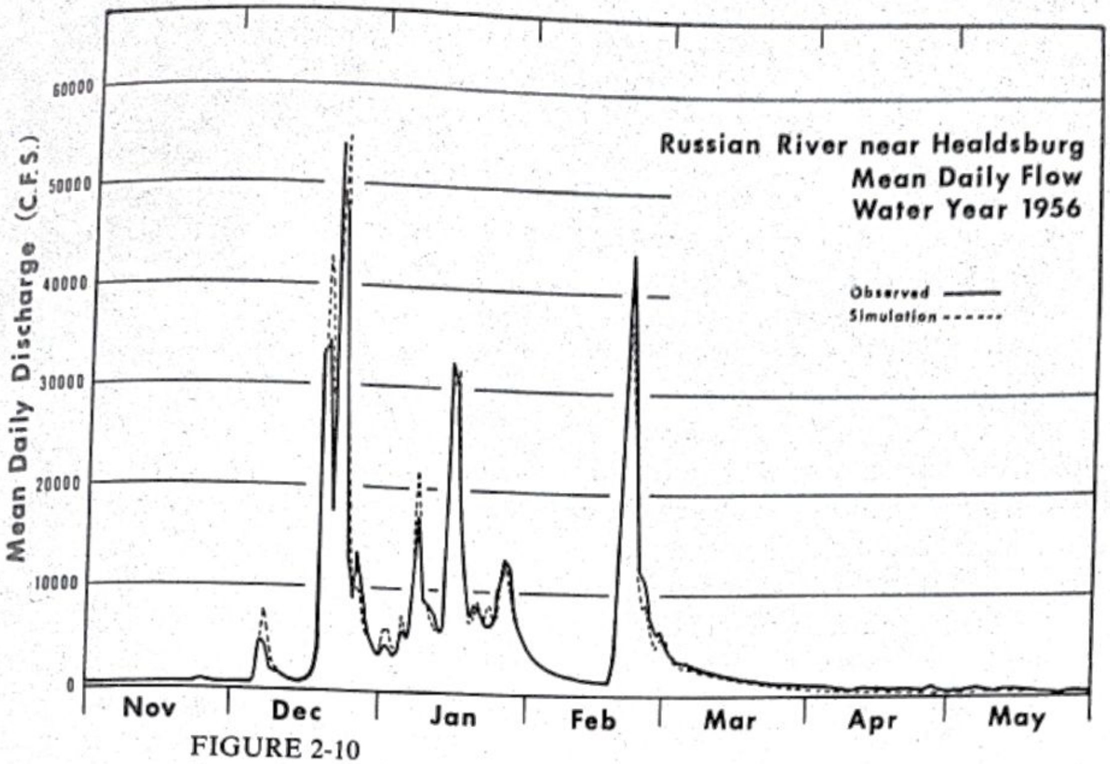

FIGURE 2-10
Comparison of observed and simulated mean daily flows for Russian River near Guerneville, California, for 1956 water year.

interest. For forecasting of flow, the simultaneous comparison of observed and predicted flow is important. Thus, the design application can be made successfully with data which would be unsatisfactory for forecasting.

In summary, it can be said that a fully general model can simulate flow within very close tolerances on any watershed for which adequate physical data and hydrometeorologic data are available. Simplified models developed for particular basins may do as well on the basins for which they are developed but may be considerably less adequate when applied in different hydrologic regimes. In general, simulation will be more accurate on large watersheds, because the basin storage modifies the flow and attenuates the effects of both input and simulation errors.

2-15 SIMULATION OF SNOWMELT

Simulation of snowmelt is a more difficult task than simulation of runoff from rainfall, because it is usually necessary to simulate snowfall and snow accumulation. Data on water equivalent of snowfall and snow on the ground are not usually available on even a daily basis. Thus, the occurrence of snow must be estimated from precipitation and concurrent temperatures, and a continuous accounting of the water equivalent and density of the snow on the ground must be programmed.

The primary sources of heat for snowmelt are solar radiation, warm air, condensation of water vapor, heat content of rainfall, and heat from the underlying ground; groundmelt is small and can apparently be adequately simulated by assuming a fixed rate of 0.25 to 0.5 mm/day. Rainmelt can be calculated by assuming that the temperature of the rain equals the air temperature—not a bad assumption during rainfall when the wet-bulb depression would be small.

