METROPOLITAN WATER INTELLIGENCE SYSTEMS

COMPLETION REPORT - PHASE II

prepared by

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FOREWORD

This is the completion report for Phase II of a three year research project on "Metropolitan Water Intelligence Systems," sponsored by the U. S. Office of Water Resources Research. This report supplements the Phase I Completion Report which was issued in June 1972.

The objective of the research is to develop criteria, rationale and guidelines for planners, managers and designers concerning implementation of automation and control facilities for urban water facilities. This particular research project has focused on wastewater management systems, specifically combined sewer systems. The combined sewer system includes collection and transmission of combined sewage and dry and wet weather treatment and disposal.

Phase I of the research project laid a broad foundation of reports on a number of issues related to the automation problem. The list of reports issued under Phase I is descriptive of the work accomplished.

MWIS Phase I Reports

Technical Report No. 1 - "Existing Automation, Control and Intelligence Systems of Metropolitan Water Facilities" by H. G. Poertner.

Technical Report No. 2 - "Computer and Control Equipment" by Ken Medearis.

Technical Report No. 3 - "Control of Combined Sewer Overflows in Minneapolis-St. Paul" by L. S. Tucker.

Technical Report No. 4 - "Task 3 - Investigation of the Evaluation of Automation and Control Schemes for Combined Sewer Systems" by J. J. Anderson, R. L. Callery, and D. J. Anderson.

Technical Report No. 5 - "Social and Political Feasibility of Automated Urban Sewer Systems" by D. W. Hill and L. S. Tucker.

Technical Report No. 6 - "Urban Size and Its Relation to Need for Automation and Control" by Bruce Bradford and D. C. Taylor

Technical Report No. 7 - "Model of Real-Time Automation and Control Systems for Combined Sewers" by Warren Bell, C. B. Winn and G. L. Smith.

Technical Report No. 8 - "Guidelines for the Consideration of Automation and Control Systems" by L. S. Tucker and D. W. Hill.

Technical Report No. 9 - "Research and Development Needs in Automation and Control of Urban Water Systems" by H. G. Poertner.

Final Report - "Metropolitan Water Intelligence Systems Completion Report - Phase I" by G. L. Smith, Neil S. Grigg, L. S. Tucker and D. W. Hill.

The objectives of Phase II of the MWIS Project are concentrated in the following four areas of emphasis:

1. Formulation of Design Strategy for Automation and Control of Combined Sewer Systems. The design strategy problem is concerned with the development of a control strategy to achieve objectives of the automation and control strategy.
2. Development of Model of Real-Time Automation and Control Systems (RTACS). The actual design of an RTACS including all of its constituent components, can best be done by using a computer simulation model to describe the entire system. The most difficult task is the design of the control criteria and many different control strategies can be tested on a computer simulation model before the actual control model is implemented.
3. Description of Computer and Control Equipment. The hardware available for RTACS is increasing rapidly. The designer or manager concerned with implementing such a system must know what his requirements are. The objective of this portion of the study is to describe the requirements for computer and control equipment for RTACS.
4. Nontechnical Aspects of Automation and Control. Implementing an RTACS involves more than simply designing an RTACS as the best method for solving a technical or engineering problem. Indeed, the implementation of an RTACS contains all of the socio-political dangers in any automation system. This portion of the research is designed to describe and offer potential solutions for these problems.

This Phase II Completion Report describes progress in the four areas listed above. This report is supplemented by the following technical reports which are in press.

Technical Report No. 10 - "Planning and Wastewater Management of a Combined Sewer System in San Francisco" by Neil S. Grigg, CSU and William R. Giessner, Robert T. Cockburn, Harold C. Coffee, Frank H. Moss, Jr., and Mark E. Noonan, all of the San Francisco Department of Public Works.

Technical Report No. 11 - "Optimization Techniques for Minimization of Combined Sewer Overflow" by John W. Labadie.

Interim Report - "Preliminary Control Strategy Development, Vicente Basin, San Francisco, California" by Neil S. Grigg, Bruce H. Bradford, and Paul D. Trotta.

In addition to the Technical Reports listed above, Technical Reports are currently being prepared in the areas of the nontechnical aspects and computer and control equipment and will be issued at appropriate times during the project. Also, a Ph.D. dissertation on the optimal control problem should be forthcoming soon.

This Completion Report draws heavily on the Technical Reports previously cited. Detailed information on the topics summarized herein may be obtained from those reports.

ACKNOWLEDGMENTS

Several persons deserve credit for their assistance in the conduct of this research. Appreciation is extended to Dr. George Mangan, Project Monitor for his helpful suggestions and advice. We are also indebted to Dr. Edward Altouney who was the Project Monitor on Phase I of the project and part of Phase II. Mr. Murray B. McPherson, Director of the ASCE Urban Water Resources Research Program, deserves a great deal of credit for arranging liason between the CSU project and the Department of Public Works of the City of San Francisco, particularly Messrs. Robert Levy, A. O. Friedland, and W. R. Giessner. This initial arrangement has been extremely valuable to the investigators, both in their understanding of the real world problems involved and also because of the technical expertise made available by the City of San Francisco. In particular, Mr. W. R. Giessner has been extremely helpful in advising us on the project.

ABSTRACT

METROPOLITAN WATER INTELLIGENCE SYSTEMS
COMPLETION REPORT - PHASE II

- Neil S. Grigg, John W. Labadie, George L. Smith
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The results of Phase II of the Colorado State University project "Metropolitan Water Intelligence Systems" (MWIS) are reported. The special type of MWIS considered is the fully automated control system for combined sewer systems. The report contains technical data on computer and control equipment, on the formulation on the control strategy problem and on optimization techniques for developing control logic. The Real-Time Automation and Control System (RTACS) Model is presented as a simulation model which can be used off-line to develop control logic. The hydrologic, hydraulic and control models needed in either an RTACS or an RTACS Model are discussed. The socio-political problems associated with implementing a MWIS are related to similar problems experienced in implementing any information system or automation effort. The problems facing local decision makers who must comply with shifting standards under heavy time, technological, financial and political constraints are related to their personal objectives and proposals are advanced for social modeling techniques which could help in MWIS implementation.

GLOSSARY

Items in this section are from references (2,35,46,48)

Access Time - time required by computer to locate a word in core memory and transfer the word to a register.

A.C.U. - auxiliary control unit: cabinet containing electronics, relays, etc. located between T.C.U. and station local control system.

Address - an identifier denoting a register, memory location, or unit where certain information is stored.

Algorithm - a fixed step-by-step procedure for accomplishing a given result.

Analog - the representation of a numerical quantity by some physical variable, e.g., translation, rotation, voltage or resistance.

Assembler - a computer program that translates mnemonic operation codes into machine language instructions.

Autoanalyzer - copywritten term referring to equipment which automates chemical tests on samples. After initial set-up of equipment and sampling unit, no further human effort is needed other than interpreting a strip chart.

Background - a low priority, unprotected processing area in a computer where batches of programs are compiled, tested and run without affecting other protected control and processing areas.

Benchmark - a test program written to test the speed, performance and capacity of a computer and often to compare the results of a run on different computers.

Bit - an abbreviation of binary digit, a binary digit being either 0 or 1.

Byte - a term meaning 8-bits of information.

Character - for digital computers in general, the symbols frequently encountered on a typewriter; a number of bits are required to represent a character.

Checkpoint - a point in time where computer processing is stopped, all machine variables, registers and background area copied to a rapid magnetic storage device so that a large foreground program can temporarily use all or a part of what is normally called background area.

Compiler - a computer program that translates a higher level language, such as FORTRAN (FORmula TRANslation) into machine language; this is usually accomplished in several steps.

Control Criteria - the control criteria establish the objectives of control and define all the constraints under which they must be accomplished. Some of the factors bearing on control criteria are: local political conditions; regional or state pollution control regulations and objectives; economic, sociological and legal considerations; local wastewater control agency objectives; public relations; and technical feasibility.

Control Logic - after control criteria have been established, development of a set of rules or logic operations is necessary in order to meet the specified criteria where certain field conditions occur. The control logic is this set of rules or logic operations. Control logic is part of the RTACS and constitutes the core of a real-time operational control system.

Control Model - a model for use on the computer which contains the control logic.

C.P.U. - central processing unit: that portion of computer excluding input-output and external storage units, where arithmetic, logical, storage and control functions are centered.

CRT - Cathode Ray Tube: television, for visual data presentation.

Digital - the use of discrete numbers to a given base to represent all quantities in a problem or calculation. Most often all information is stored, transmitted or processed by a dual state condition; e.g., on-off open-closed, true-false.

Direct Memory Access - enables information to be transferred at very high rates between external components and the computer memory; interchanges take place independent of other operations by stealing computer memory cycles to read into or write directly from core memory.

Executive Monitor, Executive System, Supervisory Program - a master software program which controls the overall operation of a computer system.

Feedback (Control) - an automatic furnishing of data concerning the output of a machine to an automatic control device so that errors may be corrected.

Hardware - the physical equipment and devices which comprise a computer or computer system component.

Indirect Address - an address which does not designate the location of a certain item, but rather the location of the address of the item.

Information System - a term meaning the informal or formal system by which information moves horizontally and vertically in an organization.

Input-Output Devices - devices for entering and extracting information from computers: card readers, card punch, typers, printers, cathode ray tubes, etc.

Integrated Municipal Information System (IMIS) - The hypothetical information system that ties together the elements of local government.

Interface - a common boundary between parts of a computer system.

Interrupt - a special signal which temporarily halts the normal operation of some computer job for the purpose of accomplishing another more important short task, after which normal operation resumes.

Logic - the science of combining electronic components in order to define the interactions of signals in an automatic data processing system.

Machine Language - computer instructions written in such a manner they can be utilized directly by the computer without further translation.

Magnetic Core Storage - a memory device utilizing doughnut-shaped ferrite cores which may be magnetized in either of two directions to represent a binary digit.

Management Information System (MIS)- a term referring to the formal information system used by management to gather intelligence on the organizational activities.

Management Information and Control System (MICS) - a term referring to a variation of an MIS whereby control is exercised over some process.

Mathematical Model - the characterization of a process or concept in terms of mathematics, which allows the simple manipulation of variables in an equation to determine how the process would act in different situations.

Memory Capacity - the number of pieces of information that can be stored in the computer.

Memory Cycle Time - the time required to transfer one word from magnetic core storage to the central processing unit, and replace the same word in core.

Memory Protect - computer hardware which affords protection for the executive monitor and associated software programs against equipment malfunction and programming errors.

Metropolitan Water Intelligence System (MWIS) - a system which provides for automatic operational control of metropolitan water systems. In its ultimate form, the intelligence system, according to McPherson (32), would be in the closed-loop mode and would be computer centered. Using field intelligence -- precipitation, water and wastewater treatment facilities, water demands and distribution system rates and pressures, settings of regulating structures -- as inputs, the computer decision program would resolve best service - least operating cost options, taking into account estimated reliability and risks, and would actuate field regulating and control facilities to approach elected option states. Feedback features would be such as to permit manual supervisory intervention at any time.

Mini-Computer - a small, inexpensive, general purpose digital computer.

Modeling - a simulation technique for the analysis of operations and systems.

Off-Line Computer - a free standing digital computer not tied into an industrial process.

On-Line - tied into a process and operating continuously.

On-Line Computer - a computer which is integrated into the dynamics of a process; a process control computer.

Peripheral Devices - input/output equipment used to make hard copies or to read in data from hard copies (typer, punch, tape reader, line printer, cathode ray tube, plotter).

Priority - degree of importance assigned to some computer task.

Process Computer - a digital computer having direct communication capability with an industrial process for data sampling and equipment control.

Real-Time Automation and Control System (RTACS) - a system which provi es for control in real-time of some physical system (such as a combined sewer drainage basin) through use of at least the following components: sensing elements (rain gauges, flow meters, etc.), a centralized data processing unit, a mathematical model and/or rule curves which govern all or part of the physical system, a control program, a data bank and control elements which operate within the physical system. The objective of the RTACS is to achieve the objective established for the water resources system upon which it operates. The functions of the various components of the RTACS will be explained later.

Real-Time Automation and Control System Model (RTACS Model) - a simulation model of the physical system and the major RTACS components which allows for simulation of RTACS operating under different external and internal conditions. The purpose of the RTACS model is to aid in the design of the different components of RTACS.

Real-Time Clock - a clock that initiates time-sequenced computer operations and enables the calculation of elapsed time between certain events.

Real-time Control - control of a system by using computers and timing such that the speed of response to the input information is fast enough to effectively influence the performance of that system.

Register - device consisting of miniature electronic components including transistors, where a specific number of bits are stored and operated upon.

Rule Curves - a set of curves which relate storage and discharge for a given reservoir under different control conditions.

Scan - the collection and storage of data from all points at all stations in system by computer.

Scanner, Remote - a device which will, upon command, connect a specified sensor to measuring equipment and cause the generation of a signal suitable for input to a computer.

Simulation - operating a logical-mathematical representation of a concept, system or operation.

Software - the programs or instructions which often control the hardware to perform some computer operation or extend the capabilities of the system.

Subroutine - a compact set of instructions to perform some repetitive task quickly and return to a main program.

Telemetry - the system of measuring, transmitting and receiving apparatus for indicating, recording or integrating at a distance, by electrical translating means, the value of a quantity.

T.C.U. - Telemetry Control Unit: interchangeable electronic cabinets, convert between telemetry and station control signals.

Time-Sharing - the simultaneous use of a computer system from multiple terminals; provides economics through cost-sharing.

Word - a group of characters treated as a unit by the computer in its operations; the word length is the number of characters in the group.

MATHEMATICAL NOTATION

In this report, for notational convenience, no attempt is made to distinguish between column and row vectors. It is presumed that the reader can distinguish this for himself.

$x \varepsilon E^n$	a *vector* $x = (x_1,\ldots,x_n)$, or an element of (ε) n-dimensional *Euclidean space* E^n. If $x_i \geq 0$ $(i = 1,\ldots,n)$, then $x \varepsilon (E^n)^+$.
$f(x)$	a *vector-valued function* $f(x) = (f_1(x),\ldots,f_m(x))$, also denoted as $f{:}E^n \rightarrow E^m$ or $f(\cdot) \varepsilon E^m$.
$\nabla_x f(x)$	the *gradient* vector of f, or $\nabla_x f(x) = (\frac{\partial f}{\partial x_1},\ldots,\frac{\partial f}{\partial x_n})$.
$x_i(k)$	component of a *matrix* of numbers, also denoted as $x(k) \varepsilon E^n$ $(k = 1,\ldots,m)$, $x_i(\cdot) \varepsilon E^n$ $(i = 1,\ldots,n)$, or $x(\cdot) \varepsilon E^{m+n}$.
$x \cdot y$	*scalar product* of two vectors $x,y \varepsilon E^n$, where $x \cdot y = \sum_{i=1}^{n} x_i y_i$.
$\{x \mid P(x)\}$	*set* S of elements $x \varepsilon E^n$ satisfying some given property P, where S is a subset of E^n, or $S \subset E^n$.
$[a,b]$	set defined over *closed interval* $a \leq x \leq b$, $x,a,b \varepsilon E^n$.
(a,b)	set defined over *open interval* $a < x < b$, $x,a,b \varepsilon E^n$.
convex set	set S is *convex* if and only if for every $x,y \varepsilon S \subset E^n$, $(\alpha x + (1-\alpha)y) \varepsilon S$, for all $\alpha \varepsilon [0,1]$.
int(S)	the *interior* of the set $S \subset E^n$, or the largest *open* set contained in S.

$X \times Y$	*cartesian product* of two sets $X \subset E^m, Y \subset E^n$; or $(X \times Y) \subset E^{m+n}$
$\dot{x}(t)$	vector of *derivatives* $(\frac{dx_1(t)}{dt},\ldots,\frac{dx_n(t)}{dt})$.
x^*	*global solution* of optimization problem $\min\{f(x) \mid x \in S\}$, where $S \subset E^n$, or $f(x^*) \leq f(x)$, for all $x \in S$.
x^o	*local solution* of optimization problem $\min\{f(x) \mid x \in S\}$, $S \subset E^n$, or $f(x^o) \leq f(x)$, for all $x \in S \cap N$; where $N = (x^o - \varepsilon, x^o + \varepsilon)$, for some scalar $\varepsilon > 0$.
$\triangleq$	equal by definition
=>	forward implication (*implies*)
<=	reverse implication (*is implied by*)
<=>	equivalence, or if and only if (*iff*)

A	area of drainage basin
C	percent runoff from rainfall
h(t)	ordinates of the instantaneous unit hydrograph (IUH)
K	parameter of the single linear reservoir model
Q(t)	ordinates of runoff hydrograph
P_E	precipitation excess
τ	a dummy time variable
T_R	duration of rainfall excess
U	urbanization factor
$x(\tau)$	values of rainfall excess over time

SUMMARY

The four principal areas of emphasis in Phase II of the Metropolitan Water Intelligence Systems Project have been the following:

1. The study of the problem of developing control strategy for combined sewer systems,
2. The continued development of the Real-Time Automation and Control System Model (RTACS Model), particularly the optimization routines,
3. The study of computer and control equipment for RTACS, and
4. The study of nontechnical aspects of implementing RTACS, particular socio-political problems.

During Phase II the problem areas 1. and 2. have come closer together as the development of control strategy using simulation techniques increasingly points to the need for optimization as an aid to the development of better control logic.

During Phase II an in-depth study was conducted of the problems of controlling a single drainage basin with only a few control alternatives. Hydrologic, hydraulic and control models were prepared and integrated into a simulation model of the basin. The simulation model can be used to study control strategy for different contingencies in the basin. Some of the problems that can be studied are:

1. Optimal control strategies for uniform rainstorms,
2. The consequences of rainfall variations on control objectives,
3. Equipment malfunctions,
4. Design problems of optimum retention basin size and location, rain gauge location, etc.

The level of effort required to model one basin as has been done demonstrates the immense problem associated with modeling an entire city. The basic problems of describing the system and preparing data for model calibration are more significant than the analysis problem in most cases.

Optimization techniques for developing control logic were examined during the study and it was concluded that finite dimensional (discrete-time) optimization was preferable to infinite dimensional (continuous-time) optimization.

Mathematical programming approaches to the determination of optimal control logic appear to have promise. Linear programming can only be used if some sort of linearization procedure is used. Generally it is difficult to obtain a global solution to the original non-linear problem under these conditions. Standard dynamic programming does not appear to be feasible due to dimensionality difficulties. Incremental dynamic programming may be applicable, but will only guarantee local solutions. Non-linear programming can only assure local solutions. In order to deal with the problem of finding local solutions, an approximate-flow technique is presented which may have lead to a solution of this problem.

An RTACS has many of the components of other types of Management Information and Control Systems (MICS) and therefore shares the difficulties of implementation. The hardware and software problems are also similar and a great deal of literature is available on the implementation problem in the aerospace and defense industry. The RTACS is somewhat unique in that it addresses a difficult problem in urban hydrology. Also, solutions must be found feasible subject to all of the constraints of the public sector including political constraints.

The concept of an Integrated Municipal Information System (IMIS) is emerging in local governments and it may be possible to relate it to RTACS (and MWIS) through shared data banks, shared hardware or other means. This approach has not yet been really considered due to difficulties in getting control systems started even without interfaces into an IMIS.

The socio-political problems of implementing an RTACS are formidable. They relate to the problems of implementing environmental quality programs in the face of shifting standards. A host of local problems associated with agency development also constrain the consideration and implementation of control systems. The motivations for implementing solutions to water quality problems must be considered. Two incentive models, one a tax sharing model and the other an incentive programming approach, are presented as possibilities for studying organizational response to different incentive stimuli.

Concerning agencies' response to problems which might be solved with control systems, one problem is the shifting ground rules upon which choices are made. Some typical social data is presented in support of this finding. Values held a decade ago are rapidly shifting.

More directly, some data concerning public works decision maker characteristics is presented. The data is only preliminary but can serve as the basis for hypothesis generation for further testing.

The computer and control equipment available is increasing rapidly and control techniques available to use the equipment are not keeping pace. It is shown that hardware limitations preclude the use of the most sophisticated prediction models, but that current minicomputers have ample capability to implement an RTACS. Some recent installations and plans are summarized.

I. INTRODUCTION

Background

This is the completion report of Phase II of a three-year project. As such it has the objective of presenting findings and data generated in the last year. This report is supplemented by separate Technical Reports which are issued at appropriate times during the year. At the conclusion of Phase III, a final report will be prepared containing research results from the entire three-year effort.

The concept of a "Metropolitan Water Intelligence System" (MWIS) was conceived by McPherson and is intended to mean a Management Information and Control System (MICS) for urban water systems (1). The MICS is a general concept applied widely in industry and now becoming of interest on a wide scale for application to urban water systems. Figure I-1 shows the general formulation of a MICS (36).

Figure I-2 shows the MICS concept as applied to a combined sewer system. As a system, it is similar to many other applications, but the problems associated with a combined sewer system are unique.

There are several variations of real systems such as is shown on Figure I-2, either in the construction, planning or developmental stages. Some of these are in Minneapolis-St. Paul, Seattle, Cleveland, San Francisco and Detroit. A number of others are in the incipient planning stage.

McPherson's definition of the MWIS concept is a description of

> "... the hardening concept of multiservice automatic operational control, wherein field intelligence on all aspects of urban water might be acquired, including: precipitation; stream stages and flow rates; water and wastewater treatment facilities; water demands and distribution system rates and pressures; settings of regulating structures; quality parameters for watercourses and impoundments, and within conveyance systems; and the status of special facilities such as recreational ponds and lakes. Possibilities exist for incorporating non-water related service intelligence, including traffic and air pollution monitoring, because these are affected by precipitation and the trend for their control is towards a centralized operation. In its ultimate form, the intelligence system would be in the computer centered closed-loop mode. Using field intelligence as inputs, the computer decision program would resolve best service-least operating cost options, taking into account estimated reliability and risks, and would actuate field regulating and control facilities to approach elected option states. Feedback features would be such as to permit manual supervisory intervention at any time." (32)

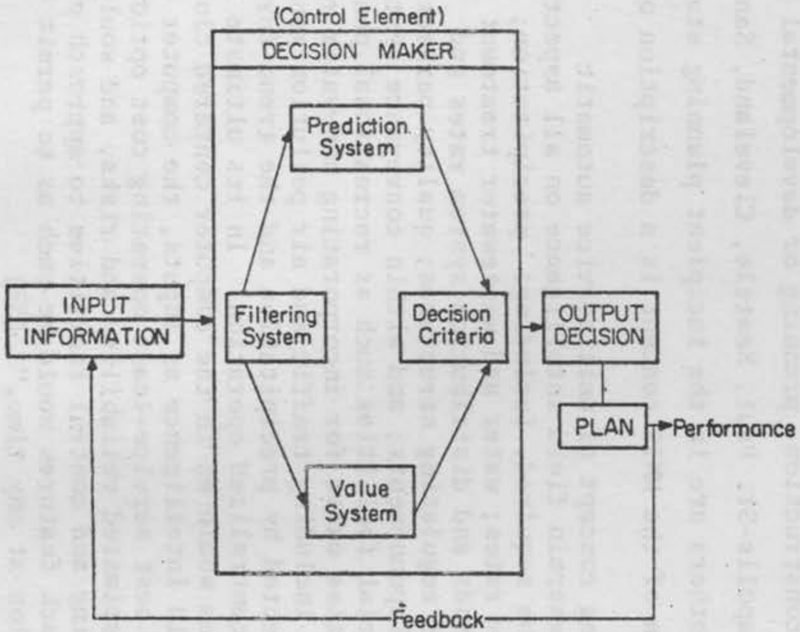

Figure I-1. A Generalized Management Information and Control System (36)

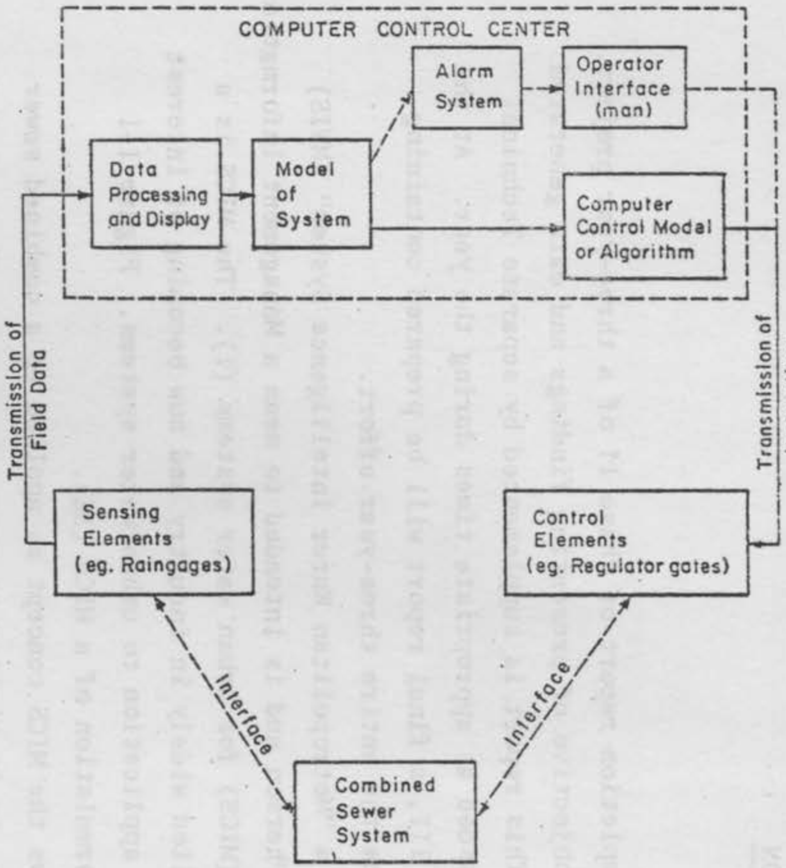

Figure I-2. Components of a Combined Sewer Control System in Automatic Mode

The above states that in its ultimate form, the MWIS would operate in the computer centered closed loop form. The MWIS is essentially a form of automatic control of water systems.

Total automatic control requires the presence of on-line computer(s). These are becoming useful in many commercial applications ranging from airlines reservations to business accounting functions to industrial process control. The computer hardware technology has been advancing at a rapid rate, but control techniques have been lagging behind the hardware available (12). A continuing message of this project is that the hardware is there and the problem is there and the two need to be welded together on a technically, financially and socially feasible basis.

The scope of this report is to report on progress and accomplishments in four areas of study:

1. The Formulation of a Design Strategy for Automation and Control of Combined Sewer Systems,
2. The Development of a Model of a Real-Time Automation and Control System (RTACS),
3. The Study of the Socio-Political Problems Associated with Implementing Control Systems, and
4. The Study of Computer and Control Equipment for RTACS Systems.

Separate technical reports are scheduled in each of these areas when the study effort is completed. This report contains a substantive discussion of the findings and indications to date.

Description of the Problem and Review of Literature

In Phase I of the MWIS project a completion report was prepared which described a number of related problems associated with implementation of automation and control systems for combined sewer networks (46). This report described basic research needs and management considerations for nine problem areas:

1. Integrate information on current systems.
2. Study relationships between urban growth and requirements for automation and control systems.
3. Evaluate automation and control schemes for combined sewer systems.

4. Develop a model for a real-time automation and control system (RTACS).
5. Evaluate computer and control equipment needs.
6. Formulate a design strategy for automation and control of combined sewer systems.
7. Study nontechnical aspects of automation.
8. Describe research and development needs.
9. Establish a project advisory committee.

The combined sewer overflow problem is under attack by a number of cities, agencies and private firms. The most concentrated effort is that mounted by the U. S. EPA which has a number of significant activities underway. Their program through about 1971 was summarized well in a recent overview report (19).

During the interim period the writers have become aware of a number of ongoing EPA projects, research and demonstration, which address the combined sewer and stormwater problem. They look forward with interest to additional overview reports such as the one previously cited by Field. A source of data concerning the literature in the field is available in the abstracts from the Franklin Institute Research Laboratory (20).

The reader is referred to the EPA overview reports and to the Franklin Institute abstracts for information on activities in the storm and combined sewer problem area. The literature is growing rapidly in all of the problem areas.

There are of course, several water resources abstracting services with material on urban hydrology. A recent report by the U. S. Geological Survey may also be of interest to readers working in the area of combined sewers (26).

<u>The Next Step - Control of Stormwater</u>

So far most of the control emphasis has been on control of combined sewage. Many of the problems with combined sewer overflows also exist in separated stormwater, however, and it may not be too long before control, storage and treatment of storm runoff is also considered. A recent article by an EPA staff member presented this argument rather convincingly. His conclusion is presented below:

"What we have determined is that storm runoff from urban areas is a significant water pollution factor. This concentrated pollution load, this large slug of polluted water, enters the receiving streams, bays, estuaries, or lakes in all but the dry sections of the country about 120 times a year. They produce a shock effect which takes a great deal of time and considerable water course to dissipate. A significant portion of the pollutants are not degradable and pollutants hazardous to biota can concentrate. However, the exact effects of the cumulated loadings have yet to be fully assessed.

From this it is reasonable to assume that legislated controls will be placed on the quality of urban runoff either directly or by receiving water quality standards.

Therefore, with new and more stringent legislation on the horizon, and for the sake of the water environment, our preparation to abate this pollution source should begin now." (11)

II. MANAGEMENT INFORMATION SYSTEMS AND THE MWIS

There is increasing activity evident in the application of management information systems (MIS) to problems of public works management. Two recent reports by the American Public Works Association (APWA) address this problem (3,4). As the interest in the MIS concept increases, many valuable experiences from government and industry will be found applicable to the MWIS problem.

Because of the similarities between the MIS and the MWIS concepts, this section will present a brief discussion of the two so that the linkages can be identified at the municipal level.

The information system as applied across different municipal subsystems is sometimes referred to as an "Integrated Municipal Information System" (IMIS). Information about the different subsystems shown in Figure II-1 might be required here. Note that the combined sewer system falls into the area of environmental management subsystems. This is from an engineering point-of-view. From a city management point-of-view the IMIS "wheel" is similar to the urban system just shown (see Figure II-2).

There has been considerable research and demonstration activity in recent years concerning the IMIS. The principal focus of activity has been the Federal Urban Information Systems Inter-Agency Committee (USAC). The activities of this committee to date are summarized in the following section:

"THE USAC PROGRAM AND THE DOCUMENTED RESULTS OF USAC PROJECTS

The USAC program is an effort to sponsor research into, and development of, transferable, operationally based, municipal information systems. The effort was initiated in 1968, when the Federal Urban Information Systems Inter-Agency Committee (USAC) was founded. This body is chaired by the Department of Housing and Urban Development, and includes members from the Department of Health, Education, and Welfare, and the Departments of Commerce, Justice, Labor, and Transportation. The Office of Management and Budget, the Office of Economic Opportunity, the Office of Civil Defense, and the National Science Foundation are also members of the committee.

Six cities were selected competitively early in 1970 to receive Federal assistance in performing research and development tasks toward the municipal information system effort. Each city is the prime contractor for its project, and is being assisted by a computer systems firm and a university as subcontractors. Each project includes city personnel as team members, and is

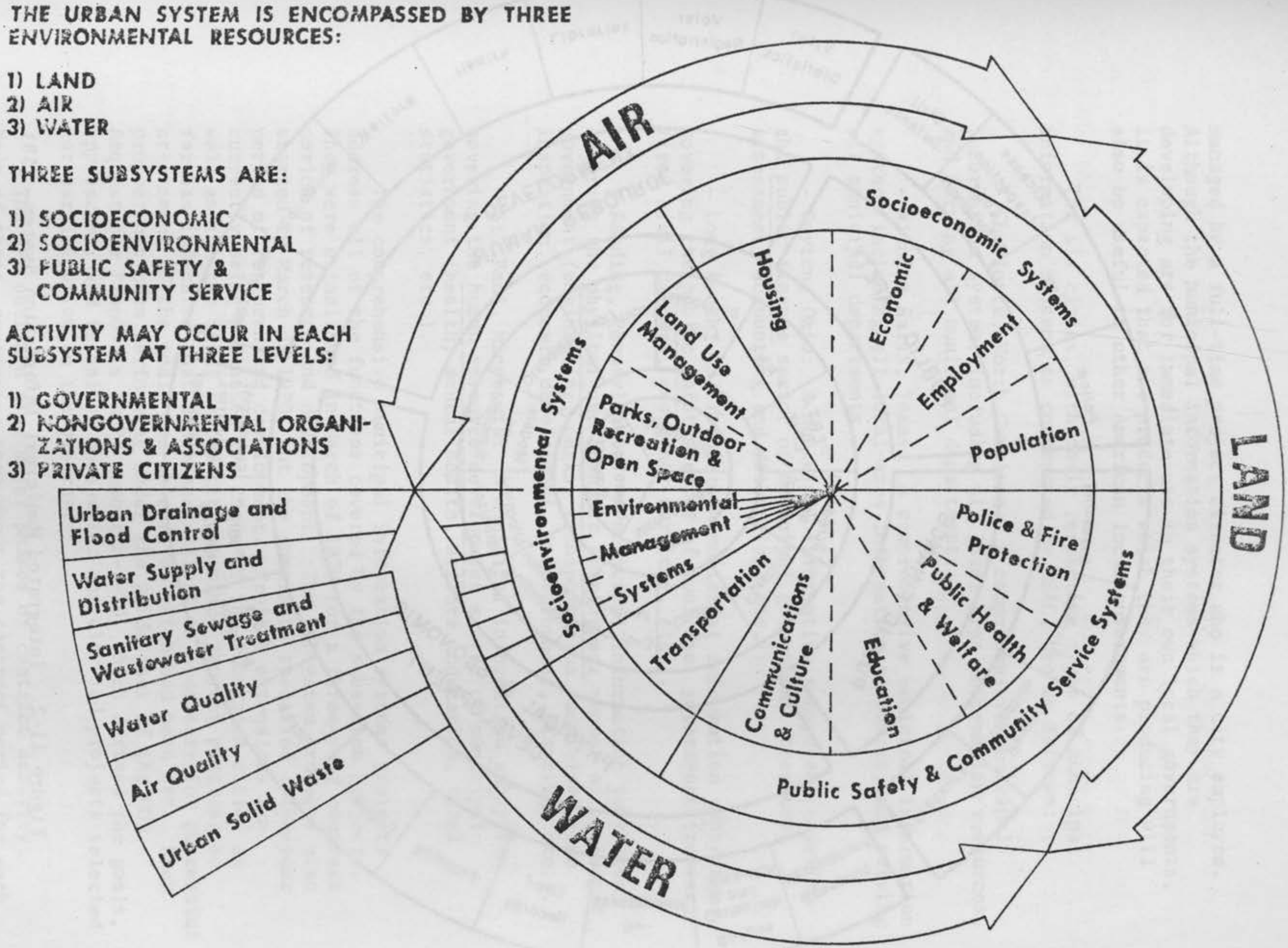

Figure II-1. The Urban System (18)

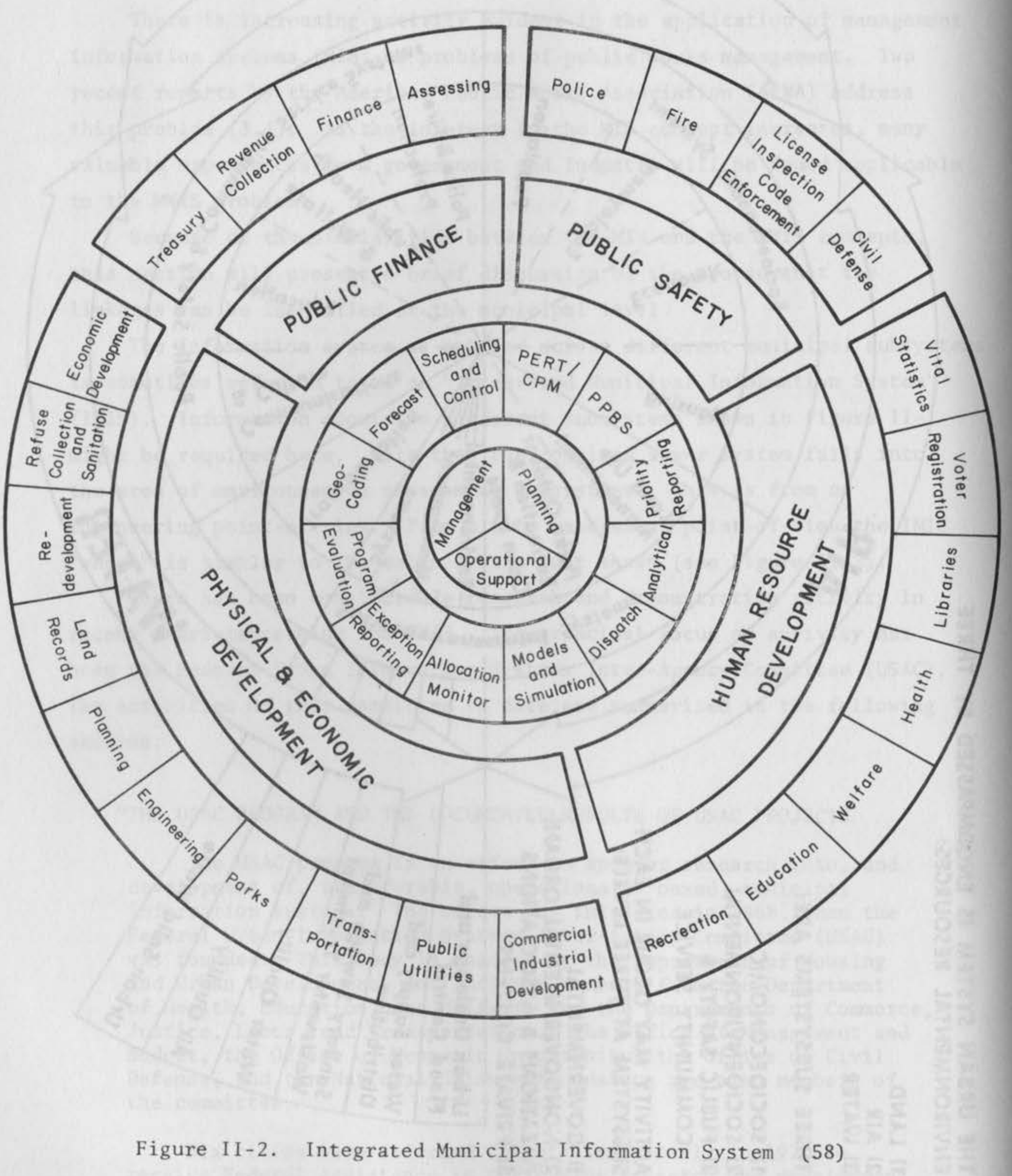

Figure II-2. Integrated Municipal Information System (58) managed by a full-time project director who is a city employee. Although the municipal information systems which they are developing are for immediate use in their own local governments, it is expected that the products which they are producing will also be useful to other American local governments.

The six cities, with their respective types of municipal information systems as contracted by USAC, are as follows:

- Charlotte, North Carolina: A comprehensive municipal information system, including all local-area information resources, and serving all municipal departments.

- Wichita Falls, Texas: A comprehensive municipal information system, including all local-area information resources, and serving all municipal departments.

- Dayton, Ohio: A municipal information subsystem, covering the public finance sector of municipal government (treasury, assessment, accounting and disbursing, etc.).

- Long Beach, California: A municipal information subsystem, covering the public safety sector of municipal government (police, fire, civil defense, emergency services, etc.).

- Reading, Pennsylvania: A municipal information subsystem, covering the physical and economic development sector of municipal government (engineering, parks, transportation, municipal code inspection, economic development, redevelopment, planning, etc.).

- St. Paul, Minnesota: A municipal information subsystem, covering the human resource development sector of municipal government (health, mental health, welfare, education, vital statistics, etc.).

The comprehensive municipal information systems projects address all of the functions covered by the subsystem projects. They were established in March of 1970 for a three-year contract period of research and development. The subsystem projects also started in March of 1970, but the contracts specified a two-year period of research and development. Project extensions are currently being processed for three of the subsystem cities as well as the two total system cities, since project progress so far has indicated that additional effort is necessary for successful attainment of the goals and objectives which had been set. Each project has been performing under the guidelines of the HUD Request for Proposals (RFP) number H-2-70, which defined the goals, approaches, and technical phases for the city-led projects selected for participation in the program.

The RFP outlined nine major phases of contract activity. Four of these, continuing throughout the contract period for each project, are Project Administration and Organization, Orientation and Training, Monitoring and Evaluation (assessment of the impact of the system and other research topics), and Systems Evaluation (ongoing assessment of the major task discussed below). Each project consortium (city, systems firm, and university) has been carrying on these four continuous tasks.

The five major development tasks, which include major research activities, are basically sequential in order of performance. There are Systems Analysis, Systems Conceptualization, Systems Design, Systems Development, and Systems Implementation.

Each project has completed Systems Analysis. This task involved the thorough analysis of all municipal information activities, including those which crossed city departmental boundaries and those with agencies outside of the city government. It also included analysis of decisions of municipal leaders, managers, and operational personnel, and how these decisions were, and best could be, assisted by provision of timely and valid information.

Most projects have completed Systems Conceptualization, which is a broad, function-oriented design of an information (sub)system which will provide updated information to city personnel for day-to-day operations. One project, however, has only partially completed this task, but has progressed further into Systems Design and Development through its use of an alternative approach.

Systems Design is the detailed design of the new municipal information (sub)system. When this task is documented, the result will be detailed specifications of the new (sub)system, suitable both for the individual USAC cities and for other cities wishing to use such products in developing their own municipal information (sub)systems. Systems Development includes the detailed computer program specifications development and the actual coding, testing, and integration of the computer programs. Systems Implementation is the task in which the training of city personnel in the operation of the system will be completed, and in which the city personnel will use the new system in their day-to-day operations and the city itself will begin full maintenance and use of the operational system.

The projects are in various stages of design, development, and implementation, depending on the functional area of the municipal government which is involved. Parts of certain functional areas have already been implemented by the USAC cities, especially those portions which were implemented as part of the early demonstration efforts. Other functional areas, or parts of functional areas, are in various stages of the design-development-implementation cycle. The complexity of the effort has forced each city to prioritize the pieces of their system which are to be implemented. Many of these prioritized pieces have yet to enter the design stage. This is especially true in the total system cities, where the effort is so much larger than in the subsystem cities. As "stand-alone" pieces of each system are implemented, however, the associated documentation will be submitted to USAC for distribution through NTIS as outlined below.

It should be noted that a key feature of the systems being developed by the USAC sponsored cities is that of an integrated system operating on an integrated data base. The concept is that as much redundant data is eliminated from the data base as possible. This is accomplished through the use of pointers which link related data elements.

The four phases which continue throughout the course of each city project will most likely be documented near the end of each project. Orientation and Training materials, however, are currently receiving emphasis in the projects and may be available earlier, due to the need for such materials in the early stages of the projects.

In addition to the six USAC city projects mentioned above, there are five additional USAC management support contracts in existence. These are designed to afford consultation, technical evaluation, and other services to the USAC staff. These contractors are Claremont (California) Graduate School, the International City Management Association, Long Island University, the National Bureau of Standards, and the National League of Cities. Also, a research contract has recently been awarded to the City of Des Moines, Iowa. This effort will involve research into the area of geocoding, specifically studying the economics involved in starting from scratch in making areal photographs and converting these photographs to charts for use in the city planning and operations activities. This effort is scheduled to continue through the end of calendar year 1973.

The attached material is provided so that interested parties can obtain information on the various USAC-sponsored activities. This material includes a list of all documents which have been submitted to USAC (the Federal sponsors) and reviewed by USAC and which have been released for publication by Commerce Department's National Technical Information Service (NTIS). This list of documents includes the NTIS order number and the cost of each document from NTIS. The telephone and mailing address and other information needed to order the documents from NTIS are also provided along with details on the mechanics for ordering desired documents, and the latest available information on the pricing of NTIS-published documents.

The availability of all USAC documents will be announced through the NTIS-issued "Government Reports Announcements" (GRA) volumes and also through the NTIS-issued "Weekly Government Abstracts" pamphlet series. Each of these announcements is carried in all university libraries, and many municipal libraries. The following information is presented for those who desire to order either or both of these announcement series directly from NTIS. The GRA volumes cover all research areas and are published semi-monthly at a cost of $52.50 per year. All USAC documents will be listed under Group 5B, "Documentation and Information Technology." The WGA series which describes the USAC documents as they become available is entitled "Management Practice & Research" and is available weekly as series WGA-70 for $17.50 per year. These can be ordered from:

National Technical Information Service
Department of Commerce
5285 Port Royal Road
Springfield, VA 22151

Further information can be obtained directly from NTIS by calling:

(703) 321-8888 General Information
(703) 321-8543 Order Desk

The titles of the documents listed in the attached material are short and perhaps not completely informative as to their contents. The full title, a set of identifying descriptor terms, and an informative abstract are provided for each document listed in the GRA, while the full title and informative abstract are provided for each document announced in the WGA. The reader is urged to obtain more detailed information on the nature and contents of the USAC documents through the use of the GRA and WGA prior to ordering them from NTIS." (58)

Although a great deal of investigation has not been conducted in the linkages between information systems and the MWIS, some information is becoming available. The letter reproduced below was the result of a brief review of the MWIS project by a consultant to the USAC Committee (31).