The other melt factors are more difficult. A fairly comprehensive study of snowmelt is available,[46] but the data problem is critical. If solar radiation data are, in fact, available for use, an albedo must be estimated for the snow pack in order to calculate the reflected short-wave radiation and long-wave radiation must be estimated from the snow-surface temperature in order to calculate net radiation. If radiation data are not available, clear-sky radiation and cloudiness data may be a useful substitute. Convective melting by warm air is dependent on wind velocity and air temperature. Temperature data are usually available, although often an assumption as to the change in temperature with elevation must be made to adjust station temperatures to the snow-pack elevation. Because of this, it is convenient to utilize watershed segments which are elevation zones when snowmelt is simulated in mountainous watersheds. A separate accounting of snowmelt, water equivalent, and density is carried for each elevation zone. Wind data are less likely to be available, but if reasonable estimates of wind at the snow-pack level can be made, equations for convective melt can be applied. Condensation melt is dependent on wind speed and the vapor content of the air, which can be determined from dewpoint temperature. Dewpoint temperature is often not available, but estimates can be based on minimum temperature, which under conditions of radiative cooling will often closely approximate the dewpoint.

If necessary data cannot be obtained or estimated with reasonable accuracy, it is possible to fall back on a simple degree-day computation, but this will be considerably less satisfactory than use of the more complete melt equations.[47,48] It can be expected that snowmelt simulation will be less reliable than simulation of rainfall-runoff because of the data limitations and the much more complex simulation required. If the accounting of snow water-equivalent on the ground is in error, the simulated melt volumes are necessarily in error. Snowmelt rates computed by the type of simulation described above are, of course, not runoff rates. The simulated melt must be used in lieu of (or in addition to) rainfall as input to the basic runoff simulation discussed earlier in order to account for storage and delay in the soil, in overland flow, and in the channels. Here again, some further uncertainty may be introduced because of ice-layering in the snow or at the soil surface, which may prevent infiltration, and by ice on the streams, which will alter the channel-flow characteristics.

Despite the difficulties described above, snowmelt simulation must be considered a useful tool and a considerable advance over other methods. The ability to treat the process in detail both in space (by using elevation zones) and in time (by calculating on a hourly basis) makes it possible to simulate flow more accurately than by methods which treat the basin as a whole and utilize average values of temperature as the sole index of melt.

2-16 SIMULATION OF OTHER HYDROLOGIC FACTORS

Given the basic precipitation-runoff simulation model, simulation of other hydrologic factors is possible. Negev[49] and Fleming[50] demonstrated the feasibility of simulating sediment transport. Erosion results largely from the impact of raindrops.[51] Since short-interval rainfall is an input for flow simulation, it may also be used as an index to the erosion process. Transport of the eroded material over the soil surface to a channel occurs primarily in overland sheet flow. Downslope splash also contributes, but the rate of movement is relatively slow. Since overland flow is calculated in a flow simulation model, it is fairly direct to incorporate sediment transport algorithms. The final transport mechanism is in the channel, and this can also be conveniently simulated. If a routing procedure is used which calculates flow velocity reach by reach, it should be possible to treat both bed load and suspended load (except for the problem of obtaining data for verification of the bed-load transport). Negev obtained excellent results with the SWM using a Muskingum-type routing. His results are a good verification of the adequacy of the overland flow computations, since in no case did he simulate significant sediment transport which did not occur, nor did he fail to simulate any significant sediment transport events which were observed. However, not every case of rainfall resulted in sediment outflow, because overland flow did not occur in many of the lesser storms.

Other water-quality parameters can be simulated in conjunction with a flow-simulation model. The concentration of dissolved salts depends on the relative quantities of ground water and surface water in the flow, which is readily determined from the flow-simulation model. Huff[52] was reasonably successful in simulating the streamborne quantities of fallout radionuclides using a version of the SWM. Water temperature, dissolved oxygen, algae, and other quality parameters can also be simulated.[61,62]

In discussing simulation of quality parameters, a distinction between continuous simulation models and steady-state models should be drawn. A number of models for simulating stream-water temperature, dissolved oxygen, salinity, and other parameters have been developed. These are steady-state models, in that a given flowrate is assumed and the models indicate the variation in the quality parameter with time or distance downstream from a location where the pollutant is injected. Some models are designed to simulate the effect of multiple injection points along the stream. A model which can provide continuous simulation over time of the variation in load or concentration of natural and man-made pollutants in streamflow on the basis of rainfall data and schedules of man-made inputs is needed. Such continuous simulation is essential if probability concepts are to be employed in pollution studies.[63]