(Letter from Lyon and Associates Follows)

LYON & ASSOCIATES
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January 9, 1973

Dr. Neil Grigg
Engineering Research Center
Colorado State University
Ft. Collins, Colorado 80521

Dear Dr. Grigg:

This letter is sent as a summary of my thoughts and observations concerning the Metropolitan Water Intelligence System project on January 3, 1973.

One of the primary areas of discussion was the utilization of data produced by the MWIS for purposes other than the direct control of storm water and sewage. There is currently in process a joint project funded by a consortium of Federal Agencies and the participating local governments to develop an Integrated Municipal Information System. The central office of the project is located in the Office of Research and Technology, U.S. Department of Housing and Urban Development and is known by the acronym USAC, standing for the Urban Interagency Systems Advisory Committee. The committee is chaired by Mr. Robert Knisely of HUD. I presently serve the project as a consultant in the area of system utilization in local government and evaluation of the efforts centered in public finance.

This project has the overall aim of assisting local governments through development of prototype Integrated Municipal Information Systems (IMIS). It is theorized that through automation of operations of vertical functional areas, such as fire, police, finance, and public works the operational data produced by one function becomes available horizontally to another function and can assist that function in its day to day operations as well as in the overall management of the government.

One of the classic examples of horizontal data transfer and usage is the fact that the data entered on a building permit application if transferred and re-aggregated properly can be utilized by the traffic function in determining advisability of a street drive permit, the utility function in issuance of a water and sewer tap permit, the finance function in licensing and fee collection, the fire function in inspection scheduling and identification of potential high risk, and the police function in identification of potential loss.

Dr. Neil Grigg
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January 9, 1973

Although there does not exist a complete Integrated Municipal Information System, the research to date indicates that not only is one feasible, it may be one of the most significant potential improvements in management of local governments in recent years. I will be forwarding a copy of the list of IMIS related publications available through the National Technical Information Service as soon as I receive the current listing. You may also wish to contact Mr. Knisely directly.

There appears to be a great deal of compatibility between the MWIS project and the IMIS project when one looks at the two from the standpoint of production, manipulation and utilization of data. The data gathered about the rainfall and flows throughout the system has potential usage and interaction with other functional areas and provision of municipal services. Those that appear very likely are set forth below, although I do not believe the listing is in any way conclusive.

1. The data collected from the present MWIS operations in San Francisco concerning rainfall could be correlated with incidents requiring some type of immediate or non-immediate public assistance in order to predict service demands upon the local government. For example, if it is known that a 3" rainfall over a 3 hour period correlates with police calls in a residential area, then it should be possible to shift patrol units and manpower assignments to the area in which the rainfall occurs in advance of service demands. Findings such as this could have a significant positive impact upon the management and operations of local government. It would also provide a demonstration of the application of data produced by one governmental function being key to the operation of another function. It is reasonable to assume that a number of obvious and perhaps not so obvious service demands may correlate with rainfall if one considers the terrain, extent and type of land use, and characteristics of the area's resident population.

I believe such findings are of sufficient importance that they should be considered as a component of the overall MWIS study. It also would seem that an important consideration to governments contemplating the installation of a MWIS is any potential that system has in assisting other areas of governmental service responsibility.

2. In relationship to the above but from a broader viewpoint, I do not believe that there is any scientific documentation about what takes place in an urbanized area during and following various types of rainstorms. Besides service demands upon the local government, are there other characteristics which are meaningful to man's dealing with his environment. For example, could there be a correlation between worker absence and rainfall, and, if so, why? Does there exist a relationship between consumer purchases and rainfall, as another example.

Dr. Neil Grigg
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January 9, 1973

Answers to these types of questions which assist in predicting behavior and understanding man are sought quite vigorously in the social sciences. It would seem that the rainfall records being developed in the City of San Francisco have great potential for this type of research.

3. In certain types of MWIS applications, the data should be usable in disaster avoidance and warning. For example, if it is known that a heavy rainstorm in the upper regions of a basin is occuring, an area subject to flash flooding may be evacuated on the basis of an early warning.

4.. The MWIS might interact with emergency services to correlate actual field conditions with the readings provided by the various sensors throughout the system. Such a correlation could result in the MWIS being able to supply data to the emergency services about hazardous problems to life or property in a rainstorm.

5. On a static basis, the MWIS model of the area served by the drainage system might be utilized to predict flooding and alert emergency services on the basis of weather forecasts.

6. It may be desirable in terms of cost and automation capability to investigate the utilization of existing municipal computer configurations rather than establishing an independent computer center for the MWIS alone.

7. The question of redundancy in the data collection, transmission, processing and control devices should be investigated. If portions of the physical system are critical to the protection of property and person, a failure in one of the automated components can result in serious damage. In these cases, redundancy of equipment or another backup system is usually warranted.

In conclusion, I believe that there is a great deal of benefit to local government which can be derived from the development of a MWIS. This benefit lies in the control of storm drainage and waste water and in the interchange of the data produced as a by product of operations in areas of functional responsibility other than the MWIS. It is this interchange of data which I believe deserves in depth research and investigation.

I appreciate the opportunity to review the MWIS Project and hope that the above comments prove of value to the project.

Very truly yours,

Stephen A. Lyon

Stephen A. Lyon

SAL:amc
Encl.

As a form of automation, the implementation of a MIS does not always meet with instant success among employees. Some reasons for this were given in a recent technical report from this project (51).

Recognizing the difficulties inherent in implementing the MIS, other researchers at Colorado State University have addressed the question of predicting the outcome of an information systems effort (40). This is closely related to the problem of predicting the <u>internal</u> organizational effect of a MWIS.

The socio-political constraints associated with implementing a MWIS were detailed in an earlier technical report (51). These constraints were basically:

1. The technical difficulty of achieving performance potentials with control systems,
2. The lack of political visibility of control systems compared to other solution alternatives,
3. Peculiarities of the parameters of the social choice system and its decision making subsystems,
4. The need and demand for specific justifications, especially monetary justifications,
5. The possible failure of control systems to produce what is prophesied by the technical and environmental feasibility measures. (This results partially from a lack of support by management in the first place -- an interactive effect.)
6. The possible failure of lay and even professional management and political decision-makers, as well as the public, to perceive many of the benefits when they accrue, which is a partial function of 5, below,
7. The communications barrier between the technological expert and the rest of society,
8. The inherent regional character of water problems despite the existence of few viable regional concepts and little or no means for implementing and institutionalizing regional plans.
9. Inadequate skill levels and financial resources.

It is interesting to note the similarities in the problems associated with implementing a control system and those associated with information systems in general. In a paper describing the problems of implementing an MIS, Gibson lists a number of "critical factors" which might bear on the outcome of the MIS effort (22). His list is reproduced below. It should be noted that his factors are not in any order of priority but that they are hypothetical critical factors.

CRITICAL FACTORS IN IMPLEMENTING MIS (22)

INVOLVEMENT in system design by management
IDENTIFICATION of informal organization
ATTITUDE of management toward a given system effort
ABILITY of management to use information generated
RECOGNITION of intangible benefits by management
KNOWLEDGE of computers possessed by non-computer personnel
EDUCATION and retraining of employees
DETERMINATION of company objectives
JUSTIFICATION of system cost
ATTITUDES of management toward design team members
EXPERTISE and creative ability of design team
IDENTIFICATION of information needs of management
ATTITUDES of employees toward computers
ADEQUATE staffing of design team
RESISTANCE to change by employees
ATTITUDES of design team members toward management
SOPHISTICATION and ambitiousness of design
DEFINITION of objectives of the system
COMMUNICATION abilities of design team
ADEQUACY of time frame for system effort

By noting Gibson's list there are definite similarities with the socio-political constraints on implementing control systems. Therefore the general problems of implementing automation and information systems have a great deal to offer in instruction for implementing MWIS.

III. COMPUTER AND CONTROL EQUIPMENT FOR MWIS

A real-time automation and control system such as shown in Figure I-2 requires a great deal of hardware. From Figure I-2 the items of hardware needed are:

1. Sensing equipment
   a. Rain gauges
   b. Water quality sensors
   c. System state monitors
      1) Pipe flow monitors
      2) Treatment rate sensors
      3) Tank level sensors
      4) Control position sensors
2. Control Equipment
   a. Valves, other controls
   b. Pumps
   c. Associated control software
3. Computer Equipment
   a. Input unit
   b. Memory unit
   c. Central Processing Unit
   d. Output unit
   e. Peripheral units
      1) Auxiliary Storage
      2) Displays, Console Equipment

One of the most difficult tasks associated with implementing an RTACS is the selection and implementation of this mass of equipment. In many ways the problem is similar to those which NASA faced and overcame in the Apollo program. It is clear, therefore, that the problem can be solved if sufficient technical and financial resources can be brought to bear on it. (for a discussion of some constraints on this implementation the reader is referred to Sections II and VI of this report and to reference (51,54).

There is no doubt that excellent hardware is available for most of the task. The hardware is ahead of the techniques for using it.

"...there is probably no field where the capabilities of available hardware so far exceed its application as in control engineering today. The extremely fast advance of technology during the past decade has produced a vast array of practical hardware, especially in electronics and computers, of course, but also in pneumatics and hydraulics (fluidic devices, for example), and in measurement (swirlmeters, digital techniques, on-line analysis instruments). The list of examples could go on and on, in all areas of control system functions and disciplines.

And yet, with all this very sophisticated and reliable equipment just waiting to be used, control engineers have hardly scratched the application potential. In particular, the hardware has been up-dated, but the control techniques being implemented are straight from days of yore!

You can indeed point to the broad use of electronics in process controllers for the chemical-petroleum industries for many years, with wide use of ICs even showing up in recent designs. But the newest circuitry merely copies conventional and very old controller equations. Progress has been painfully slow in the light of present electronic capabilities.

The first applications of digital computers to on-line control go back some fifteen years, and the latest minicomputers in the $10,000 class rival in power and speed computers of those days that sold for around $1 million. Reliability of such systems, now taken for granted, was almost hopeless back then. So it would seem we have come a long way.

But perhaps only the computer has. Control engineers, after all, still use the computer to calculate the same old control equations that we used to solve with analog devices--only now a lot faster and a bit more precisely. Speed and precision are useful certainly. But shouldn't we expect these very reliable and complex computer systems to do more than refine the calculations of ancient mechanical computers? Shouldn't electronic process controllers by now be digital and nonlinear? And shouldn't programmable controllers do more than copy relay logic?" (12)

There is evidence that control techniques and hardware are infiltrating into urban water practice rapidly. The professional and trade journals contain increasing quantities of material on information systems, automation, control and computer techniques.

The state-of-the-art of hardware and software adaptations to urban water applications is advancing too rapidly to be reported well in this brief section. A technical report issued earlier from the project did attempt, however, to report on existing and planned projects (47). This survey is summarized in Table III-1. It should be considered neither complete nor necessarily up-to-date, but it can be considered as a introductory survey on agencies plans and activities.

Table III-1

APPLICATIONS OF INSTRUMENTATION AND CONTROL (47)
In Water and Wastewater Systems

Notes:
1. A parenthesis ( ) in any column indicates "future capability" (being implemented or designed).
2. The last column contains the "Exhibit No." or "Summary No." (for additional information).
3. Under "Type of Equipment", the word "usual" means sensors, telemetry, data displays, recorders, & controls.
4. "Use" Categories (Nos. 1,2,3,4,5, and 6) are defined at end of table.
5. An "x" in a Use column designates an application; an "M" designates "manual operation".

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary *
1	Alabama, Birmingham Water Works Board City of Birmingham	Water Pumping & Storage			x	x			Usual	1960	S-1
2	Alabama, Jefferson County Jefferson County Commission of Jeff. County	Wastewater Treatment and Disposal						x	Usual	1957	E-1
3	California State of California Dep't. of Water Resources	Water Pumping & Conveyance	x	x	x	x	(x)		Digital Computers Data Loggers	1970 (circa)	S-2
4	California, Alameda County Alameda County Water District	Water Pumping, Conveyance & Storage			x	x			Usual	1965	E-2
5	California, Fresno City of Fresno Public Works Dep't., Water Div	Water Pumping & Conveyance			x	x			Usual	?	E-3
6	California, Los Angeles City of Los Angeles Dep't. of Public Works	Wastewater Treatment (Hyperion Plant)	x			x			Data Logger	1966 (circa)	S-3
7	California, Los Angeles City of Los Angeles Dep't. of Public Works	Wastewater Treatment (3 New Plants)	(x)	(x)			(x)		Digital Computers (with Data Logging)	(1973)	S-4
8	California, San Francisco City & County of San Fran. San Francisco Water Dep't.	Water Conveyance & Storage.			x	x	(x)		Usual	?	E-4
		Water Treatment			x				Usual	?	E-4

* in reference (47)

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary
9	California, East S.F. Bay Area East Bay Munic. Utility Dist. (Oakland)	Hydrologic Data Collection,	x						Radio Transmitters Data Logger	1965	S-5
10	California, Santa Clara County Santa Clara County Flood Control & Water District	Water Treatment. Water Conveyance. Hydrologic Data Coll.	x	x	x		(x)		Digital Computer for Logging & Control	1964 and later	S-6
11	Colorado (Rocky Mountains) Goble, Sampson Assoc., Inc. Denver, Colorado	Hydrologic Data Collection (Snow)						x	Analog Recorders, Analog-Digital Converters, Solar Cells	Circa 1960's	S-7
12	Colorado, Aurora City of Aurora Utilities Department	Water Treatment			x	x			Usual	1967	S-8
13	Colorado, Boulder City of Boulder	Water Treatment. Water Pumping & Conveyance			M M				Usual Usual	? ?	E-5 E-5
14	Colorado, Colorado Springs City of Colorado Springs Dep't. of Public Utilities	Water Treatment			x				Usual	1969	S-9
15	Colorado, Denver Denver Water Board	Raw Water Conveyance. Water Distribution. Water Treatment.	x x (x)	 (x) (x)	x x x	x x x	(x) (x) (x)		Digital Computers for Logging (for control in future).	1968 1971 (1980)	S-10 S-10 S-10
16	Colorado, Grand Junction	Water Treatment			x				?	?	E-6
17	Colorado, Westminister	Water Treatment			x				?	?	E-6
18	Connecticut, Bridgeport City of Bridgeport	Wastewater Treatment					(x)		Digital Computers, Data Loggers	(1972)	S-11
19	District of Columbia Dep't. of Sanitary Engineering, Water Operations Div.	Water Pumping & Distribution			x	x			Usual	?	E-7

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary
20	Florida Central & Southern Florida Flood Control District	Hydrologic Data Collection				x		x	Usual	?	E-8
21	Florida, Miami City of Miami Dep't. of Water & Sewers	Raw Water Conveyance & Water Treatment			x				Usual	?	E-9
22	Florida, St. Petersburg City of St. Petersburg Water Department	Water Pumping & Distribution			M				Digital Controls	1966	S-12
23	Georgia, Atlanta City of Atlanta Public Works Dep't.	Wastewater Treatment	(x)	(x)			(x)		Digital Computer for Data Logging & Control	(1973)	S-13
24	Georgia, Atlanta City of Atlanta Dep't. of Water Works	River Monitoring &	x						Data Logger	1963	E-10
		Tap Water Monitoring.	x						Data Logger	1963	E-10
		Water Distribution.	x		M				Data Logger	1951	E-10
25	Illinois, Cook County M.S.D. of Greater Chicago	Equipment Monitoring.	(x)						Computer-Data Logger	Future	S-14
		Water Quality Monitorng	x	x					Computer-Data Logger	1969	S-14
		Wastewater Treatment			M	x			Usual	?	S-14
		Wastewater Pumping			M	x			Digital Telemetry	?	S-14
26	Illinois, Chicago City of Chicago Bureau of Water	Water Treatment	x	x		x			Computer-Data Logger	1964	E-11
27	Illinois, Springfield	Water Treatment			(M)				Usual	(1972)	E-12
28	Indiana, Ogden Dunes Gary-Hobart Water Corp.	Water Treatment			(M)				Usual	1966	S-15
29	Iowa, Des Moines City of Des Moines	Wastewater and Stormwater Pumping						(x)	Usual	(1972)	S-16

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary
30	Iowa, Dubuque City of Dubuque	Water Treatment	(x)	(x)			(x)		Digital Computer Control, Data Logging	Circa (1974)	E-6
31	Minnesota, St. Louis Park City of St. Louis Park Water Works Dep't.	Water Pumping, Storage & Distribution			x				Usual	1964	S-17
32	Michigan, Detroit City of Detroit Metro Water Department	Combined Sewers & Pumping Stations	x	x	M		(x)		Digital Computer-Data Logger	1971	S-18
33	Minnesota, Minnpls.-St. Paul Metropolitan Sewer Board	Combined Sewers	x	x	x	x	x		Digital Computer-Data Logger	1969	S-19
34	Missouri, Kansas City City of Kansas City Poll. Control & Water Dep'ts	Water Pumping & Treatment			M	x			Usual	1957	E-13
35	Missouri, St. Louis City of St. Louis Dep't. of Public Util., Water Division	Water Pumping & Distribution			M				Usual	?	E-14
36	Nebraska, Omaha City of Omaha Public Works Dep't.	Wastewater Pumping & Grit Removal						x	Usual, plus T-V	1969	E-15
37	New Jersey, Passaic River Passaic Valley Sewerage Cmrs. (Newark)	River Monitoring. Sewer Overflow Regulation	(x)	(x)	(x)				Usual	(1976)	S-20
38	New Mexico, Albuquerque City of Albuquerque	Well & Booster Pumps, Reservoirs	x		x				Data Logger	1958	S-21
		(After improvements)	x	x			(x)		Digital Computer-Logger	(1972)	
39	New York, Hudson River State Dep't. of Environmental Conservation	Water Quality Monitorng	x	x		x			Digital Computer-Data Logger	1968	S-22

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary
40	New York, Monroe County Monroe County Water Authority	Water Pumping and Distribution	x	x			x		Digital Computer-Data Logger	1971	S-23
41	New York, Syracuse City of Syracuse Dep't. of Engineering	Water Pumping.			x				Usual	?	E-16
		Water Storage.						x	Usual	?	E-16
42	New York, Troy	Water Treatment.			M	x			Usual	?	E-17
		Water Pumping.			x	x			Usual	?	E-17
43	North Dakota, Bismarck City of Bismarck Dep't. of Public Works	Water Storage						x	Usual	?	E-18
44	Ohio, Ohio River & Tributaries Ohio River Valley Water Sanitation Commission	River Monitoring	x	x					Digital Computer-Data Logger	1960	S-24
45	Ohio, Akron City of Akron Public Utilities Bureau	Water Pumping.				x		x	Usual		E-19
		Water Metering.						x	Remote Meter Readers	(1972)	E-19
46	Ohio, Cincinnati Metropolitan Sewer District of Greater Cincinnati	Sewers & Sewage Lift Stations			M				Usual	1966	S-25
47	Oklahoma, Oklahoma City City of Oklahoma City Water Department	Raw Water Conveyance			M				Microwave	1964	E-20
48	Oregon, Coos Bay-North Bend Coos Bay-North Bend Water Board	Water Pumping & Storage						x	Usual	?	E-21
49	Oregon, Portland City of Portland City Engineer	Wastewater Treatment			M				Usual	(1974)	S-26

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary
50	Pennsylvania, Philadelphia City of Philadelphia Water Department	Water Pumping & Distribution.	x	x	M				Mini-Computer, Microwave	1960's	E-22
		Water Quality Monitorng.	(x)	(x)				x	Computer, Orbiting Satellite.	Future	E-22
		Water Treatment	(x)	(x)			(x)		Dig. Computers, Microwave	(1975)	E-22
51	Tennessee, Memphis City of Memphis Light, Gas & Water Div.	Water Pumping			M	x			Usual	1965	S-27
52	Texas, San Antonio City of San Antonio City Water Board	Water Pumping & Distribution.	x	x			x		Digital Computer	1968	S-28
53	Texas, Dallas City of Dallas Water Utilities Dep't.	Water Pumping & Distr.	(x)	(x)	(x)	x		x		?	S-30
54	Texas, Houston City of Houston Dep't. of Pub. Works, Water Division	Water Pumping & Distr.	(x)	(x)		x	(x)		2 Dig. Computers-Data Logger	(1973)	S-31
55	Texas, El Paso City of El Paso El Paso Water Util. Public Service Board	Water Pumping & Distr.	x				(x)		Dig. Computer-Data Logger	(1972)	S-32
		Water Reservoirs.						x			
		Sewage Lift Stations						x			
56	Virginia, Richmond City of Richmond Dep't. of Public Utilities	Water Pumping			M				Usual	?	E-23
57	Washington, Metropolitan Seattle, City of Seattle Water Department	Water Storage & Distr.			M				Usual	1959	S-33
58	Washington, Metro Seattle Munic. of Metro Seattle	Combined Sewers	x	X	X	X	x		Dig. Computer	1971	S-34

No.	Location Owner & Operator	System	"USE" Categories #1	#2	#3	#4	#5	#6	Type of Equipment	Operation Began	Exhibit or Summary
59	Washington, Tacoma Dep't. of Public Utilities	Water Pumping & Distr.			x			x	Usual, F-M Radio Sig.	1959 to Date	E-24
60	Wisconsin, Madison Madison Water Utility	Water Pumping			M				Usual	1952	S-35
61	Wisconsin, Milwaukee Sewerage Commission of the City of Milwaukee	Wastewater Treatment	(x)		(x)	x			Computer-Logger being installed	(1972)	S-36
62	Wisconsin, Milwaukee City of Milwaukee Dep't. of Public Works	Water Pumping. Precipitation.			x			 x	Usual Usual	1968 ?	E-25 E-25
63	Wisconsin, Racine City of Racine	Water Quality Monitoring.						x	Usual	1971	S-37
64	Manitoba, Winnipeg (Canada) Metro. Corp. of Greater Winnipeg	Water Pumping	x		x				Dig. Computer- Data Logger	1960-'68	S-38

"Use" Categories

1 Data Logging and Analysis (all or individual);

2 Data Processing and Reduction;

3 Conventional Supervisory Control (remote; "hardwired" or manual);

4 Automation of Parts of a System;

5 Computer Control (central automatic control, digital, "softwired"); and

6 Monitoring "only".

Table III-2 lists Minneapolis-St. Paul, Detroit and Seattle as having combined sewer control systems in some stage of development. To this list should be added San Francisco and Cleveland as both of these cities have taken steps in that direction. A number of cities are considering control systems.

Any attempt to describe the state-of-the-art of computer and control technology in this report would be naive. The editorial statement given earlier is accurate concerning the ratio of hardware technology to control techniques available. What is needed, however, is a description of hardware needs to utilize different types of control approaches.

The operation of an RTACS is described in Section V. It is shown there that two basic models are required for the computer control center; a prediction model and a control model. The prediction model predicts hydrologic and hydraulic responses of the system to rainfall, runoff and control changes and the control model specifies how best to control the system to achieve the control objectives.

In order to select the hardware for a computer control center the level of sophistication of models to be used should be known. Alternately, and more likely, the hardware could be selected and the models tailored to fit within the capacity available.

To focus on the specific requirements of selecting hardware for a control center, consider the following hypothetical case for the basin shown in Figure III-1. The basin has essentially two points where decisions can be made: flow can be diverted either out of or into storage and flow can be sent to overflow or through the treatment plant.

Consider that the basin is controlled by the RTACS shown in Figure III-2. The two models are shown in the computer center. The system model must be able to predict discharges in the system as a function of time and space and the control model must be able to issue instructions based on these predictions.

The prediction model problem has three basic components: hydrologic prediction, hydraulic routing, and routing through the auxiliary storage basin shown. One model which will perform these tasks is the EPA "Stormwater Management Model." It requires the equivalent of an IBM 360/65 with peripheral storage devices and usable core capacity of at least 350K bytes (33). A breakdown of the storage requirements of the separate blocks of the model in representative runs are as follows:

Table III-2. Summary of Activities in Combined Sewer Control Systems

City	1973 Stage of Completion	Equipment in Computer	Equipment in Control	Equipment in Instrumentation	Representative References
Minneapolis-St. Paul	Hardware in. System in operation.	DEC PDP/9	In-System Regulators.	Telephone telemetry. Raingages, flow monitors, quality sensors.	(34)
Detroit	Hardware in.	Central Digital	In-System Regulators.	Telemetry, raingages, flow monitors.	(1)
Seattle	Hardware in. Programming continues on a phased program.	XDS Sigma 2	In-System Regulators and pumping stations.	Telephone telemetry. Raingages, flow and quality monitors.	(35,21)
San Francisco	Data Acquisition System in. Extensive Master Plan complete	Data Acquisition Honeywell 316	Auxiliary and Tunnel Storage being considered.	Rainfall and runoff gages. Telephone telemetry.	(43,23)
Cleveland	Data Acquisition System in operation.	Data Acquisition	In-System Regulators planned.	Telephone telemetry, Raingages, flow monitors, quality sampling program	(39)

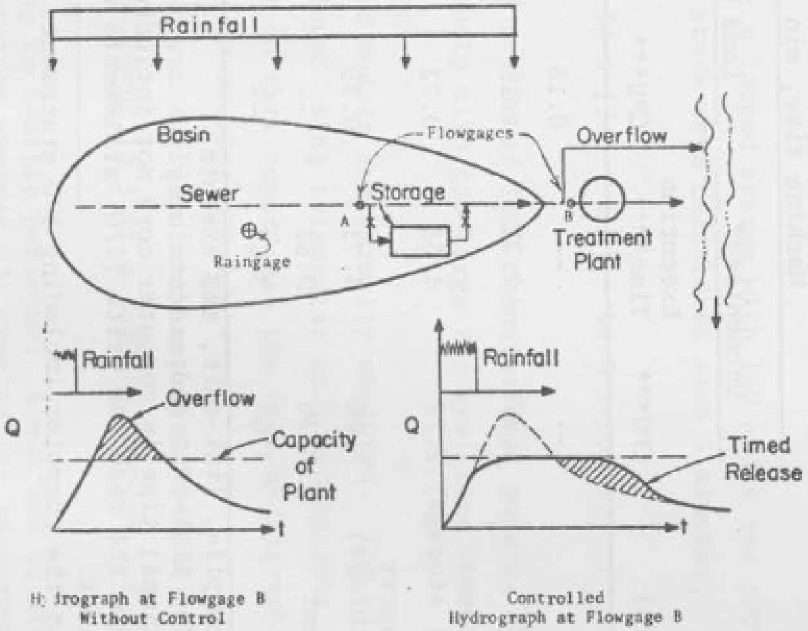

Figure III-1. Single Basin Controlled by RTACS

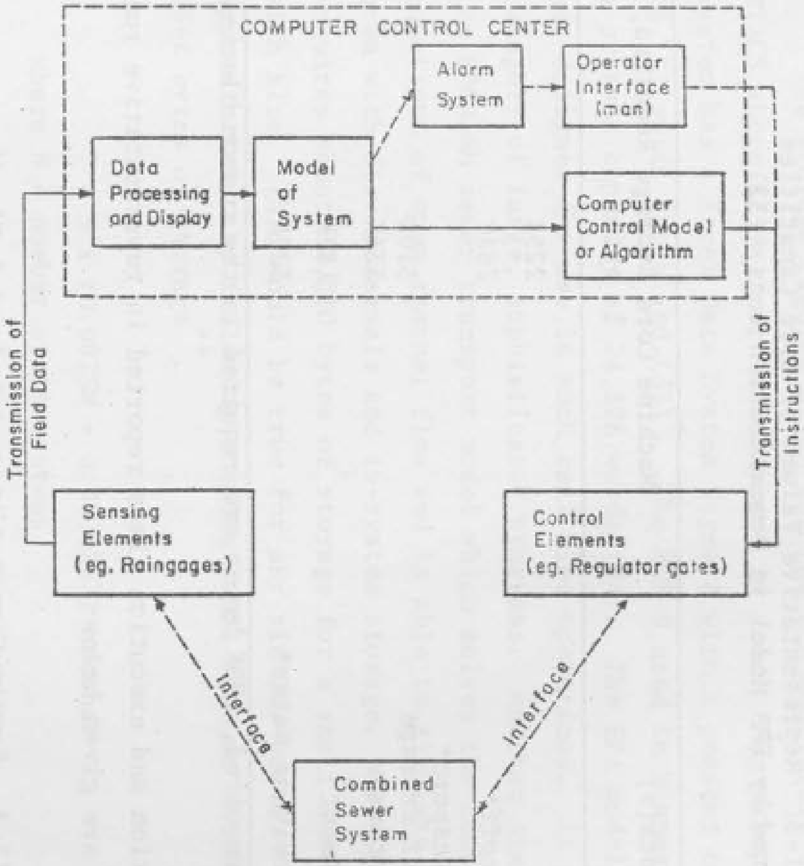

Figure III-2. RTACS to Control Single Basin

Table III-3. Representative Values of Core Capacities Required by EPA Model in Demonstration Runs (33)

Program Block(s)	Machine Core Storage Required, bytes
Executive*	225K
Executive and Runoff*	264K
Executive and Transport*	
Without internal storage	310K
With internal storage	334K
Storage and Treatment	183K
Executive and Receiving Water*	327K

*Of the storage required, 170K bytes are required in the common blocks.

The compilation and execution times reported in representative runs on an IBM 360/67 are given below:

Table III-4. Sample Compilation and Execution Times on Demonstration Runs, EPA Model on IBM 360/67 (33)

	Machine time, min			
	Uncompiled*		Load Module**	
Program Block(s)	CPU***	Execution Time****	CPU***	Execution Time****
Executive	--	--	0.18	0.28
Executive and Runoff	1.39	2.22	1.15	1.97
Executive and Transport (without internal storage)	2.77	4.38	0.72	1.16
Executive and Transport (with internal storage)	3.06	4.71	0.85	1.30
Storage and Treatment	0.36	0.52	--	--
Receiving Water	2.60	3.57	--	--

*Time includes compile, link-edit, and execute.
**Time required for link-edit and execute only.
***Actual computational time in computer core not including the time needed to execute the read and write (I/O) statements or to run the peripheral devices.
****Time required in the computer including I/O statements.

The storage figures given for the EPA model rule out its use in an RTACS where a small or minicomputer is used. For example, the Seattle system has a Xerox Data System Sigma 2 with a present core capacity of 49,152 words installed (35)*. The PDP-9 used in Minneapolis-St. Paul has a present capacity of 24,576 words (34). The EPA model was obviously not designed for use in such real-time operations. It falls into a category of large, sophisticated programs. Another similar program is the SOGREAH sewer transport model which solves the complete St. Venant equations of open channel flow and is able to simulate large sewer networks even with flow reversals and in-system storage. This program apparently requires about 65,000 bytes of storage for a small network, increasing with size. This would be true for any similar model. It requires approximately the following computational time on an IBM 360/65 with 256K bytes of storage**.

$$T = N \times (0.0025M + 0.00002n^2) \text{ seconds}$$

where N = number of time steps

M = number of computational points

n = number of nodal points when the network is looped.

When the network is branched, n = 0

Thus, for a looped system with 100 nodes and 1000 computational points, if a two hour storm were calculated each 5 minutes,

$$T = 24 \times (2.5 + 0.2) = 64.8 \text{ seconds}$$

For a branched system of 1000 computational points, T = 60 seconds. This model is obviously also too large for real-time operation if a minicomputer is being used.

Simplified models are normally employed. The Minneapolis-St. Paul RTACS has been developed using triangular unit hydrographs (25). The models examined later in this report use the unit hydrograph approach combined with a Muskingum sewer routing procedure.

As pointed out earlier in this project (48,54) the selection of computer and control equipment is just a complex problem. A large number of primers

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*According to Seattle personnel, about 26K of storage is devoted to foreground operation whereas 13K remains for background model operation.

**Personal communication from J. Cunge, Engineer with SOGREAH.

and other guidelines exist which purport to tell managers or other users how to select equipment. The computer and control industry has grown so large that the National Technical Information Service now issues abstracts in that area as one of seven main categories of information. It appears that managers who must purchase and implement this equipment will increasingly require good advice from engineers who understand computers and urban water problems.

IV. SOCIAL MODELING AS AN AID TO IMPLEMENTING CONTROL SYSTEMS*

In Phase I of the MWIS study the social and political feasibility of automating sewer systems was investigated. The Phase I completion report summarized material from a Technical Report issued specifically on this subject (51).

It is important to understand the characteristics of social systems as they contain intricate and complex interrelated characteristics and functions, many of which have never been adequately defined or understood. Among their more crucially important characteristics are:

- their insensitivity and resistance to change.
- the paucity of points at which they can be affected and changed.
- the tendency for them to generate short-term solutions at the expense of long-term consequences.
- the consequent tendency to turn managers into short-term "hole-pluggers" and "firefighters."

Many of the problems associated with implementing control systems are also present in any automation or information systems effort. This was discussed earlier in Section II. Combined sewer control systems are complicated by the presence of environmental constraints and standards and by the fact that they are in the public sector. The problems that they are designed to correct are highly visible, therefore the control system solution is tightly constrained by a number of factors.

Since control systems are enormously expensive they cannot be installed as an experiment to see if they will work. Nor can public

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* R. McGreggor Cawley of Colorado State University assisted in the preparation of this section.

agencies afford to pour space-program levels of funding into their implementation. Since implementation is complicated by many socio-political factors, it behooves the manager to gather as many facts as he can regarding his problem before finalizing his plans. One approach to studying the implementation problem beforehand is through social modeling.

Social modeling is a rather broad term which can be used to refer to quantitative modeling of social systems such as Jay Forrester has recently done (59) or forecasting approaches such as the Delphi method or to behavior models such as the ones considered here. The discussion in this section is intended to set the stage for modeling approaches to environmental quality problems in general, and as their subset, to the problem of automation of control systems for combined sewer systems.

Statement of the Problem

The basic problem is to implement water quality standards for combined sewer overflows in the face of shifting standards and requirements. This problem must be faced by a number of individuals and agencies in large U.S. cities. They preside over work directly under municipal officials and heads of local agencies. It is the people who manage and operate local sewer agencies who face the problem most directly.

The problem is not restricted, of course, to water quality. The same question faces those working in other areas of pollution control. The problem as addressed here, however, is confined largely to the question of water quality; more specifically, it is constrained to water quality for combined sewer flows.

A primary source of the difficulty in reaching satisfactory solutions is the traditional dichotomy between the responsibility for development and responsibility for implemntation of policy and standards. The quality standards are usually developed in one arena and implemented in another. A federal agency such as the Environmental Protective Agency (EPA) establishes standards under its Congressional authority, but reponsibility for achievement of standards rests with local agencies who must define the techniques and installations for achieving the standards as well as implement the process. Those agencies are normally direct arms of the state administration in which they are located thus giving them a large degree of independence of federal control, but likewise, placing them under extremely tight state controls if state legislatures decide to assert the control which is theirs. The state legislative power over cities and towns, for example, is supreme with respect to urban government ordinances and action that involves protection of health, welfare, safety, and morals (police powers). Thus positioning of the agencies in the governmental structure further compounds the problem since most local units are closely bound by state law and regulations. This makes urban governments responsible for compliance with state policy, regulation, and standards, fulfilling the U.S. constitutional functions under the states' reserved powers to protect health, welfare, safety, and morals. State standards frequently differ from federal standards, and requirements freqently conflict with each other.

A second source of difficulty in reaching solutions is the uneven development of local agencies. Techniques and development for control of pollution are much further advanced in some cities than in others.

Some of these disparities are rooted in variations of available resources, especially economic or financial; others are rooted in variations in personnel, especially in the varying levels of receptivity to new information and technology. Likewise the variance in leadership characteristics plays a vital role.

It is doubtlessly true, too, that underdeveloped and backward agencies encounter greater difficulty in meeting established standards than do the more developed ones. They apparently also find it more difficult than developed agencies to resolve problems arising from conflicting or shifting standards. Deficiency in social, political, and management skills tends to characterize the underdeveloped agencies. They usually lack information in larger quantity than do developed agencies, and this problem is further compounded by limited skill in using information they do possess.

Among the formidable generators of difficulty in meeting or complying with standards, however, is system obsolescence. Many systems which cannot be completed within a three to five year period are likely to be obsolete before they are fully operational. Thus, wise amortization to meet sound taxing, financing, and resource allocation policies are likely to conflict with sound technological policy. Indeed, taxing and financing policies are frequently designed to amortize human pain and inconvenience in the long-run by series of short-run incrementalist phasing. Potential long-run obsolescence frequently becomes a secondary factor in overall or comprehensive policy.

Certainly, too, the problem is compounded by the simple appeal of the new and different. Even the most stodgy specialist tends to tire rather quickly of the changes that were once exciting, new and innovative. Americans are especially prone to push on, initiate new changes, or redevelop before they have completed what was recently new. This is partially the story of metropolitan sewer control systems. They have been sluggish in development. Few have advanced beyond the first or second stage (phase) of implementation, and none at this writing have advanced to a fully automated state.

Phase I of this study indicated that several factors, events and other characteristics of local sewerage agencies have a high potential for constraining development. These constraints might be listed briefly (although somewhat incompletely described) as follows as they are taken from a case study of the Metropolitan Sewer System of the Twin City area: (51)

1) Inadequate communication within administrative hierarchies:
   a) tendencies for communication to flow upward with far greater difficulty than for information that flows more downward
   b) attitudes toward status along the hierarchical channels
   c) tendencies for managers to constrain their worlds and thus reduce the scope of the problems they face by limiting or constraining information inputs
   d) structural constraints on communication channels imposed by bureaucratic hierarchical structures
   e) limitations on time available for adequate in-system communication
   f) tendency for urban growth patterns and enlargement of the bureaucracies to extend lines of communication
   g) although not identified in the Minneapolis-St. Paul system, a tendency for select personnel to hoard or control certain information because of the power advantage information control affords
   h) organizational status distance. As distance increases between statuses, the volume of communication decreases.
   i) high levels of specialization among a wide variety of persons and positions lowers the volume of communication
   j) professional language barriers
   k) preconditioned and acquired attitudes
2) The paucity of points in any system at which the system can be entered and changed or re-directed.

3) The tendency of most systems to seek courses of least resistance and to produce short-term solutions, many of which are counter-productive to long-run solutions.

4) Insensitivity of social systems to the need for policy change, new programs, or new solutions.

5) Low visibility:

   a) low public visibility of sewer systems, their administration, or what they accomplish or need to accomplish

   b) low administrative visibility of a control system, its functions and its potential as a problem-solver (this appears to be a direct function of the proportionate size of the control system budget to the total sewer budget, the small size of the control system, staff, the position of that staff in the hierarchy, etc.)

   c) low visibility among operators and other lower echelon personnel of a control system, its functions and its potential as a problem-solver

6) Political Constraints

   a) low political skills, especially among selected specialists and hybrids

   b) conflicts resulting from

      i) differing sets of in-group loyalties
      ii) differing between-group goals
      iii) differing group styles within the organization
      iv) differing group goals within organizational groups
      v) organizational recruitment practices and customs
      vi) differing applications of the labor ethid

   c) low political awareness on some counts

   d) civil service and salary constraints on recruitment and promotion of adequate skills

   e) patronage constraints and investments in select personnel

7) The sunk costs in established systems

8) Organizational structures

9) Economic constraints:

   a) demand that new ventures be economically feasible

   b) failures to consider social, environmental or other consequences of activities or changes in activities

   c) a tendency to depreciate social and environmental feasibility and statements of them

   d) economic resource inadequacy to accomplish objectives

These comprise no more than an incomplete listing of a wide variety of socio-economic-political constraints. Their relative intensities as constraints vary with differing circumstances and conditions as well as the way in which their forces interact with each other. Their number soon outruns the present capabilities for adequately refined measurement, since the underdeveloped techniques of social science measurement do not provide a basis. Without such a basis, key or control variables--those which traffic other variables--cannot be examined in a manner which would enable analysts to use them more fruitfully in problem solving.

Nonetheless, such constraints can be identified and used. They have been isolated as constraints, or as symptoms of constraints, in the past as well as the present. Yet, the constraints established during Phase I must be considered hypothesized constraints at this juncture. But this, as the psychologist, B.F. Skinner, suggests, may be sufficient to provide a route to alternate solutions (61). Possibly, as he also suggests, the social scientists' fetish with more precise measurement is admirable but dysfunctional to reaching vital solutions. Briefly, we cannot allow the need for precise measurement to overrun our need for solutions. The problem in Phase II of this research, as in Phase I, has been to isolate constraints on sewer system development to meet standards, but more importantly, to devise, suggest, and experiment with means for overcoming them in a manner that would cause the least disturbance to the social system and maximize the result of the change. In this case, certain precision in measurement would doubtlessly prove very helpful, but it may not always prove to be a necessary and sufficient condition for reaching solutions.

The primary focus, therefore is on alternate solutions. It must be accepted that social and political systems constrain technological changes, especially those that involve shifts in public policy. Any alternative, plan, or change in technology to meet EPA standards, for example, must necessarily run the test of public acceptance, either among the public's decision-makers, the public itself, or both; otherwise, it has no political feasibility. Without political feasibility, an alternate solution is in about the same state as one which has no technical feasibility. Hence, social and political constraints must be identified and technological alternate solutions to problems must be considered in terms of those constraints and the probable success of mechanisms for overcoming them.

Model Development for Solution

Technological implementation is ultimately, indeed, always a matter of human choice. There will be no advance to the final automation stage in Minneapolis, San Francisco, or anywhere else unless someone decides to do it. Such decisions need not come from one person or from many persons, from high status or low status; but someone decides. Sometimes the decision is made without full realization on the part of the one who makes it of what is being accomplished. Hence, the major question for the purpose here is what motivates the properly located persons to make the choice.

Theories of motivation remain highly suspect and often without much clout in many quarters. The recent debates over the death penalty bear witness to this. Traditionally, Americans have relied heavily upon utilitarian views of the world or utilitarian theories of political and social motivation as a basis for prodding men to act in particular ways. Essentially, that theory builds on a Hobbesian premise that man's primary concern is safety of life and limb (safety values) and that the primary motivating force is fear. Basically, it is assumed that men bond with each other into communities to avoid a state of total conflict resulting from man's selfish drives.

Secondly, the theory builds on another premise which holds that men will naturally seek (when they perceive benefits) to maximize their benefits and minimize their personal costs. This has wide currency in America and underlies such traditional formulae and models as the benefit/cost ratio and the economists' classical model of economic man. To many Americans, this is what defines "rationality." It helps define the "Rule of American Reasonableness" in the courts and the model of economic man for the American economists.

The stress of American utilitarianism, therefore, has been on punishment and reward as motivating forces. Such a simplistic theory can be readily understood by most anyone, a fact which undoubtedly accounts for its wide popularity and appeal in America and many parts of the world.

Historically, governments, industries, and business, as well as other institutions have sought negative and positive motivating or incentive devices and programs to move men toward solution of problems or away from the creation of problems. The historic grants-in-aid program is one example. Tax sharing is a recent adaptation of aid programs. Indeed, the grant idea under which this very research is supported constitutes a type of incentive mechanism and give credence to the efforts being made in behalf of solution on the part of the researchers.

In 1972, the national administration undertook a search for new incentive programs. An example was the Administration's charge to the National Science Foundation to develop and test new incentive programs for the transfer of technology and information. Coupled with this was the reorganization of the federal government structure and its image. The modification of the structure is a long painful process. Any such change is usually measured in both pain and time. The image, however, has changed considerably and very quickly. One factor involved in this changing image has been the new revenue sharing program. A new picture of government has begun to emerge which portrays government as different sort of provider for the people. Images of the bureaucracy have shrunk some and there is a decline in the feeling that government takes more and more tax money while providing fewer services. Although tax sharing is too new to claim any tangible success, it is a good example of attempts to provide new incentives.

To repeat for emphasis, the concept of incentive processes is not a new one to the government. Without considerable concern directed towards incentives, many existing highways, including the first Cumberland road would be nothing more than dirt trails, if that. Education, universities in particular, are quite cognizant of the impact of governmental incentives oriented toward research. Grants and grants-in-aid are not the only components of the incentive matrix used by the government. There are also overt incentives such as depletion allowances and tax breaks, and more covert ones such as conferences which encourage the transfer of knowledge and technology. Also, there is the other side to this picture--the wide varieties of negative incentives at the disposal of the government. These are of particular importance here, for they make up the bulk of incentives presently used in the struggle for pollution abatement. The laws dealing with pollution, dating back as far as the mid 1800's, have continually emphasized the negative approach--penalty.

Though the bulk of legislation has offered grants, the letter of the law has remained rather constant. Polluters will be punished with litigation and fines. This is as negative in connotation as murder being punished with imprisonment and death. Given the national administration's recent emphasis on location of new incentive processes, it seems appropriate to consider new incentive processes to achieve minimization of pollution effects. To punish the discharger for creating or contributing to pollution, is to be both myopic and unrealistic. It is myopic because the cost levied against the discharger will be passed onto the public in terms of higher prices. It is unrealistic because the discharger exists largely and survives to produce goods and service for public consumption. If the discharger's product were for the benefit of him only, then such punitive action might be justified. But urban populations are major dischargers without much profit motive attached to their effluent in many instances. Possibly an incentive program might be devised to punish the discharger if he continues to pollute, and more importantly, reward him if he cleans up the air and water. Yet, it must be recognized that to reward the discharger directly often creates political repercussions so severe that it defeats any accrued advantage.