2-17 APPLICATIONS OF SIMULATION

The most obvious application of hydrologic simulation is for the extension of streamflow records. Given precipitation records which are longer than the available streamflow record, an extension of the streamflow record can be made. A study by Ott[53] has shown that estimates of flood frequency based on short records can be quite unreliable and that even the mean and variance of monthly streamflow cannot be determined accurately with short records. Thus, for flood-frequency estimation or for an improved data base for stochastic analysis, flow extension can be helpful.

Simulation programs can also be used for flow forecasting, for design of urban drainage,[63] highway culverts, small reservoirs, and in many other situations where a total lack of streamflow data has in the past forced the use of empirical or approximate methods. Application of simulation to ungaged watersheds requires that parameters be estimated from one or more gaged watersheds nearby. These parameters can then be used as determined or adjusted subjectively for application to the ungaged watershed. For this procedure to be effective, parameters should have physical significance so that there is some reasonable basis for adjustment. While no existing model utilizes parameters which are rigorously related to the physical process, it is apparent that simplified models which ignore portions of the runoff process or lump parts of the process into a single function are less likely to be useful.

Since the essence of system operation is forecasting, simulation is a tool of considerable potential for water-system operation. A simulation model can not only forecast flow but also simulate the operation of the system. The best operating procedure could be found by trial if other means cannot be used.

Probably the most significant utility of simulation programming is its ability to predict the effects of change. Statistical and empirical relations can, at best, indicate the expected flows from a watershed in the condition that prevailed when the relationships were derived. Rarely can such relationships indicate the quantitative effect of the changes. Simulation techniques using a water-balance model with physically based functions has the potential to reproduce the flows which would have occurred under historic climatic sequences if the change had been in effect. Changes brought about by man can affect the hydrologic regime of a watershed in four ways: change in evapotranspiration (vegetation management, forest fires), change in infiltration (soil amendments, impervious cover), change in overland-flow hydraulics (land grading, terracing), and change in channel hydraulics (reservoirs, levees, channel improvements). To these must be added the possibility of weather modification.[64] A well-calibrated model with its parameters properly adjusted for the changed conditions can quickly reproduce the entire historic flow series for comparison with observed flows. Peaks, runoff volumes, low flows, and recession rates can all be compared and the effects determined. If no historic flow record exists for comparison, it too can be simulated, albeit with somewhat less certainty.

It should be noted that many (if not most) of the available flow records include the effect of changes in the watershed during the record period. If the effect is large, the historic record is not homogeneous and is inappropriate for analysis of peak frequency, reservoir yield, etc. Here again, simulation calibrated on the most recent record can provide an adjusted record for analysis. If the data are to be used for long-range planning, it is appropriate to use simulation to produce a flow series representing the conditions to be expected in the future. Obviously, this depends on a forecast for future changes, which may not actually be realized; but all planning must deal with this type of uncertainty, and it is surely better to adjust in the right direction rather than not adjust at all.

Simulation would seem to have potential as a supplement to a stream gaging program. It is probable that all streams where data may be needed will never be gaged. A program could be initiated in which stream gages are installed temporarily at locations where no need for a permanent station exists. After a period of 3 to 10 years when sufficient data had been accumulated for a good calibration of a flow-simulation model, the station might be moved and the simulation considered the source of flow data, if and when it is needed. The physical condition of the watershed at the time of calibration should be well documented with maps, aerial photography, and terrestrial photos of the channel system so that parameter adjustment could be made, if needed, as the result of change.

Finally, simulation should prove to be a useful research tool in hydrology. A calibrated model might well serve as a control in watershed experimentation, eliminating the need for a control watershed and the ever-present doubt about the similarity of paired watersheds. Analysis of data collected by simulation could provide a running check on an experimental watershed and alert the operators to unsuspected changes, the need for additional data, etc. Simulation might be used to predict the effect of experimental changes, to give assurance in advance that the effects will be of detectable magnitude. Real time forecasts could also be used to alert field crews to the need for specific observations required under special conditions.