However, incentives are available which could be offered the state and local governments in a manner that would encourage them to apply pressure on the dischargers. Basically, for example, the states could possibly be induced to utilize revenue sharing to achieve pollution abatement. If successfully implemented and possibly coupled with penalties, this process might not only serve to achieve EPA standards, but it might also provide some decentralization of federal controls.

Indeed, the information on pollution abatement points to a need for some decentralization because of the varying pollution situations. In fact, given the successful implementation of revenue sharing for pollution abatement, a model might be provided for use in attaining other national goals (e.g., technological transfer), thereby eliminating many road blocks which appear in the search for social solutions.

Such a program is obviously experimental in nature. It must be tried if it is to be tested. Obviously too, if that is to be accomplished, an act of Congress would be required which is a highly improbable condition to impose on an experiment. It is safe to predict that Congress would not act in any manner that fulfilled the necessary conditions of the experiment.

The question, therefore, becomes one of how incentive programs might be tested to determine their viability in the real world. This research has surfaced two incentive programs which might prove worthwhile in efforts to overcome common constraints on development of means for meeting environmental standards. One program involves the use of tax sharing or some variants of grants-in-aid in a revised incentive context. The second involves incentive programming and experimentation. For both the search and the tests must be geared to the identification of an incentive process which would be strong enough to stir state, urban, and other officials to overcome the combinations of constraints on progress that are peculiar to their domain. Constraints, such as those listed above from a Phase I report obviously differ in intensity and the manner in which they combine from jurisdiction to jurisdiction. This inevitably means that each setting requiring or demanding progress will have to assess the types and intensities of constraints peculiar to it.

The Crucial Question: Acceptance and Use of Demonstrably Successful Incentives and Technological Alternatives by the Social System

Each of the incentive programs suggested above involve pragmatic and utilitarian response to the growing public and national administration's demand for practical and pragmatic tests of alternatives in the real world. The crucial question, however, is whether demonstrated alternatives will be accepted in the public realm. This brings the processes of social choice into focus as a primary element. It is this element that is seemingly so frustrating to technologists and managers of technological systems for the past two to three decades. The question might be phrased for many technologists and managers of technology as one of political or social choice feasibility.

Research efforts in Phase I of this study revealed that almost everywhere the researchers looked, there was frustration over the varying criteria used for choosing alternatives as the alternatives were moved from one realm of choice to another (51). Attempts were made during that phase of study to point out that ground rules for making choices change as alternatives are moved from one realm of choice to another. It also appeared obvious to the investigators that efforts should be made to spell out the underlying basis for such changes. Failures to understand what is behind the changes is a source of confusion and frustration to both choosers and sponsors of alternatives. This is understandable since almost everyone functions in terms of expectations based upon what worked in the past, and when those expectations are violated they are confused about the cause.

The point is, however, that the ground rules in choice realms have not only shifted some, they have shifted dramatically in the past decade.

Technologists and managers technological social systems are naturally startled by such changes in ground rules, especially if those rules are at wide variance with the ones they embrace and find most familiar. Readers will recognize a similarity in this phenomena and those reported in Toeffler's book, Future Shock (56). Studies in Phase I demonstrated unmistakably, for example, that technologists were increasingly baffled by the growing tendency for political choice systems to reject demonstrably efficient and effective alternatives when the selection process was moved from the planning to the political realm. A key to overcoming such frustration is a clear understanding of the basis of such rejection. It is this basis that is poorly understood and sorely neglected.

The basis of which we speak here involves the premises, assumptions, and beliefs about the political and social system as well as the premises about environments in which those systems reside and function. Briefly, in the words of Walter Lippman, men have "pictures in the head" of how a system functions, and they also have "pictures in the head" of how a system should function (30). Discrepancies or variances between the two pictures in a single head makes revolutionaries of some people and disgruntled or disenchanted alienates from the system in other instances. Briefly, the wider the discrepancy between what is and what should be or how the system seems to function and how the particular person believes it should function is a key variable in directing his behavior and responses to the system. On the one hand, decision-makers and managers choose in terms of the ways in which the "pictures in their heads" see the world functioning as well as how they believe it should function; on the other hand, non-leaders and other members of the body politic respond to their leaders' choices in terms of the same type of complexes of perceptions which often vary sharply from those of the leadership. These perceptions of what "is" and what "should be" vary from person to person; but in a single culture there are usually common threads, points of consensus, or areas of broad agreement. Problems are apt to emerge when those common threads break.

Persons skilled in the management and operation of technological systems or those skilled in the development of technology are frequently caught unaware by the breaking of such threads (the shifts in the underlying premises on which choices are based). This is especially true of persons who lack either social analytic skills or the information about the social milieu on these scores. Tragically, the upshot is that persons faced by problems arising on the heels of such shifts are likely to be led down blind alleys that merely confound them and generate further frustration.

To illustrate the problems posed both by and for the technologists and the managers of technological systems, let us consider some verifiable shifts and their apparent effects. Americans have traditionally believed in something called a democratic procedure or just plain "democracy". They may have and still do disagree over its exact characteristics or nature; that is, some have defined it as a way of governing, others as a way of life, still others as little more than a method of selecting leaders, and so on. Early in American history, a common thread (conception of a proper system for American society) was a high priority on limited government or constitutional constraints on government action. A second thread gave high priority to property rights of the individual; a third thread involved high priority to equal opportunity for individual persons. Equality was a goal and policy was to be judged in terms of of advance toward the goal and not judged in terms of achievement of full equality in fact. Furthermore, equality was to be defined largely in terms of opportunity and equal treatment by persons who had political status or as equal treatment under the law. Briefly, the criterion, rightly or wrongly, for judging whether a system was "proper" or "democratic" was the types of government constraints and their effectiveness. The central concerns of earlier political theorists and scientists, indeed demonstrate this irrefutably. Most, although not all of them, asked questions and sought answers which keyed on constitutionalism and limited government, whether their names were Jefferson, Madison, Paine, Wise, Goodnow, Wilson, Calhoun, Munroe, or Willoughby. Similarly, the actions and utterances of political actors in Congress, state legislatures, courts, and administrations overwhelmingly document the same central concerns, especially prior to World War I.

It seems equally apparent that a considerable shift has occurred in the focal points of concern and concentration. Old and revered criteria have been moving up the priority ladder and are becoming a focal point of concern. Two such criteria were the amount of participation and the direct effect of the individual person in the policy choices. Earlier theories, especially those prior to the emergence of populism, did not evince a deep concern about direct participation or as it has come to be called since 1964, "maximum feasible participation." Not that theories of participatory democracy have displaced older theories such as constitutional democracy; it is that they have won a larger place in the American political sun (38). Equality, moreover, has become a question of achieved equality in fact as opposed to equality as a goal. It speaks to equal economic advantage and result, an equal education, and so forth (7).

The point need not be labored further here; for it should be apparent to even the most unskilled social theorist that some sort of shift has occurred--a thread has been broken. Again the shift is eloquently documented by the changed foci of modern political theorists such as Robert Dahl, Floyd Hunter, Robert Agger, and even Havlicek who was heavily involved in the Susquehanna study for the U.S. Army Corps of Engineers. The concern has been with such questions as: Who makes decisions? What is the role of influentials on those who influence decision-makers? How can individual citizens participate directly and influence decisions? How is maximum feasible participation obtained? Jefferson and earlier theorist were far less concerned with such questions. The ground rules have shifted; those shifts have been profound, especially in the sixties; and they have been even more frustrating and baffling to many technologists who remain convinced that the rules of the game still obtain.

What has all this to do with sewers? It is just this! The choices made for solving sewer problems and selecting incentive processes for transferring technology to obtain adequate and timely solutions are inextricably linked to the belief systems that channel and constrain choice. Those underlying patterns need attention in a rapidly changing physical and social environment.

Evidence of frustration lies all about us. Problem solutions frequently must weather a variety of storms and there is growing concern about the times and places that storms are not weathered. When programs and plans are cut down at some point, time, effort, and money are wasted; the social and economic costs are high.

<u>Boulder: A Case Example</u>: Possibly a case example will illustrate the growing frustration with the choice syndrome. Boulder Creek poses

a flood threat to life, limb, and property. It has posed such a threat for a very long time, but flood experience has been modest. Following a flood event in the late 1940's, the city fathers called on the U.S. Army Corps of Engineers for assistance. The Corps studied the problem and recommended hard treatment and channelization as an economically feasible solution. The city rejected this and did little until an event occurred in 1969. Again, the Corps was called into the picture. This time it undertook a more extensive study considering effects on water quality, vegetation, animal and marine life, as well as other ecological factors. Social impacts and political viability of various alternatives were assessed. At the first City Council meeting in 1973, the Corps made its preliminary recommendation to the City and was received coolly. That recommendation called for soft channel treatment, levees, and floodwalls as an alternative which best met the feasibility requirement according to measures of feasibility on the economic, social, and environmental accounts. These accounts were closely geared to those developed during the 1960's by the U.S. Water Resources Council.

Following the formal presentation by a representative of the Corps, members of the Council quizzed him about the possibility of more expensive and less economically feasible alternatives that they indicated as possibly more acceptable to them and the citizenry. Specifically, they wanted to know whether it was possible for them to authorize city expenditures in order to enable an economically non-feasible alternative. Briefly, the U.S. government and the city would expend matching funds to the point of feasibility and the city would add the remainder to care for the non-feasible portion. The Corps representative said that this might be possible if accomplished in a manner similar to a solution reached in Littleton, Colorado below the Chatfield Dam; but they also indicated little enthusiam for it at the Council meeting.

Very little about the meeting seemed to bode well for future solution. A conflict involving basic values and premises was apparent. This conflict is probably best conceptualized in terms of basic differences in decision-making criteria between the city decision-makers and the Corps leadership as both of these relate to the public. Obviously the Corps and the city are each following a set of values and preferences which underpin the decision-making criteria and cause different reactions and outcomes from each decision-making cluster. The public's own values and criteria, of course, muddies the water further.

One of the critical consequences of the underlying changes in our time is to constrain the decision-maker's and the technologist's flexibility for reaching solutions by adding constraints which result from changing values without removing or mitigating others. Indirectly, the Corps was very reluctant to look for mechanism to circumvent or ingeniously redirect the economic feasibility criterion. The Corps was clinging to their traditional criteria in the face of evident change in values elsewhere; and they were doing it despite their valiant efforts in recent times to give themselves a "new look."

Values and assessments have changed dramatically as evidence from a study completed in Boulder by the writers during 1972. A 90% response from 460 randomly selected respondents within the city shows that public perception of community problems have changed dramatically since 1962.

Table 1

Public Assessment of Severity of Problems Over Time
(Scaled 1-5)

	Mean Scale Scores		
	1962	1972	1982
Water Supply	2.2	3.4	4.3
Creek Pollution	2.1	3.9	4.5
Sewage Disposal	2.5	3.8	4.4
Creek Flooding	3.0	3.5	3.6
Floodplain Development	2.4	3.7	4.1
Recreational Needs	2.1	3.2	3.6
Air Pollution	1.9	3.9	4.7
Crime Rate	2.2	4.0	4.3
Solid Waste Disposal	2.2	3.6	4.2
Traffic Congestion	2.0	4.3	4.7
Drug Distribution	1.8	4.2	4.2
Destruction of Beauty	2.3	3.9	4.3
Education	2.7	3.6	3.9

Legend: 1 = no problem; 5 = severe problem.

Table 1 provides the mean scores for 397 Boulderites out of 413 who registered their perceptions on the 39 scales.* Significantly, without exception, all problems are perceived as worsening over time. That, in itself, is out of keeping with longstanding American optimism and may indicate a severe shift in outlook. Generally, everything is apparently getting worse (in the eyes of the Boulder public) and apt to continue in that direction. On nearly all problems, less than ten percent saw any problems as minor and improving over time. The pattern of pessimism was unusually strong and regular over the sample.

Significantly, also, air pollution, traffic congestion, and drug distribution take the highest jumps over time in growing severity according to the Boulder public's perceptions. It is therefore very likely that these are the types of problems which the public generally finds the most important for their leadership to address. By comparison, in the eyes of Boulderites flood control and recreational needs are far less pressing than the others. Significantly, the Boulder public assesses flooding to be the <u>most severe</u> problem ten years ago and the <u>least severe</u> ten years hence. They see it as worsening at a much slower rate than other problems. A return visit to 55 interviewees showed that they persisted in this view because they saw flooding as more solvable and getting more attention. Forty-three reported this reason.

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* The scales employed are updated versions of the scale first generated by Rensis Likert more than forty years ago. See Rensis Likert, "A Technique for the Measurement of Attitudes," <u>Arch. Psychology</u> (New York, 1932), Vol. 140, pp. 1-55.

This is not to say that the public correctly evaluates its needs; rather, it is to say that if such a public assessment and criterion have an effect on the decisional outcomes, then they should be honestly weighted and related to other relevant criteria. How to do this correctly, however, is a moot question. Nevertheless, it should be done if for no other reason than that management needs to know how to relate to its publics and their differing expectations. They especially need to know their publics' priorities and what underlies those priorities.

With respect to general public policy priorities (what the public expects its decision-makers to maximize), the Boulder residents expressed a ranking shown in Table 2 below. That ranking is the product of convergence of three public rankings of priorities which they find essential to maximize or order in priority for maximization as policy is being developed.

Separate rankings were obtained to reduce the problem involved in overloading the individual respondent's power of discrimination. Charles Osgood has found that individual powers of discrimination dissipate beyond seven to eight intervals (37). Each ranking therefore was kept to no more than eight intervals or items to be ranked and each also included some items common to all sets for ranking the common items were used as factors for keying mathematical manipulations for the converged overall ranking.

The converged <u>mean rank scorings</u> of priorities for use in developing policies and selecting alternatives for solution fit a national pattern. Among property owners, life and limb come first, the pocketbook is second, and the environment gets what is left. This fits a traditional mold. The preservation of human life and the human being's opportunities,

Table 2

Boulder Publics Expressed Policy Priorities

	Mean Rank Score	
	Total Sample	Property owners only
Protection of life and limb	2.46	2.57
Protection of public health	2.67	2.76
Elimination of major flooding	2.80	3.28
Non-Interference with Natural Creek Functions and Uses	3.70	4.90
Non-Interference with present natural beauty of creek	3.75	4.95
Elimination of all flooding	3.80	4.35
Preservation of all natural conditions on creek	4.11	4.58
Enhancing the creek's beauty	4.28	5.79
Keeping taxes low	4.28	3.67
Keeping Damage to Existing Structures on Flood Plain Low	5.18	5.29
Protecting Flood Plain Property and Investments	6.35	6.13
Keeping Costs Low for Flood Plain Property owners	6.37	5.93

1.0 = high priority
8.0 = low priority

conveniences, and comforts take precedence. There is high priority given to safety values by nearly everyone. Non-owners, however vary sharply in their priority hierarchy from owners on the position of tax priorities. Owners are, however, quite similar to the non-owners on the order in which they desire to have other values maximized; and significantly, property values lag badly behind environmental values for everyone. It should be noted here that tests of floodplain dwellers showed very little variance from the other residents.

At an instructional meeting with the interdisciplinary group in February 1972, one of the authors quizzed Corps representatives closely about the nature of the Corps needs with respect to public and leadership roles. Responses to the questions soon made it crystal clear that property values and property owners loomed larger in the Corps attention span than did many non-property elements. These basic premises were echoed once again in various ways at the meeting of the Boulder City Council in January, 1973. More importantly, however, was the Corps' obvious reluctance (but not refusal) to entertain means for ingeniously reducing the effect of the economic feasibility constraint.

Basically, the Corps is bound to the economic feasibility constraint by a 1936 Act of Congress. Actually, the Corps has little choice. The Corps, however, has not been opposed to the imposition of other criteria such as social, and environmental feasibility. What was not so apparent, at least on the surface, to the Corps in the Boulder situation, was that economic feasibility constraints were not having their negative effects mitigated by requiring alternatives to meet social and environmental feasibility measures. The intoduction of these new criteria only made the economic constraints more severe since they further reduced the number of available alternatives. Briefly, many, or at least one alternative--channelization--was eliminated by the new criteria. Reductions in the number of alternatives merely reduces probability of reaching a solution.

Another severe constraint on the effectiveness of the decision-making process in reaching a satisfactory solution (which is what nearly everyone apparently wants), was the seeming reluctance of the Corps to consider a variety of mixes of alternatives for each creek reach. Judging by an impressionistic assessment of the stream of interaction among the Corps, the Council, and the various publics, the Corps effectiveness was suffering from failure to be attuned in its operations to the changing values which comprised its social environment. Seemingly, Corps behavior was governed by longstanding theories or "pictures in the head" of what gives direction to the way the world works. Economic payoffs remained almost iron-fisted criteria which underpinned more traditional theories of property rights. Those rights have declined somewhat over the years in relation to other priorities.

Denver: A Second Case Example

The Boulder case exhibited a basic conflict in the underlying values between an external agency and a community agency and its public. Recent failure of a Denver Water Board bonding proposal for water supply development illustrates an underlying conflict in values between a community agency and its public. The Board sought funding for development of mountain supplies from the Colorado River watershed. Tied to this was requested funding for development of re-use facilities as well as other ingredients. The real issue involved water supply futures.

Denver's water board has a long history of policy which seeks to insure adequate water supply against future growth and development. After a long planning period, the development plan was formulated, the issue was formed, and it was laid before the public for their approval by election. In an almost unprecedented manner, controversy developed and the people turned down the proposed bond issue. Even the League of Women Voters, a longstanding political ally of the board on public policy, defected prior to the election.

Two surveys in which the authors were involved reflect some underlying traffickers of conflict and constraints on the decision. One study of the Denver public by Robert Carley of the Civil Engineering Department at the University of Colorado showed that interest in water was high for a randomized sample of 447 Denver residents from a potential of 527 (84.8%) who were drawn orginally. Some 67% indicated relatively high interest. That probably should be scaled down some (e.g., 61%) due to the tendency of Americans to over-report interest since one is supposed to be interested (according to the cues of American culture) (9). Table 3 shows that the Denver public was also rather well informed about water issues and matters. This fact, however, did not lead to support of Denver Water Board policy goals. Significantly, the data show that Denver's public did not perceive of future supply shortages as a severe problem despite their heavily self-acknowledged dependence on the Water Board for their information on issues. They admitted to being 70% dependent. Table 4 shows that future water shortage has a miserably low ranking compared to other community problems and stresses. Air pollution and population growth are deemed many times more critical than supply shortages. Further data shows that only one-third give high

Table 3

Interest in Local Water Matters vs. Informed About Them*

	Poorly Informed %	Fairly Well Informed %	Very well Informed %	No. of Cases
Not Interested at all	56.3	25.0	18.7	32
Slightly Interested	38.2	50.0	11.8	110
Somewhat Interested	33.6	51.0	15.4	143
Very Interested	27.7	44.9	27.6	156
No. of Cases	150	207	84	441

* Carley thesis, p. 31 (9)

Table 4

Order of Concern for Selected Environmental Problems*

Environmental Problem	Order Ranked First 7%	Second 7%	Third 7%
Air Pollution	66	16	10
Population Growth	17	27	12
Water Pollution	3	25	21
Noise Problems	4	11	11
Water Shortage	3	4	9
Urban Growth	4	10	11
Recreation Needs	2	5	16
Radiation Increases	0	1	4
Other	2	1	1
No. Cases	446	443	427

* Taken from Carley data. (9)

priority choice to mountain development and an equal number give the high priority to restrictions as a future supply alternative. The rest opt for limiting lawn size, reuse, and growth restrictions. Finally, some 42% tend to believe or do believe rather firmly that present supplies will likely be adequate twenty years hence. Another 13% are not sure but tend to believe supply may not be adequate twenty years down the road.

Whatever underlying values may be causing the impasse, beliefs about growth and development are certainly among them. There are also many indications of radical shifts on this basic element; efforts in the Denver suburb of Boulder to limit population by legislation are certainly evidence of radical shifting.

On this score, the Board personnel seems not to have shifted. A few months prior to the bond election some 83% of the Board's top and middle management personnel were convinced Denver growth was inevitable and that the agency was bound to a policy of water acquisition to meet that growth.*

Modeling for Measurement

The problem emerging from the above is the crucial role of underlying premises which drive the decisional engines. They provide some of the keys to politial feasibility. In the words of a local Director of Public Works, "We need to know what is politically acceptable in somewhat the same manner we learn what is technically acceptable to avoid running down blind alleys." Then he added, "At least, we need to know what is unacceptable to avoid pursuit of causes lost before we start."

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* From private files of data held by Gary Eastman and Duane W. Hill on 46 members of management echelons in the Denver Water Department.

In the model developed for social analysis during Phase I (see Figure IV-2) the primary effort was directed at development of a scheme which comprised a close analog to reality in the processes of decision-making. The model is a stepwise or a branching one (a variant of a decision tree) which moves from decision point to decision point seeking to specify the hypothesized channeling agents and effectors or constraints that are anticipated to be control points leading to decisions at each decision point. Actually, the model is designed to enable observers to monitor a process as it moves from decision point to decision point; but it further seeks to enable measurement of effectors during the monitoring.

On the far left at the entry point to the model lies an all-important box of system characteristics, one type of which was discussed above. It is within this box that a great deal of effort, modeling, measurement, and analysis needs to be conducted. Within it are a vast number of independent clusters of interdependent elements that exert influence from decision point to decision point. Their influence flows throughout the model. In fact, at the entry point, if one does not know how to fit his program and behavior to them, or if he does not "luck" onto a way for doing so, he may find himself exiting the model almost before he enters it. This seems to have been partially responsible for what has been going on in Boulder for the past twenty-five years in the abortive attempts to light on a politically, technically, and environmentally feasible set of flood control alternatives.