2-18 STOCHASTIC METHODS AND SIMULATION

Stochastic applications in hydrology were the other major development of the 1960s fostered by computers. There appears to be a substantial opportunity for stochastic methods and simulation to demonstrate a very useful complementarity. The critical constraint on stochastic methods lies in the fact that stochastically generated flows are only as reliable as the parameters of the distribution used in their generation. As yet, appropriate specifications for reliability are only imperfectly known. Burges[54] studied the record of Arroyo Seco in California and found that 33-year samples gave notably different parameters than the 65-year record. Ott[53] found that a record length of nearly 100 years was necessary on Dry Creek in California and Fisher River in North Carolina to obtain stable values of the mean and variance. Serial correlation and skew, both important parameters in stochastic studies, require a long record length. Slade[55] states:

> Skewness is never a truly significant characteristic when the sample from which it is computed contains less than 140 items . . . and it is quite meaningless to use this measure when there are fewer than 50 items. (page 426)

Anderson's test[56] suggests that with record lengths of 100 years a calculated serial correlation of 0.2 is not significantly different from zero at the 0.95 confidence limit.

Thus, it would appear that application of the usual stochastic methods to streamflow records of less than 50 years in length may yield seriously misleading results. An obvious step to correct this is to extend the streamflow record by simulation. If a record of 20 years can be extended to 50 years, the reliability of the parameters will be greatly enhanced. While it may be argued that the simulated data are not as accurate as the observed data, and therefore the effective length of the extended record is less than 50 years, the uncertainty based on the short record is so large that an extension of almost any effective length is better than no extension. The comments earlier in this chapter about the nonhomogeneity of many long streamflow records because of man-made (or natural) changes in a watershed are also relevant. It is quite possible that even a long record should be adjusted by simulation to current (or future) conditions before parameters for stochastic analysis are calculated.

A second alternative is to consider the rainfall inputs as the stochastic element, since it is the variability in rainfall (and evapotranspiration) that really induces the variability in streamflow. Starting from this assumption, a stochastic generator for producing daily[57] or hourly precipitation[58,59,60] might be developed. A long stochastic series of rainfall would be generated, and a simulation model would be employed to convert this record to flow. A fairly short precipitation record yields a large number of daily (or hourly) values so that the parameters of the distribution may be determined with some certainty. No significant evidence of long-term serial correlation in precipitation has been advanced so that this factor is less important. Using short-interval rainfall, one is also less concerned with the tail of the distribution. A single hour (or day) of excessively heavy rainfall does not introduce the major perturbation in the streamflow that might result from several hours (or days) of moderate to heavy amounts. Maximum or minimum months or years in the flow series are dependent not on a single random selection in the stochastic generator but on many selections. Finally, this procedure produces the entire synthetic streamflow record in detail as to peaks, flow minima, etc., which provides detail not possible with the usual monthly stochastic flow generator.

One must, of course, take the results of a procedure such as that suggested above on faith because there is really no way in which it can be shown that a stochastically generated sequence is valid. This constraint applies with equal force to a synthetic flow sequence generated from streamflow parameters.

Ott[53] employed the techniques suggested above to generate two 500-year flow sequences (Dry Creek in California and Fisher River in North Carolina). The derived sequences were used to study the period of record required for flood-frequency analysis and the type of distribution best fitting the long flood records.

2-19 FUTURE OF SIMULATION

It has already been suggested that simulation is in all probability the method of the future in parametric hydrology and that it may be useful as a complementary tool in stochastic hydrology. This is not meant to suggest that simulation has reached its maximum development. Future generations of computers with larger core storage and faster computational time will certainly permit further refinements in simulation programming. Precisely what refinements will be developed cannot be said with certainty. Possibly some empirical functions will be replaced by more physically based functions. Possibly new functions will be added—for example, it may someday be practical to deal with two (or more) layers of lower zone storage. Perhaps upper zone storage will be separated into depression storage and upper zone soil moisture.