A basic problem with models such as these is that several thousand have been developed over time, but few have been tested and most have never run the risks of having real data loaded into them. Most have served other than directly practical purposes. Actually, the utility of

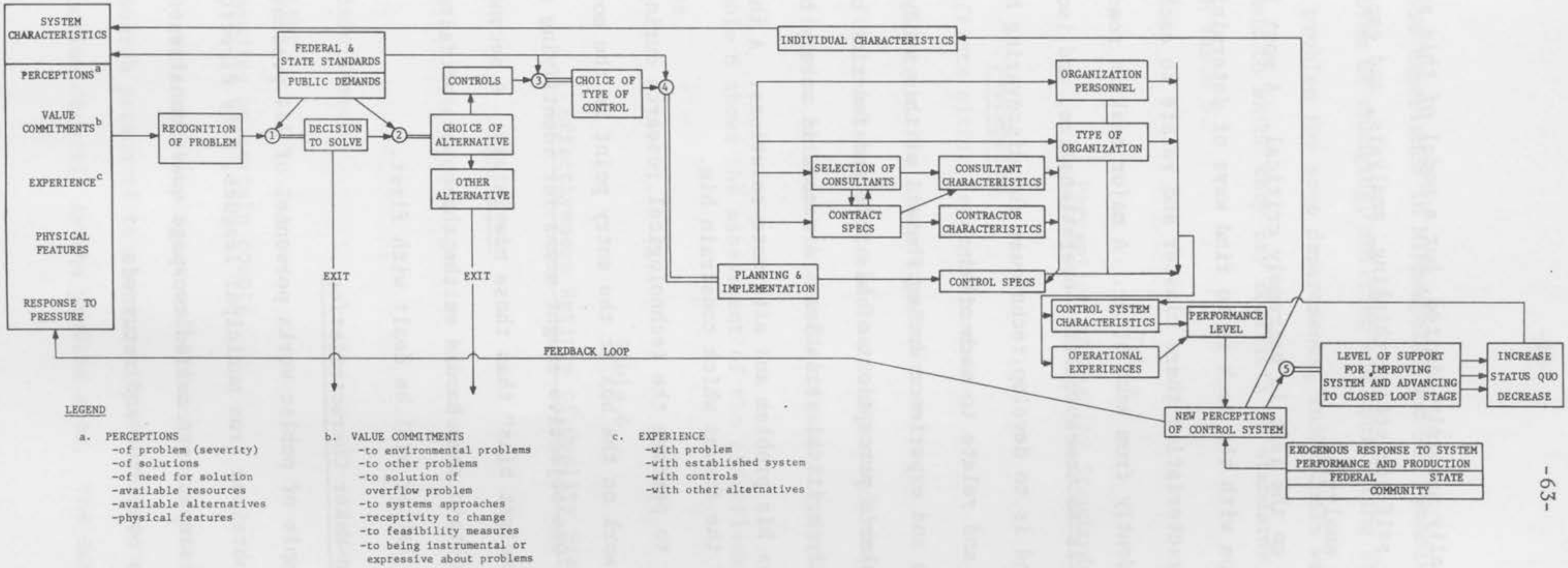


Figure IV-1. Automated Control System Developmental Model such a model is usually severely limited, but a model of this sort does provide a guide for self-corrective thinking, analysis, and especially the approach to the analysis.

Again, the box on the left is extremely critical. A most important element in getting on with the task is to find ways of determining how the elements or characteristics there cluster and relate to each other or function independently from each other. A major task in reaching such determinations is to conceptualize, operationalize, and isolate components. A second is to develop techniques for discovering how they empirically cluster and relate to each other.

Past experience and experience during Phase I of this study indicates that the decision-maker's perceptions of his role and function comprises one set of potentially critical variables. A second is surely the way in which he conceives his problem and alternate solutions. A third involves his view of the forces which constrain him.

Financial needs to perform the technological research during Phase II confined efforts to work on the box at the entry point in the model to very narrow limits. One objective sought means for identifying clusters that carried less "analyst bias" than those now in use. A second involved an effort to obtain some handle on the three sets of factors outlined above. The latter will be dealt with first.

Public Works Decision-Maker Characteristics

An arbitrary sample of public works personnel of 144 persons was selected from lists obtained from municipal leagues, city directories, etc. Members of the sample were mailed two-page questionnaires. After some prodding 94 were completed and returned.

Since experience in Minneapolis and San Francisco revealed that the problem of changing, shifting and conflicting standards was a central problem for some departments, individuals were asked to indicate the extent to which they say conflicts in standards. The results are shown in Table 5.

Table 5

Perception of Quality Standards

Perception	Percent
Saw conflicts within Federal standards.	41%
Saw conflicts within state standards.	37%
Saw conflicts between state and national standards.	35%
Saw duplication between state and national standards.	61%

Table 6 shows the assessment of the effectiveness of regulatory agencies.

Table 6

Effectiveness Ratings of Quality Standards

Statement	Percent Agreeing
The regulations of most agencies have been:	
fair	46%
well-administered	36%
consistent	37%
too demanding on certain counts	63%

The research time frame and financing constraints did not permit the research personnel to obtain a representative sample of the personnel who function directly in the problem area. The data uses should therefore be confined to very narrow limits, probably to no more than design and hypothesis generation for further testing. It is reasonable to hypothesize, however, that a great deal of conflict and duplication in standards currently infect the sewerage problem area. Further, it also seems apparent that the fairness of the present situation is being questioned on a number of counts. In this regard, future analysis should attempt to disaggregate the perceptions of unfairness in terms of criteria by which individual types of people judge what is fair. Similar tests should be made to discover the criteria used for the perceptions of conflict, inconsistency, and stringency of rules. Finally, these need to be examined for their relationships to basic values and premises, some of which were explained above.

Perceived intensity by public officials of impediments on capability to meet standards is shown in Table 7. The respondent was asked to identify the most severe constraint upon him and give it a value of 1.00. Then using that as a comparative basis, rate the rest of the items in terms of lesser intensity between 0.00 and 1.00. Respondents were free to add any they found important or necessary to add.

As frequently occurs, the pressures for precision on some persons were probably too great. After all, such perceptions are usually gross even in the mind of a scientist. For someone to say that one constraint is .39 and another .47, for example, is often well nigh impossible. Many did not do it, and several of those who did not performed a straight ranking. Therefore, the investigators were obliged to rank the items first to last for each respondent by numerical ranking as was indicated by the value ranking of the respondent. Sixteen items were ranked using a .50 interval, giving a range of 1.00-8.00, with 1.00 being most severe and 8.00 the least. Mean rank scores were then computed for each item. Three items were eliminated because certain persons appeared to have inadequate understanding of them. The final results are shown in Table 7.

Table 7

Perceived Intensity of Constraints on Capability to Meet Environmental Standards

Item	Mean Ranking
Inadequate time frame	2.13
Inadequate Financing Resources	2.26
Uncertainty and Change in Standards	2.82
Unrealistic Standards	3.54
Inadequate Information	4.01
Inadequate Definition of Organizational Objectives	4.38
Attitudes of Management Toward Planning and Design	4.41
Attitudes of Planners and Designers Toward Management	4.45
Inadequate Communication within Organization	4.45
Inadequate Organizational Structure to Receive and Accommodate New Designs and Design Groups	5.36
Resistance of Organizational Personnel Segments to Change and New Design	5.45
Inadequate Skills within the Organization	5.81
Inadequate Available Technology for Development	6.62

Legend: 1.00 = most severe 8.00 = least severe

Several problems arise in Table 7 that infect a great many such attempts at management analysis. First is the uniformity of respondent interpretation of items. Not all see the same thing in the same way. Second, an organizational bias is almost certain to emerge as it appears to do in the table. Certainly organizational judgment of the adequacy of its own skill is likely subject to bias and severe problems. Third, ranking of some items may be unrealistic for particular respondents. Fourth, the vigor and intensity of a constraint in the mind of a respondent may be misinterpreted by the respondent. What he sees may be a symptom of something else.

Nevertheless, such rankings indicate where the problems tend to be concentrated. Again, for example, time and money emerge as the harbingers. Table 8 tells something about where urban sewer personnel think the financial resources and other forms of assistance should come.

Table 8 was difficult to compile since its results are from an open-ended question which was answered in a variety of ways. Although the question asked what the respondent perceived as the single most important incentive or support for addressing the problem of meeting standards, many mentioned more than one without indicating order of importance. Several talked about grants and tax sharing as if they were exactly the same. Construction grants tended to be confused with other types. What is presented is the percentage of the total sample mentioning each. Results indicated a heavy but not exclusive reliance on financial support.

The team also asked whether the respondents believed that all urban effluent, including stormwater, would eventually need secondary treatment. Some 67 persons or 71% said "Yes".

Table 8

Perceptions of Incentive for Pollution Abatement

Perception	Percent mentioning
Direct aid tied to pollution abatement	33%
Construction grants and others	39%
Tax sharing	31%
Direct incentives to private dischargers	11%
More stringent regulations and sanction on private dischargers	9%
Lower standards to more realistic levels	6%
Other miscellaneous	6%

The data presented immediately above, as well as other data, indicate a good deal about the characteristics, severity, and difficulties surrounding the combined sewer problems and the related problems attendant to reaching successful solutions. As initially stated in the Phase I Report, the social problem was: How to define the constraining and facilitating elements for:

1. Adequate consideration, planning, and implementation of combined sewer system controls;

2. Successful operation, maintenance, and productivity of such systems.

At this time the statement probably should be revised to read: How to determine how and where MWIS systems can and should be established, maintained, and upgraded to achieve more adequate conformity with environmental standards and needs. Given technical, environmental and economic feasibility, the question narrows: How to get MWIS systems considered adequately, adopted, implemented, and made more productive. Everything in this question hinges on getting a green light in the human choice systems. It means getting through some model from decision point to decision point--such as the model presented in Figure IV-2.

A most critical juncture in that model is at the entry point where the forces delineated have great impact on getting through the model itself. Those forces simply must be subjected to an analytical scheme that enables the analyst to develop predictive powers. For example, the analyst must know how the critical forces (e.g., attitudes and values) are converging with other characteristics and forces to produce certain results. Social science as a whole has really never faced this problem--the need for prediction and explanation--as squarely as it should have in the past. The usual reason given is that the data is soft; yet, it is irrefutable that many social scientists are capable of predicting with deadly accuracy (e.g., Louis Harris; Warren Miller or the Michigan Research Center teams). They may not be able to tell why they can predict, but many do it very well.

Data Needs

In modeling the control system implementation problem it is important to be able to identify the characteristics of decision makers by groups so that their behavior can be predicted. One approach to this is by collecting profile data by descriptors where the descriptors are significant characteristics that distinguish one group or individual from another. By noting how the decision makers cluster around different descriptors an approach can be made to predicting their responses to different situations.

In placing public works decision-makers into groups according to their controlling value systems, value categories should be carefully chosen. The following list contains some of the possible categories:

Professional Values

Community Income Values

Personal Status Values

Organizational Status Values

Organizational Income Values

Personal Income Values

Safety Values

Internal Employee Satisfaction and Reward Values

Environmental Values

Personal Convenience Values

Social modeling studies for public projects which need decision-maker characteristics as inputs could perhaps draw on the above list as a start.

A technical report will be issued later which describes in detail specific data needs and the background of related data which is already available.

V. THE DESIGN OF A CONTROL STRATEGY

There has been a great deal written on the difficulties inherent in simulating the flow from one drainage basin. Literally millions of dollars have been spent on studies of this problem. The problem of controlling a large, interactive network of such basins using a real-time automation and control system (RTACS) is correspondingly more complex.

The RTACS shown in Figure I-2 for a combined sewer system contains two "models." One is the model of the (physical) system and one is the computer control model. The design strategy problem is to design the computer control model.

The objective of this model is to operate a control system in such a manner as to achieve a stated control objective. Normally the control objective would be to minimize actual mass of pollutants discharged into receiving waters. Alternative objectives might be:

1. As stated, to minimize mass of selected pollutants discharged into receiving waters,
2. Minimize volume of overflows into receiving waters
3. Minimize a multiple objective function considering both overflow control and drainage of streets.

The formulation of these objectives is complex for most real systems. Because of uncertainties a number of approximations are normally required. The objective of operating such a system is similar to the operation of an industrial process.

A. SIMULATION FOR THE DEVELOPMENT OF A CONTROL PROGRAM

In order to design a control model for the RTACS the system should be initially studied off-line. An effective method for such a study is digital simulation. Continuous simulation of hydrologic processes has been advocated in recent years by some modelers. Recent reports by Hydrocomp International have supported this view (13,14,28). The last report cited is particularly applicable to the design strategy problem at hand as it addresses, among other things, the problem of simulating storm runoff discharge from a basin with a restricted outflow. This is analogous to the case where a controlled rate of flow to a treatment plant is desired.

The use of simulation as a design tool for developing control strategies is not new, nor is it unique to hydrology. There are precedents from the war games played in high military circles. The use of simulation occurs both in on-line and off-line control situations. An excellent description of its role here is reproduced below from a recent report by the American Public Works Association (2).

The need to use simulation as a design tool for developing control strategy has previously been addressed at CSU (53). The problem is also faced by others working on similar systems. The Municipality of Metropolitan Seattle presents a discussion of this problem in their recent interim report (35).

Seattle presents a conceptual view of their control model which is planned to eventually operate their CATAD (Computer Augmented Treatment and Disposal System). This is presented in Figure V-1. Figure V-2 is presented as their simulation model block diagram.

The real-time automation and control system model or RTACS model previously referred to is a tool to simulate on the computer a complete automation and control system. In this case, a combined sewer system, it can be used to optimize or design various components of the control system. If the computer simulation model is valid it is a faithful representation of the actual physical operation of the system, including sensing, control and computer elements and therefore many different variations or experiences can be rapidly simulated and examined. Some examples of outputs might be the design of a rain gauge network, determination of the optimum location of rain gauges or flow gauges, better placement of retention basins or sizing of retention basins and other components or the design and planning for treatment facilities.

The Seattle Metro has a similar concept. By examining Figure V-1 one sees a complete model of their proposed control block. Figure V-3 shows where this control block goes in the overall CATAD. By examining Figure V-3 one sees the complete schematic diagram for the entire CATAD system including hardware components. It is within the computer that the control model operates. The control model shown in Figure V-1 contains the logic for operating the system. The basic logic is shown on the right side of the diagram in the blocks entitled "Rule Curve" and "Water Quality Control." The basic concept is that the rule curve provide the guidelines

MATHEMATICAL MODELING APPLICATIONS

Mathematical Modeling and Simulation

In the application of computers to control of a physical process, the loop is eventually closed through use of a mathematical model of the process. The mathematical model can be defined as a logical-mathematical representation of a concept, system or operation. The model operates on the measured variables and calculates the proper values of adjustable variables to actuate the required control. As an abstraction from a real world situation, the mathematical model is an attempt to simplify the existing complexities for each of the control computations, while simultaneously generating data of sufficient accuracy to represent the real system in required applications.

The word simulation occurs in association with mathematical modeling. There is a distinction in definitions although the two terms complement each other. The mathematical model is the tool, the actual mathematical-logical system, the program built for a digital computer. The applications to which the model is subjected comprise simulation. This is particularly true in digital computer programmed models where the test cases operate the mathematical model under varying simulation conditions.

Mathematical models can be used off-line in a strictly digital simulation atmosphere to study a physical system. The constants can be changed to represent different versions of the system, and the variables can be incremented to modify the operating conditions. For example, in a wastewater collection system some of the constants are shape of conduit, length of conduit, slope of conduit and friction factor. If any of these factors are changed, the represented physical system, i.e., the mathematical model, is changed. On the other hand, flow supplies, branch inputs and pump operations, are variables. When these values are changed, and in a real hydraulic system they change continually, the original system remains the same, but it has been subjected to different operating conditions. So, in a programmed hydraulic collection system, a given model is entered once into the computer, while test cases or simulation conditions on the model may be run ad infinitum.

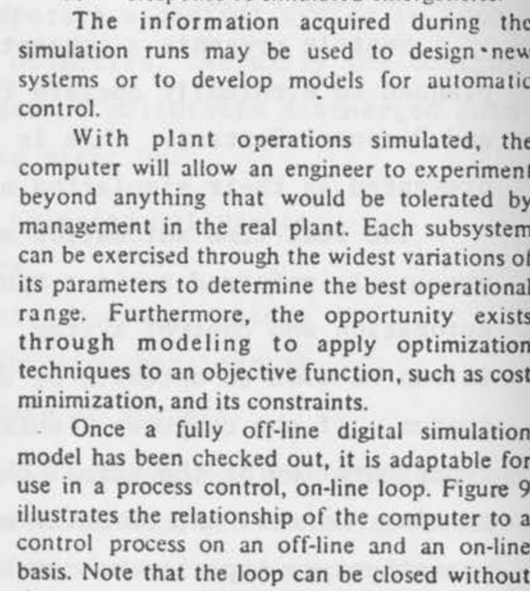
The value of digital simulation lies in the flexibility of operation. A simulated system can be put through its paces and operated under all variations of normal and extreme conditions. The system can be checked out and evaluated, and never leave the computer. Many questions can be asked during simulation. The validity of the answers is a function of how well the model represents the true system or prototype. Information that can be acquired during operation of the mathematical model includes:

1. Sensitivity and range of adjustable variables,
2. Variables most suitable for control,
3. Interactions among variables, beneficial or detrimental,
4. Variable combinations applicable to control,
5. Sources of disturbances and their corrective action,
6. Operational effectiveness and improvement,
7. Required variables and accuracy,
8. Superfluous variables,
9. Potential for model improvement, and
10. Response to simulated emergencies.

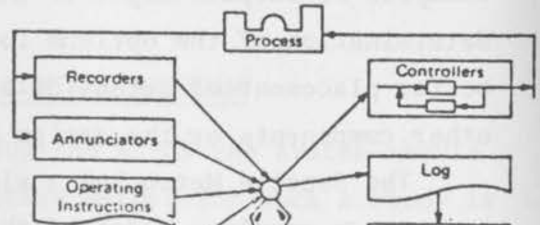
The information acquired during the simulation runs may be used to design new systems or to develop models for automatic control.

With plant operations simulated, the computer will allow an engineer to experiment beyond anything that would be tolerated by management in the real plant. Each subsystem can be exercised through the widest variations of its parameters to determine the best operational range. Furthermore, the opportunity exists through modeling to apply optimization techniques to an objective function, such as cost minimization, and its constraints.

Once a fully off-line digital simulation model has been checked out, it is adaptable for use in a process control, on-line loop. Figure 9 illustrates the relationship of the computer to a control process on an off-line and an on-line basis. Note that the loop can be closed without the man when the computer is on-line.



a. Process Operation Assisted by Off-Line Computer



b. Process Operation Assisted by On-Line Computer

Figure 9. Off-Line vs. On-Line Computer Control

FROM "Feasibility of Computer Control of Wastewater Treatment" (2)

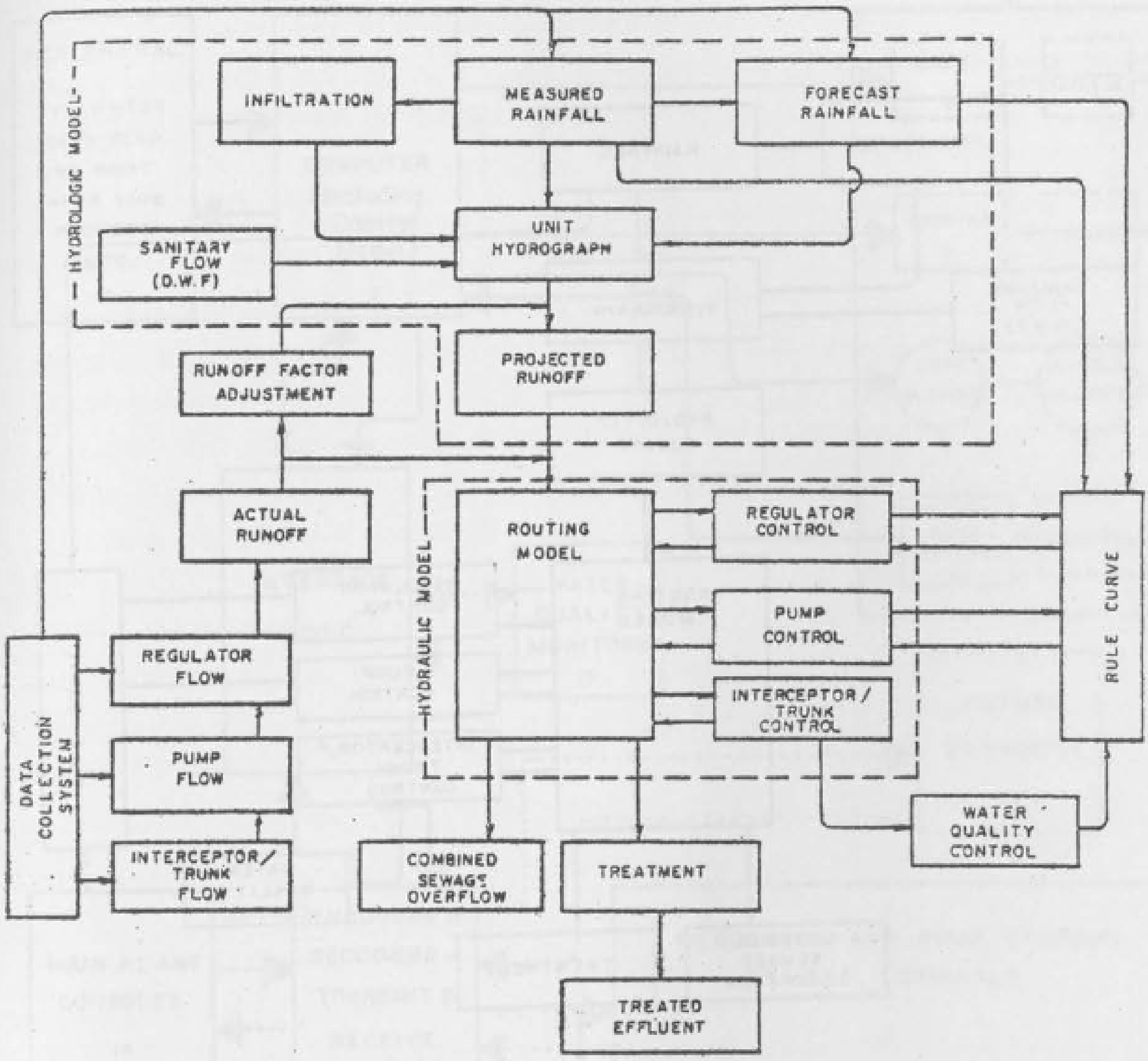


Figure V-1. CATAD Control Model Block Diagram (35)

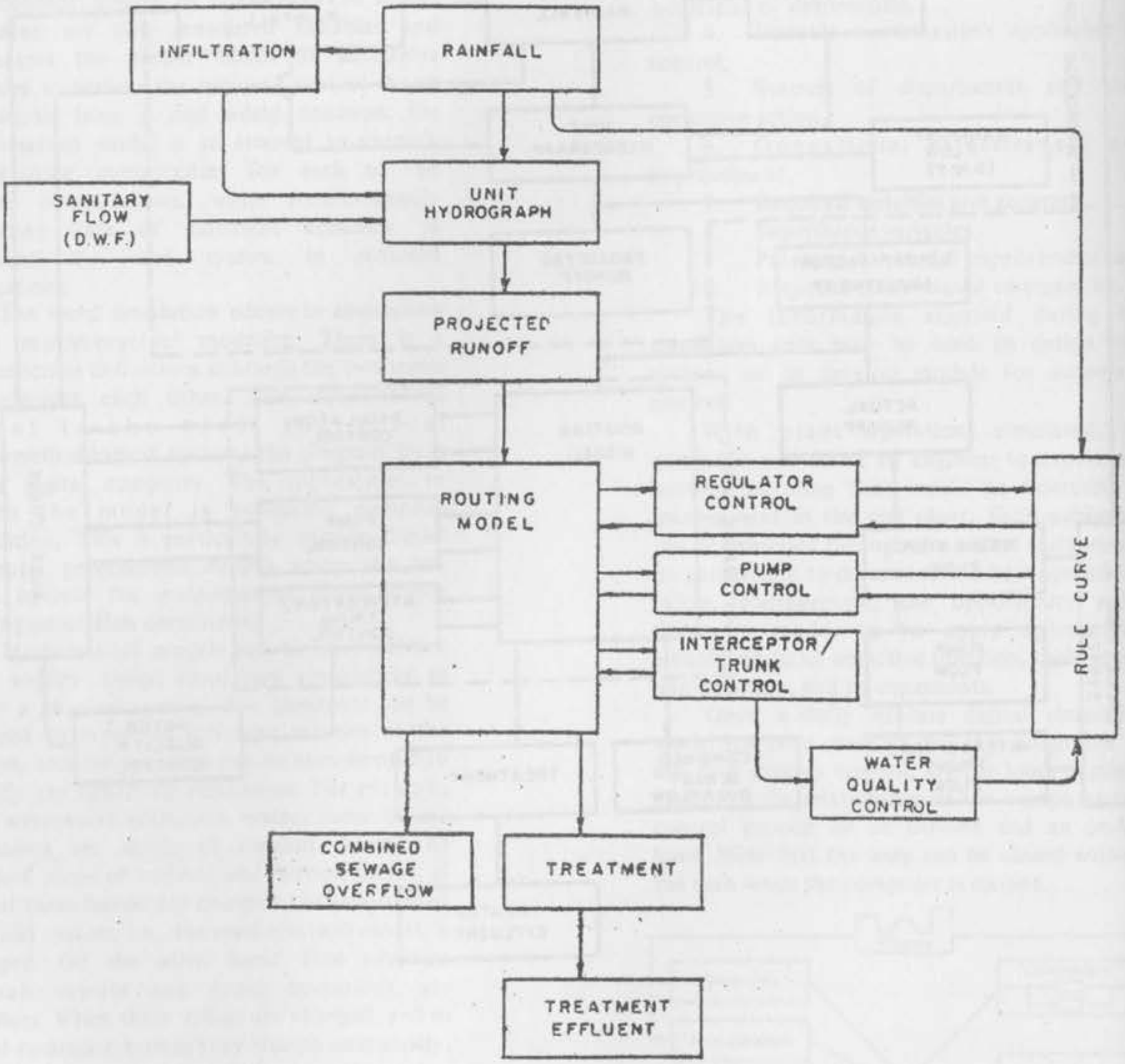


Figure V-2. CATAD Simulation Model Block Diagram (35)

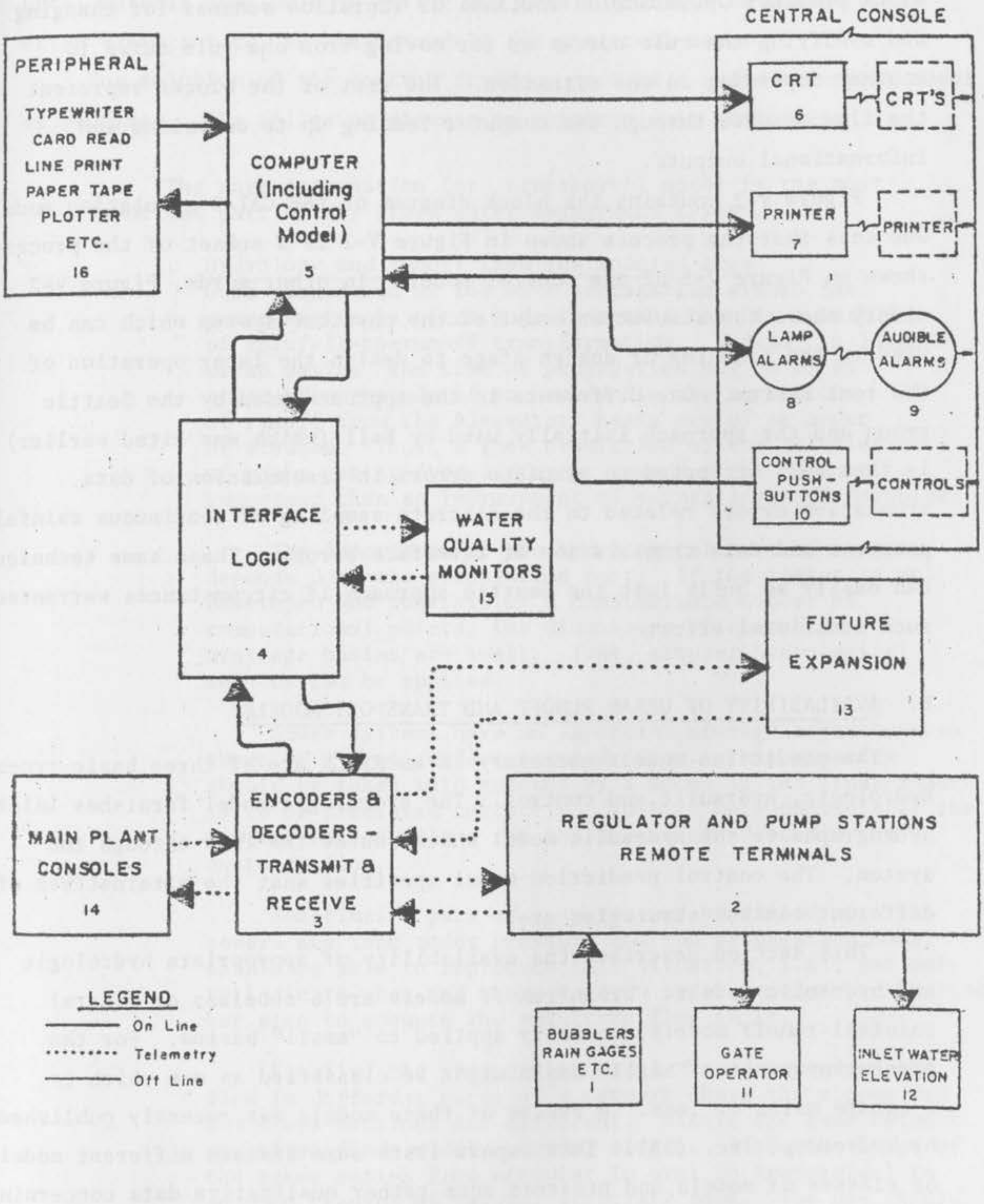


Figure V-3. CATAD System Schematic Diagram (35) for operating the system whereas the water quality control program or block provides optimization routines or iteration schemes for changing and modifying the rule curves or for moving from one rule curve to another depending on the situation. The rest of the blocks represent the flow of data through the computer leading up to decisions and informational outputs.

Figure V-2 contains the block diagram of the CATAD simulation model. One sees that the process shown in Figure V-2 is a subset of the process shown on Figure V-1 of the control model. In other words, Figure V-2 simply shows the simulation model of the physical system which can be used in the planning or design stage to design the later operation of the real system. One difference in the approach used by the Seattle group and the approach initially used by Bell (which was cited earlier) (53) is that Bell attempted to simulate errors in transmission of data, truncation errors related to the discrete sampling of continuous rainfall patterns and data transmission of interface errors. These same techniques can easily be built into the Seattle approach if circumstances warranted such additional effort.

B. AVAILABILITY OF URBAN RUNOFF AND TRANSPORT MODELS

The prediction models necessary in an RTACS are of three basic types: hydrologic, hydraulic and control. The hydrologic model furnishes inlet hydrographs to the hydraulic model which routes the flow through the system. The control prediction model specifies what the alternatives of different control strategies are.

This section describes the availability of appropriate hydrologic and hydraulic models. Urban runoff models are a subclass of general rainfall-runoff models, normally applied to "small" basins. For the present purposes a "small" basin might be classified as one which is 5 square miles or less. A review of these models was recently published by Hydrocomp, Inc. (28). This report lists some sixteen different models or classes of models and presents some rather qualitative data concerning their relative effectiveness. The report does not discuss in detail, however, the new EPA "Stormwater Management Model" (33) nor does it present linear systems methods (such as the unit hydrograph approach) in a favorable light. The report makes a strong case for continuous simulation rather than simulation of isolated storm events.

Runoff models are strongly dependent on data for their verification. Until data is available to verify the more sophisticated models it is often expedient to use simple models for practical cases.

For solution of the control strategy problem a valid transport model is required. The following discussion supports this statement:

"The wave propagation (or 'transport') model is the most important part of any storm water management system.

1. Hydrology and runoff from the modeled area
Good simulation of the wave propagation within the sewer system is often more important than is a method of rainfall-to-runoff transformation. Indeed, in large urban basins, the time of propagation may be of an order of magnitude of an hour while the variations of runoff from the elementary basin are of an order of minutes. Thus, a good prediction of the coincidence of peaks coming from different sewers might be more important than an improvement of rainfall/runoff formulae.

   The importance of the hydrological part of a model depends upon the propagation part. If the latter is well developed and consists of a considerable number of computational points, the dimensions of elementary drainage basins are small. Thus, simpler hydrological methods can be applied.

   Sewer systems have an important storage capacity when there is a free-surface unsteady flow. This capacity should be taken into account by a model if the final runoff is to be predicted correctly. This is only possible if the routing method allows for the backwater effect in the unsteady flow.

   Sometimes a part of a system may be filled up. The sewers are then under pressure and the propagation model should be able to reproduce this situation, i.e., not only to indicate when and where a given sewer becomes pressurized, but also to compute the resulting flow in it.

   Finally, the propagation model should reproduce the flow in different parts of a network where the slopes and the cross-sections are different. Within the same network one often finds widely varying slopes. Often the shape of the sewer varies from circular to oval to trapezoidal to an open channel of natural arbitrary form. The use should not be hampered because of that.

2. Management of a sewer system
A propagation model should be able to simulate a "looped" network of sewers or a "branched" one. This enables one to simulate the "relief operations" consisting of a transfer of water from one city district to another.

The model should be able to incorporate easily any structure which is normally used to control the flow. Structures such as gates, weirs, etc., have to be simulated, i.e., their backwater influence in unsteady flow must be simulated as well as possible maneuvers. Thus, the model should be able to simulate controlled overflows to storage areas, etc. These controls may work on the basis of an automatic feedback defined by certain characteristics (water levels at certain points) or on the basis of time-dependent decisions. The model must be able to simulate them.

The model may be used to simulate short-term phenomena (such as storms) or, on the contrary, long-term situations (such as dry-weather flow). Thus, from the computational point-of-view it should not be limited to small time steps which might lead to very long computation times when the dry-weather period is simulated.

3. <u>The pollution problem</u>
A good simulation of water propagation in the system is most important for the simulation of water quality. There are two main reasons for that:

(i) It is extremely difficult to simulate water quality well because the data are sparse and the theories are often not well verified. Thus, there is always a danger that the errors entailed by using very approximative methods to simulate the water propagation might hamper the simulation of the pollution transport. The most accurate available method of flood routing should be used to eliminate all doubts as to how the water propagation proceeds. Thus, the only possible sources of inaccuracy are in the pollution simulation.

(ii) When simulating the pollutant propagation through the sewers the convection is most important. Indeed, as the time spent by the pollutants in the network is short and as there is no (or hardly any) oxygen, the decay terms in the equations are small. Hence, the convective speed, i.e., the water velocity, should be computed as well as possible because the transport of pollutants depends on it. It is also important that the velocity variations due to the backwater effect be well simulated." (17)

The evaluation problem of storm water routing models is also important. The Appendix contains a paper also by J. Cunge which is addressed specifically to this problem.

The EPA Stormwater Management Model contains a runoff block, a transport block and storage treatment and receiving water routines. In addition, quality is simulated throughout all of the subblocks of the entire model. Since the model is now available, since it is so comprehensive and since its potential value is significant, it will be discussed separately in this section. The EPA Model was developed by a triumvirate of three consultants; Water Resources Engineers, Metcalf and Eddy and the University of Florida. The initial model was then put together and run as a consolidation of the three separate efforts. The programming difficulties associated with a model this large and complex are significant. Several users have managed to get the model running and to successfully employ it on a variety of problems. The EPA is currently sponsoring seminars and users' conferences in an attempt to implement the model widely across the country.

The model allows the input of multiple hyetographs resulting in multiple inlet hydrographs at a number of points into a sewer system and the subsequent calculation through the transport block of downstream hydrographs at various points in the sewer system. It can simulate in-system or external storage and provide the resulting downstream hydrograph resulting from storage strategies. Based on antecedent conditions it will also generate pollutographs at different points in the system. These pollutographs can then be routed through treatment routines and subsequently into lakes, rivers or estuaries to simulate the effects on the quality of receiving waters.

Some difficulties have been experienced with the use of the EPA Model in the transport routing. The existing model does not solve the complete St. Venant equations and therefore it is limited in its applicability in sewer systems. It is believed that at the present time difficulties are experienced when sewers are surcharged or when flow reversals occur. As these are very frequent occurrences in real sewer systems this difficulty should be overcome prior to extensive application of the model. Some private agencies and consulting firms may have overcome this difficulty already in their proprietary models, but the model available to the public from EPA does not as yet contain provision for these problems.

C. THE DEVELOPMENT OF A CONTROL SIMULATION MODEL

In Phase I of the MWIS project a model of an RTACS was developed. The model basically simulated on the computer all the elements of the system shown on Figure I-2. The operation of the model is conceptually shown on Figure V-4 along with some of the contingencies which should be considered in the modeling.

The complete RTACS model shown on Figure V-4 is rather complex. A logical way to begin to assemble such a model is to build it piece-by-piece. In the research completed to date the physical system model and the control model have been of primary interest. At the writing of the report the physical system model has been completed, but the control model is only partially complete. It is not yet known whether a control model can be constructed for the general case. The EPA Model previously described really attempts to present such a capability but has not yet really been generally applied.

The present research on control strategy was divided into two separate tasks. One task was to continue work on the RTACS Model work previously begun by Bell (53) and the other was to select a simple case for the direct development of simple control logic. This latter resulted in the cooperative work with San Francisco previously described. The continuation of Bell's work is described in the next section under "optimization techniques." The following is a description of tasks completed from the cooperative work with the City of San Francisco.

1. The Hydrologic Model

   For the development of a physical system model, the literature was searched for recent developments in simple but practical urban runoff models. At Purdue University they had evaluated a number of conceptual models for the prediction of urban runoff. The results from their work indicated that a single linear reservoir model was acceptable for small urban watersheds (less than 5 square miles) and a Nash Model was best for basins larger than 5 square miles (41). Both of these were considered for possible use as the hydrologic component for this project. In the case of the hydraulic component of the model several techniques were considered. The Muskingum routing technique was selected as being best for this application because of its simplicity and reliability for slopes that are not exceptionally flat.

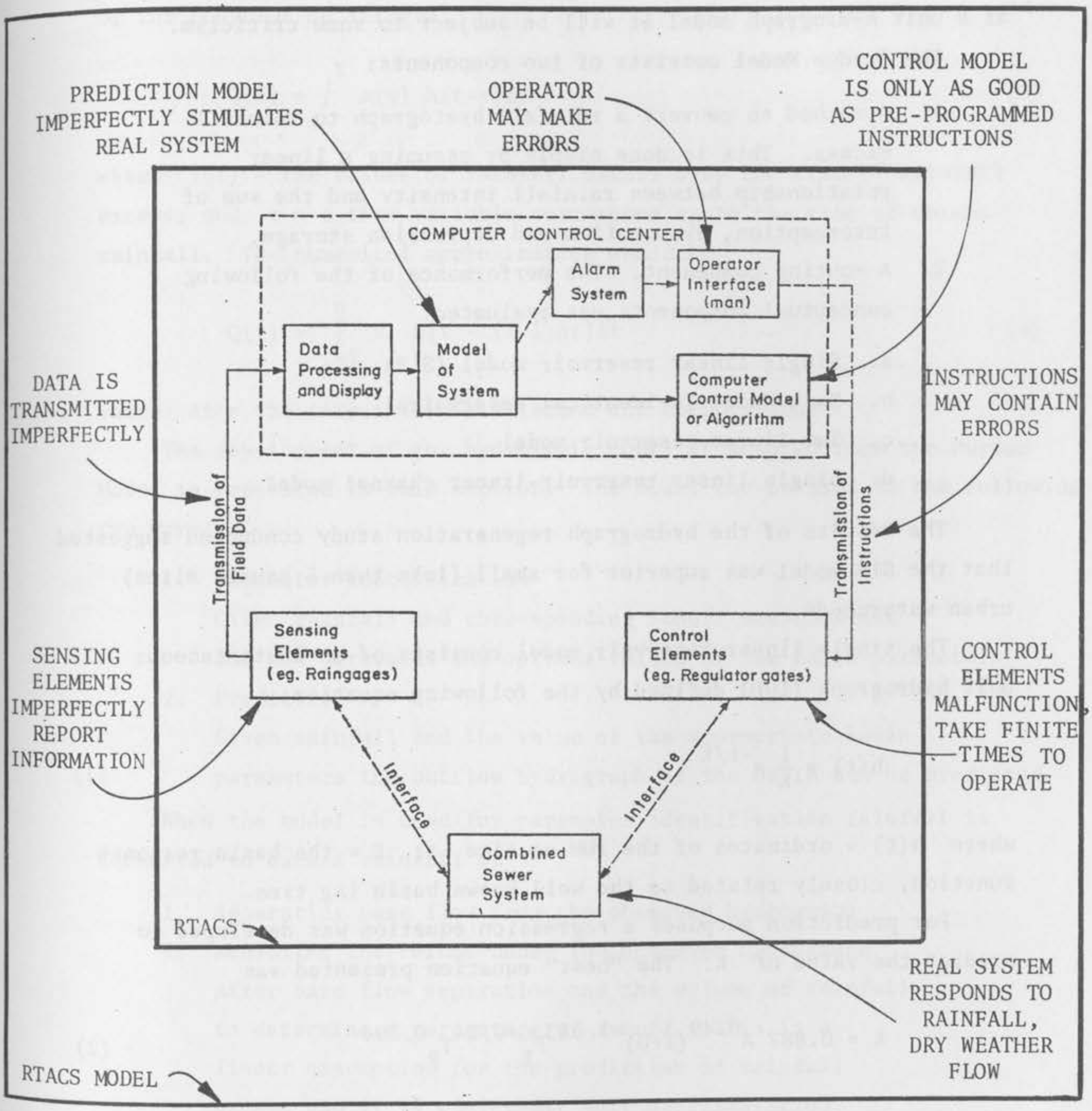


Figure V-4. Model of Real-Time Automation and Control System (RTACS)

The Purdue Model seems to be appropriate as a simple but promising urban runoff model which has been verified with some data. Of course, as a unit hydrograph model it will be subject to some criticism.

The Purdue Model consists of two components:

1. A method to convert a rainfall hyetograph to rainfall excess. This is done simply by assuming a linear relationship between rainfall intensity and the sum of interception, evaporation and depression storage.
2. A routing component. The performance of the following conceptual components was evaluated:
   a. Single linear reservoir model (SLR)
   b. Nash Model (n-identical reservoirs)
   c. Two linear reservoir model
   d. Single linear reservoir-linear channel model

The results of the hydrograph regeneration study conducted suggested that the SLR model was superior for small (less than 5 square miles) urban watersheds.

The single linear reservoir model consists of an instantaneous unit hydrograph (IUH) defined by the following equation:

$$h(t) = \frac{1}{K} e^{-t/K} \qquad (1)$$

where $h(t)$ = ordinates of the IUH at time t; K = the basin response function, closely related to the well known basin lag time.

For prediction purposes a regression equation was developed to predict the value of K. The "best" equation presented was

$$K = 0.887\, A^{0.49} (1+U)^{-1.683} P_E^{\,-0.24} T_R^{\,0.294} \qquad (2)$$

where A = basin area in square miles; U = urbanization factor, taken as percent impervious/100; P_E = volume of rainfall excess in inches; and T_R = duration of excess rainfall in hours.

The runoff hydrograph is calculated from a numerical approximation of the convolution integral,

$$Q(t) = \int_{o}^{t} x(\tau)\ h(t-\tau)d\tau \qquad (3)$$

where $\chi(\tau)$ = the values of rainfall excess over the time of rainfall excess; and τ = a time variable corresponding to the time of excess rainfall. The numerical approximation would be

$$Q(t) = \sum_{i=1}^{n} x_i\ h[t - (i-1)\Delta t]\Delta t \qquad (4)$$

where Δt = the time interval selected for computation.

The development of the hydrologic model as adapted from the Purdue Model is presented in this section. The model can be used in the following two ways:

1. Parameter Identification
   Given rainfall and corresponding runoff measurements one can determine the optimum values of the basin parameters.
2. Prediction
   Given rainfall and the value of the appropriate basin parameters the outflow hydrograph of the basin can be predicted.

When the model is used for parameter identification rainfall is converted to excess rainfall by

1. separating base flow from the observed hydrograph
2. measuring the volume under the observed hydrograph after base flow separation and the volume of rainfall to determine a percentage of runoff. This is a linear assumption for the prediction of rainfall excess and it is admittedly very oversimplified. For convenience, denote this multiplier as a "runoff coefficient, C".
3. multiplying the rainfall volumes by C to get excess rainfall

When the model is being used for prediction a conversion is made by estimating the runoff coefficient and multiplying the rainfall hyetograph ordinates by this coefficient. This procedure is described in the Purdue paper.

One of three routing component models can be used. They are:

1. a single linear reservoir model
2. a linear reservoir-linear channel model assuming a triangular time-area histogram, and
3. a linear reservoir-linear channel model with the time-area histogram specified

Some computation procedures are:

Base flow separation is necessary when the model is being used for parameter identification. Several empirical methods to separate base flow are in practice (6,24,29). These methods are arbitrary and are subject to the judgment of the individual who is preparing the data. For this reason, base flow separation is accomplished in this report manually rather than by a computer algorithm. The "observed hydrograph" input to the paratemer identification model is, therefore, the hydrograph after base flow separation.