Whatever the developments in simulation programming, it is quite clear that better field data will be necessary before a substantial improvement is made. Theory governing soil moisture movement is currently well advanced, but field data which will permit definition of the hydraulic conductivity of two or more soil layers is not yet available.[37] If they were, they might be of limited value, since rainfall stations are so widely spaced that any conductivity values must be averaged over a very large area. Possibly radar will some day[60] provide the detailed rainfall input which will permit simulation in a quasi-distributed sense; i.e., segment sizes might be substantially reduced. This will probably not be possible practically until the new computing hardware is at hand. Thus, one may expect incremental advances in simulation technology until an order-of-magnitude advance in data collection or computer technology permits a quantum jump. Meanwhile, current expansion of data-collecting activities should be planned with a view toward meeting the data needs of simulation. This suggests the exclusive use of recording rain gages (where feasible) with records capable of being reduced to 15- or even 5-minute intervals, which may be needed on small watersheds. An extension of networks to collect temperature, insolation, dewpoint, and wind in mountainous areas is needed for snowmelt simulation and could also be used for computing potential evapotranspiration. Data collecting procedures should be computer compatible. Computer processing of meteorologic and hydrologic data has been used because it simplified the data processing operation. Now, however, computer-compatible data output is essential for hydrologic analysis.

REFERENCES

1. BISWAS, A. K., "History of Hydrology," pp. 5–7, North-Holland Publishing Company, Amsterdam, 1970.
2. MULVANEY, T. J., On the Use of Self Registering Raingage and Flood Gages in Making Observations of the Relations of Rainfall and Flood Discharges in a Given Catchment, *Proc. Inst. Civ. Eng. Ireland*, vol. 4, pp. 18–31, 1850–51.
3. RUSSELL, T., Rainfall and River Outflow in the Mississippi Valley, *Ann. Rept. Chief Signal Officer, U.S. Army*, Part 1, Apr. 14, 1889.
4. MEYER, A. F., Computing Runoff from Rainfall and other Physical Data, *Trans. Am. Soc. Civ. Eng.*, vol. 79, p. 1056, 1915.
5. MEAD, D. W., "Hydrology," p. 513, McGraw-Hill Book Company, New York, 1919.
6. SHERMAN, L. K., Streamflow from Rainfall by the Unit-Graph Method, *Eng. News-Rec.*, vol. 108, pp. 501–505, 1932.
7. HORTON, R. E., The Role of Infiltration in the Hydrologic Cycle, *Trans. Am. Geophys. Union*, vol. 14, pp. 446–460, 1933.
8. SNYDER, F. F., Synthetic Unit Hydrographs, *Trans. Am. Geophys. Union*, vol. 19(1), pp. 447–454, 1938.
9. CLARK, C. O., Storage and the Unit Hydrograph, *Trans. Am. Soc. Civ. Eng.*, vol. 110, pp. 1419–1488, 1945.
10. MCCARTHY, G. T., "The Unit Hydrograph and Flood Routing," Paper Presented at Conference, North Atlantic Div., U.S. Corps of Eng., June 1938.
11. COOK, H. L., The Infiltration Approach to the Calculation of Surface Runoff, *Trans. Am. Geophys. Union*, vol. 27, pp. 726–747, 1946.
12. KOHLER, M. A., and R. K. LINSLEY, Predicting Runoff from Storm Rainfall, *U.S. Weather Bureau Res. Paper* 34, 1941.
13. BETSON, R. P., R. L. TUCKER, and F. M. HALLER, Using Analytical Methods to Develop a Surface Runoff Model, *Water Resour. Res.*, vol. 5, pp. 103–111, 1969.
14. SVERDRUP, H. U., The Eddy Conductivity of the Air over a Smooth Snow Field, *Geofys. Publ.*, vol. 11(7), 1934.
15. WILSON, W. T., An Outline of the Thermodynamics of Snowmelt, *Trans. Am. Geophys. Union*, vol. 22, pp. 182–195, 1941.
16. SNYDER, F. F., "Cooperative Hydrologic Investigations," pt. 11, Commonwealth of Pennsylvania, Harrisburg, Pa., 1939.

17. LINSLEY, R. K., A Simple Procedure for the Day-to-Day Forecasting of Runoff from Snowmelt, *Trans. Am. Geophys. Union*, vol. 24(3), pp. 62–67, 1943.
18. HORTON, R. E., Infiltration and Runoff during the Snow Melting Season, with Forest Cover, *Trans. Am. Geophys. Union*, vol. 26(1), pp. 59–68, 1945.
19. CHURCH, J. E., Principles of Snow Surveying as Applied to Forecasting Streamflow, *J. Agr. Res.*, vol. 51, pp. 97–130, 1935.
20. KOHLER, M. A., and R. K. LINSLEY, Recent Developments in Water Supply Forecasting from Precipitation, *Trans. Am. Geophys. Union*, vol. 30, pp. 427–436, 1949.
21. HAZEN, A., The Storage to Be Provided in Impounding Reservoirs for Municipal Water Supply, *Trans. Am. Soc. Civ. Eng.*, vol. 77, p. 1549, 1914.
22. HOYT, W. G., An Outline of the Runoff Cycle, *Pennsylvania State College Tech. Bull.* 27, pp. 57–67, 1942.
23. LINSLEY, R. K., and W. C. ACKERMANN, A Method for Predicting the Runoff from Rainfall, *Trans. Am. Soc. Civ. Eng.*, vol. 107, pp. 825–842, 1942.
24. LINSLEY, R. K., M. A. KOHLER, and J. L. H. PAULHUS, "Applied Hydrology," p. 533, McGraw-Hill Book Company, New York, 1949.
25. KRESGE, R. F., and T. J. NORDENSON, Flood Frequencies Derived from River Forecasting Procedures, *Proc. Am. Soc. Civ. Eng.*, vol. 81, sep. no. 630, 1955.
26. ROCKWOOD, D. M., Columbia Basin Streamflow Routing by Computer, *Trans. Am. Soc. Civ. Eng.*, vol. 126(IV), pp. 23–56, 1961.
27. LINSLEY, R. K., and N. H. CRAWFORD, Computation of Synthetic Streamflow Record on a Digital Computer, *Int. Assoc. Sci. Hydrol.*, pub. no. 51, pp. 526–538, 1960.
28. WATKINS, L. H., The Design of Urban Sewer Systems, *Road Research Tech. Paper* 55, Department of Scientific and Industrial Research, London, 1962.
29. SUGAWARA, M., On the Analysis of Runoff Structure about Several Japanese Rivers, *Jpn. J. Geophy.*, 2 (1961).
30. CHEN, C. W., and R. P. SHUBINSKI, Computer Simulation of Urban Storm Water Runoff, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, vol. 97, pp. 289–301, 1971.
31. NARAYANA, V. V. D., J. P. RILEY, and E. K. ISRAELSON, "Analog Computer Simulation of the Runoff Characteristics of an Urban Watershed," Utah Water Research Laboratory, Utah State University, Logan, 1969.
32. JOHANSON. R. C., Precipitation Network Requirements for Streamflow Estimation, Tech. Rept. No. 147, Department of Civil Engineering. Stanford University, 1971.
33. CRAWFORD, N. H., and R. K. LINSLEY, The Synthesis of Continuous Streamflow Hydrographs on a Digital Computer, Tech. Rept. No. 12, Department of Civil Engineering, Stanford University, 1962.
34. CRAWFORD, N. H., and R. K. LINSLEY, Conceptual Model of the Hydrologic Cycle, *Int. Assoc. Sci. Hydrol.*, publ. no. 62, pp. 573–589, 1963.
35. CRAWFORD, N. H., and R. K. LINSLEY, Digital Simulation in Hydrology: The Stanford Watershed Model IV, Tech. Rept. No. 39, Department of Civil Engineering, Stanford University, 1966.

36. JAMES, L. D., An Evaluation of Relationships between Streamflow Patterns and Watershed Characteristics through the Use of OPSET: A Self-Calibrating Version of the Stanford Watershed Model, Research Rept. No. 36, Water Resources Institute, University of Kentucky, Lexington, 1970.
37. CLABORN, B. J., and W. MOORE, Numerical Simulation in Watershed Hydrology, Tech. Rept, HYD 14-7001, Hydraulic Engineering Laboratory, University of Texas, Austin, 1970.
38. HYDROCOMP INTERNATIONAL, INC., "Hydrocomp Simulation Programming Operations Manual," Palo Alto, Calif., 1968.
39. PHILIP, J. R., An Infiltration Equation with Physical Significance, *Soil Sci.*, vol. 77, p. 153, 1954.
40. LIGHTHILL, M. H., and G. B. WHITMAN, On Kinematic Waves: I. Flood Movement in Long Rivers, *Proc. Roy. Soc., Ser. A*, vol. 229, pp. 281–316, 1955.
41. HENDERSON, F. M., "Open Channel Flow," pp. 366–367, The Macmillan Company, New York, 1966.
42. EAGLESON, P. S., "Dynamic Hydrology," pp. 325–365, McGraw-Hill Book Company, New York, 1970.
43. MONRO, J. C., Direct Search Optimization in Mathematical Modeling and a Watershed Model Application, NOAA Tech. Memo NWS HYDRO-12, April 1971.
44. IBBITT, R. P., and T. O'DONNELL, Fitting Methods for Conceptual Catchment Models, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, vol. 97, pp. 1331–1342, 1971.
45. LIOU, E. Y., OPSET: Program for Computerized Selection of Watershed Parameter Values for the Stanford Watershed Model, Research Rept. No. 34, Water Resources Institute, University of Kentucky, Lexington, 1970.
46. U.S. ARMY CORPS OF ENGINEERS, "Snow Hydrology," Portland, Oreg., 1956.
47. ANDERSON, E. A., and N. H. CRAWFORD, The Synthesis of Continuous Snowmelt Runoff Hydrographs on a Digital Computer, Tech. Rept. No. 36, Department of Civil Engineering, Stanford University, 1964.
48. ANDERSON, E. A., Development and Testing of Snow Pack Energy Balance Equations, *Water Resour. Res.*, vol. 4, no. 1, pp. 19–37, 1968.
49. NEGEV, M., A Sediment Model on a Digital Computer, Tech. Rept. No. 62, Department of Civil Engineering, Stanford University, 1967.
50. FLEMING, G., Mathematical Simulation in Hydrology and Sediment Transport, Report No. HO-69-5, Department of Civil Engineering, University of Strathclyde, Scotland, February 1969.
51. ELLISON, W. D., Studies of Raindrop Erosion, *Agr. Eng.*, vol. 25, pp. 131–136 and 181–182, 1944.
52. HUFF, D. D., "Simulation of the Hydrologic Transport of Radioactive Aerosols," doctoral dissertation, Committee on Hydrology, Stanford University, December 1967.
53. OTT, R., Streamflow Frequency Using Stochastically Generated Hourly Rainfall, Tech. Rept. No. 151, Department of Civil Engineering, Stanford University, 1971.
54. BURGES, S. J., Use of Stochastic Hydrology to Determine Storage Requirements for

Reservoirs—A Critical Analysis, Engineering-Economic Planning Rept. No. 34, Department of Civil Engineering, Stanford University, 1970.

55. SLADE, J. J., The Reliability of Statistical Methods in the Determination of Flood Frequencies, *Water-Supply Paper No. 771*, pp. 421–431, U.S. Geological Survey, Washington, D.C., 1936.

56. ANDERSON, R. L., Distribution of the Serial Correlation Coefficient, *Ann. Math. Stat.*, vol. 13, pp. 1–13, 1942.

57. KRAEGER, B., Stochastic Monthly Streamflow by Multi-Station Daily Rainfall Generation, Tech. Rept. 152, Department of Civil Engineering, Stanford University, 1971.

58. PATTISON, A., Synthesis of Rainfall Data, Tech. Rept. No. 40, Department of Civil Engineering, Stanford University, 1964.

59. FRANZ, D. D., Hourly Rainfall Synthesis for a Network of Stations, Tech. Rept. No. 126, Department of Civil Engineering, Stanford University, 1970.

60. GRAYSON, W. M., and P. S. EAGLESON, Evaluation of Radar and Raingage Systems for Flood Forecasting, Rept. No. 138, Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, 1971.

61. LOMBARDO, P. S., Critical Review of Currently Available Water Quality Models, Rept. Prepared for Office of Water Resources Research, Hydrocomp, Inc., Palo Alto, Calif., 1973 (NTIS Accession No. PB-222-265/1).

62. CRAWFORD, N. H., and A. S. DONIGIAN, JR., Pesticide Transport and Runoff Model for Agricultural Lands, U.S. Environmental Protection Agency, Environmental Protection Technology Series EPA-660/2-74-013, 1973.

63. LINSLEY, R. K., and N. H. CRAWFORD, Continuous Simulation Models in Urban Hydrology, *Geophys. Res. Lett.*, vol. 1, pp. 59–62, (1974)

64. LUMB, A. M., and R. K. LINSLEY, Hydrologic Consequences of Rainfall Augmentation, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, vol. 97, pp. 1065–1080, 1971.