The runoff coefficient, C, is calculated by the computer when the model is being used for parameter identification. The time interval, rainfall depths for the chosen time interval and the basin drainage area are read in. The total volume of rainfall is then calculated. Similarly, observed flow rates are read in and the volume under the hydrograph is calculated. The runoff coefficient is then calculated as the volume of runoff divided by the volume of rainfall.

The fitting criteria which measures the error between the calculated and observed hydrograph must be chosen in order to use the model for parameter identification. Two criteria have been used in this model. The first is the standard error which is expressed as follows:

$$\text{Standard Error} = \sqrt{\frac{\sum_{i=1}^{N} (Q_{oi} - Q_{ci})^2}{N-1}} \qquad (5)$$

where Q_{oi} = the observed flowrate at the i^{th} time point

Q_{ci} = the calculated flowrate at the i^{th} time point

N = the number of time points entered

The second penalizes only the fractional deviation between calculated and observed peak flows (Q_{PC} and Q_{PO} respectively) and calculated and observed times to peak (t_{PC} and t_{PO} respectively). This is expressed as follows:

$$\text{Error} = \sqrt{\left(\frac{Q_{PO} - Q_{PC}}{Q_{PO}}\right)^2 + \left(\frac{t_{PO} - t_{PC}}{t_{PO}}\right)^2} \qquad (6)$$

The fitting criteria which best describes the error between the calculated and observed hydrograph is subject to the judgment of the user. For example, the user could change the fitting criteria so that percentage errors, rather than absolute errors, were penalized by specifying the following criteria:

$$\text{Error} = \sum_{i=1}^{N} \left[\frac{Q_{ci} - Q_{oi}}{Q_{oi}}\right]^2 \qquad (7)$$

Calculation of the outflow hydrograph is based on one of the following three routing models:

1. Single linear reservoir

   The hydrograph for a single linear reservoir model is derived by assuming that the volume of rainfall excess, S(t) in a drainage basin at any time, t, is proportional to the outflow at the same time, Q(t). This is written as follows:

$$S(t) = K\,Q(t) \qquad (8)$$

   where K is the linear-reservoir routing coefficient which is prespecified in the prediction model and adjusted in the parameter identification model. The assumption of a linear reservoir coupled with the continuity conditions (i.e., Q = -ds/dt) results in the following instantaneous unit hydrograph.

$$Q(t) = \frac{V_o}{K}\, e^{-t/K} \qquad (9)$$

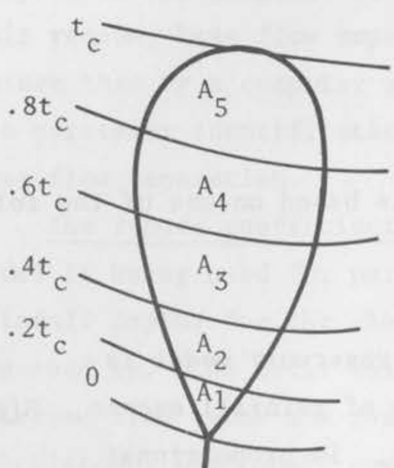
where V_o is the volume of excess rainfall (one inch over the entire drainage basin) occurring instantaneously at $t = 0$.

The runoff hydrograph is calculated by assuming that the volume of rainfall excess for each time interval occurred instantaneously at the centroid of that time interval and superimposing the hydrographs calculated for each time interval.

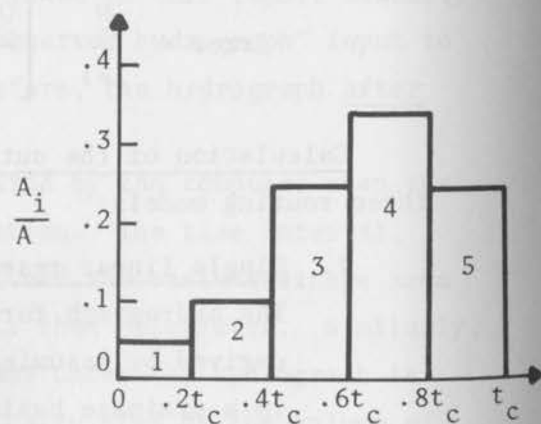
2. <u>Linear reservoir-linear channel with specified time-area histogram</u>

This type of routing method was proposed by Clark (10). It is based on considering separately two phenomena, translation and reservoir action, which actually occur simultaneously in a drainage basin

The effects of translation are found by constructing a time-area histogram, TAH, which is a plot of drainage area versus travel time t. The construction of the TAH is illustrated below:



BASIN WITH ISOCHRONES



TIME-AREA-HISTOGRAM

Each interval of excess rainfall is then multiplied by the ordinates of the TAH and these are superimposed to get the excess rainfall hyetograph after translation.

The effects of reservoir action are modeled by assuming a linear reservoir as described above. However, the excess rainfall hyetograph <u>after</u> translation is used.

3. Linear reservoir-linear channel assuming a triangular TAH

   The construction of the TAH for each drainage basin to be modeled is a time consuming process. Due to the smoothing effects of the linear reservoir routing it is often sufficiently accurate to approximate the TAH by an isosceles triangle. When this is assumed, the effects of translation can be calculated by the computer and it is not necessary to supply the TAH as input.

Optimization of the basin lag parameter, K, is accomplished by calculating the outflow hydrograph and the error between the calculated and observed hydrographs for two different values of K. "Optimization" in this case means the selection of a value of K which represents a best fit to the observed hydrograph. The value of K is then changed incrementally starting with the value of K which yielded the larger error and proceeding in the direction of the other K value. When the error for the newest K value is greater than the error for the previous K value the iteration stops. The next to the last K value is then the optimum one (i.e., the K which minimizes the specified index of error between the calculated and observed hydrograph).

It should be noted that our experience has indicated that both of the error measurements described previously are convex functions of K. This is necessary in order to guarantee that the iteration proeceure just described will converge to the true optimal value of K.

Any two values of K could be used to start the iteration, but the model uses two specific estimates. The first is the time difference between the centroids of the excess rainfall hyetograph and the observed runoff hydrograph. This value is calculated by the computer and is the theoretical value of K for a single linear reservoir model. The second is based on the following regression equation proposed by Sarma, et. al., (44):

$$K(\text{hrs.}) - 0.887A^{0.490}\ (1 + U)^{-1.683}\ PE^{-0.24}\ TR^{0.294} \tag{10}$$

where: A = basin drainage area (Mi^2)

U = impervious area/A

PE = total excess precipitation (in.)

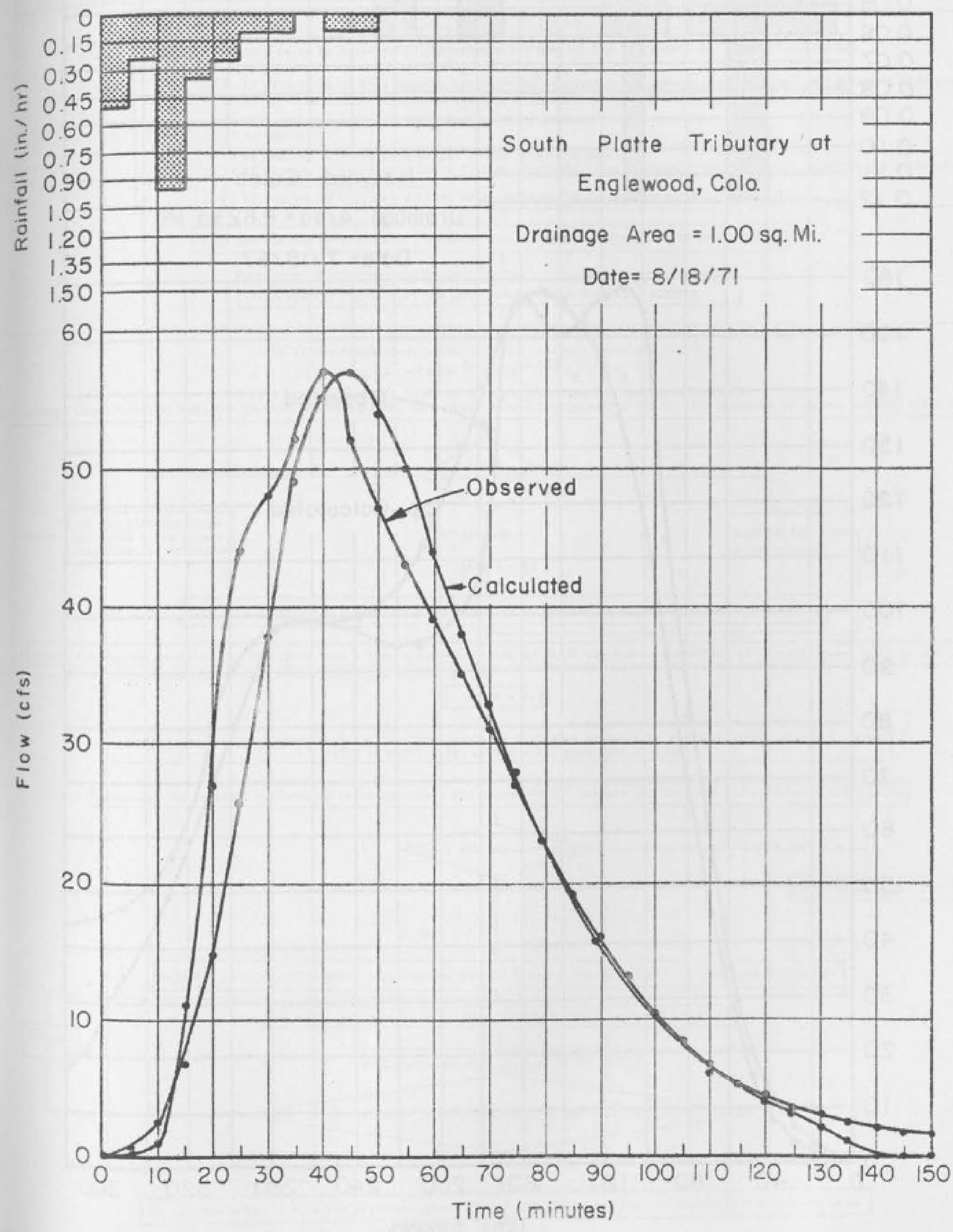
TR = duration of excess precipitation (hrs.)

Some results of the use of the hydrologic model for fitting (the Identification Problem) are shown in Figures V-5 and V-6. Figure V-7 is a description of the computer program which was developed for the parameter identification problem.

D. HYDRAULIC MODEL

Modeling the hydraulic transport phenomena in sewers is usually a problem of gradually varied unsteady flow in open channels. When the pipe becomes full the problem shifts to one of pressure flow. Therefore, the best program would be one which could handle either case. An ideal technique for solving this problem would be one which would solve the complete St. Venant equations of open channel flow which are the continuity equation and the momentum equation in partial differential form. Solution of these equations has been done in their complete form using finite difference schemes, but this approach is considered too complex for the problem at hand. Therefore, a simplified model was employed. The simplified model uses the Muskingum method of storage routing. This method originally was derived for storage routing in general, being applied to the reservoir case, and can be adapted to flow in channels or in pipes. Of course, since this is an approximate technique in the general class of solutions with incomplete equations, the range of applicability is limited. Two basic restrictions apply. First, backwater effects are not calculated when using the Muskingum method. Second, the slope of the pipe has to be significantly greater than zero. The closer the pipe becomes to the horizontal, the less applicable the Muskingum routing method is.

The Muskingum method involves repeated application of an explicit equation for which the downstream flowrate at time $t = (n+1)\Delta t$ is calculated as a weighted average of three flowrates, the upstream flowrates at time $t = n\Delta t$ and $t = (n+1)\Delta t$ and the downstream flowrate at time $t = n\Delta t$. The calculation, therefore, proceeds forward in time and downstream in direction. The Muskingum equation and a graphical illustration of its use follows:



South Platte Tributary at
Englewood, Colo.
Drainage Area = 1.00 sq. Mi.
Date= 8/18/71
Rainfall (in./hr)
0
0.15
0.30
0.45
0.60
0.75
0.90
1.05
1.20
1.35
1.50
Flow (cfs)
60
50
40
30
20
10
0
Observed
Calculated
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time (minutes)

Figure V-5

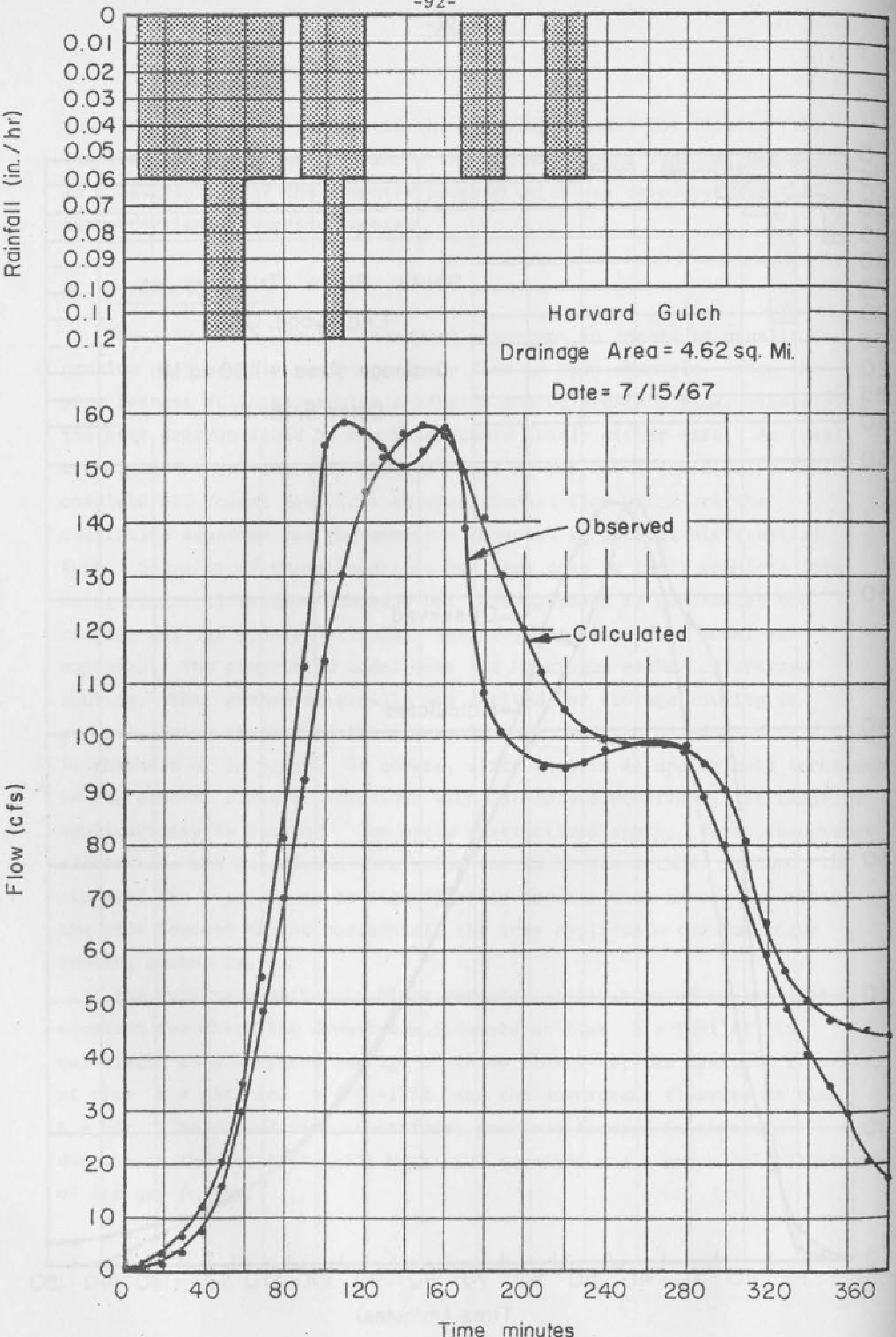
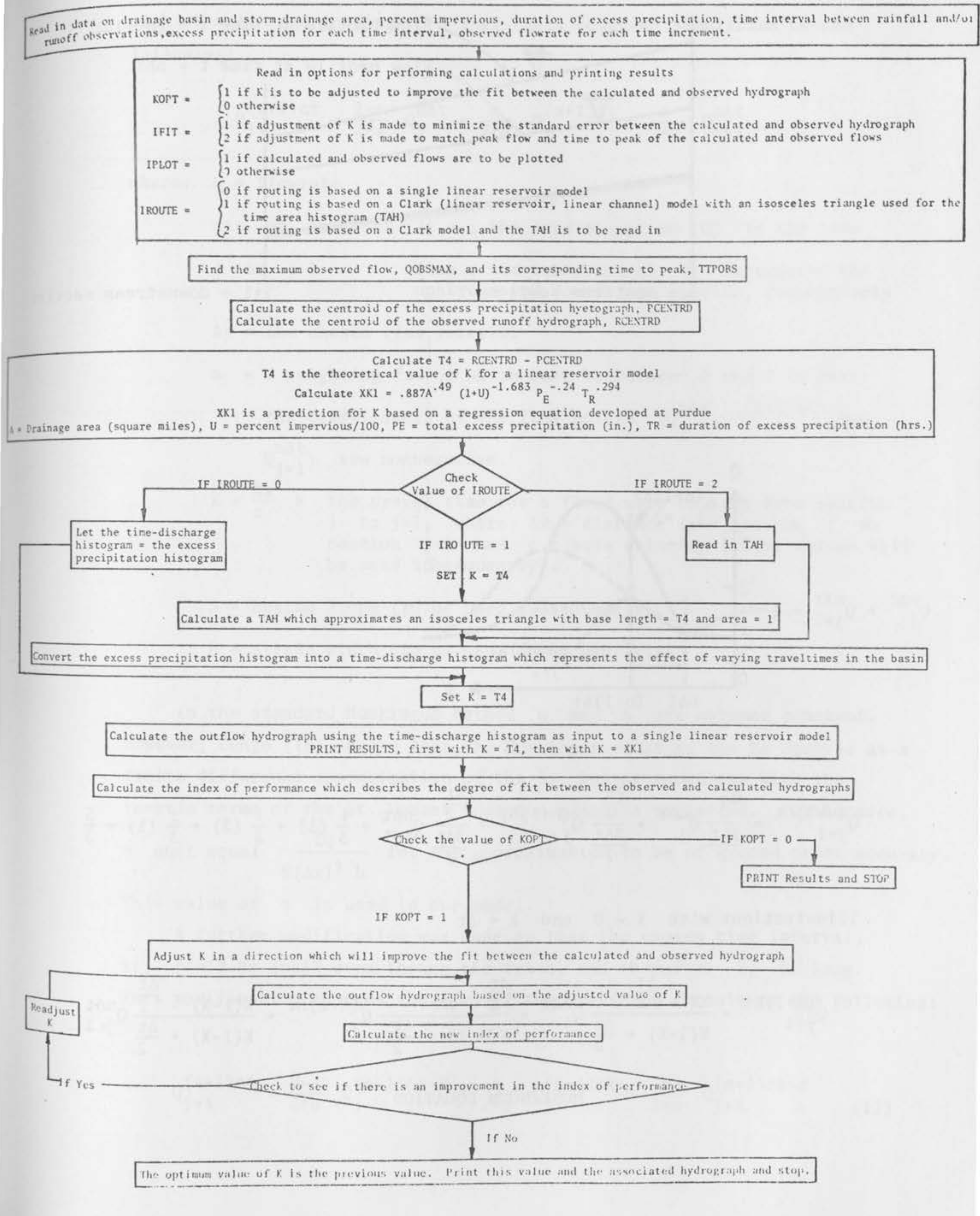
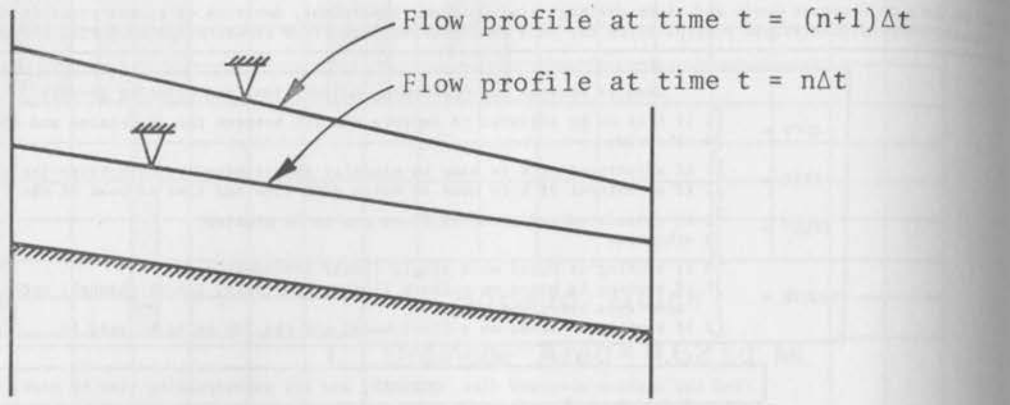
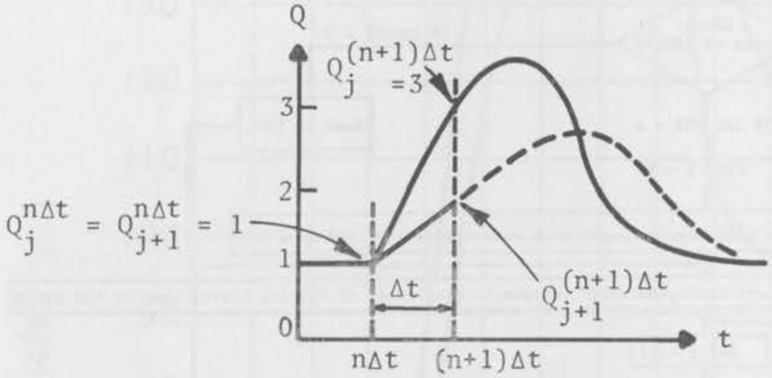

Rainfall (in./hr)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
Harvard Gulch
Drainage Area = 4.62 sq. Mi.
Date = 7/15/67
Observed
Calculated
Flow (cfs)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
40
80
120
160
200
240
280
320
360
Time minutes

Figure V-6

FLOW DIAGRAM - EXCESS PRECIPITATION ROUTING







$$Q_{j+1}^{(n+1)\Delta t} = \frac{\frac{\Delta t}{2}}{\frac{3\Delta t}{2}} Q_j^{n\Delta t} + \frac{\frac{\Delta t}{2}}{\frac{3\Delta t}{2}} Q_j^{(n+1)\Delta t} + \frac{\frac{\Delta t}{2}}{\frac{3\Delta t}{2}} Q_{j+1}^{n\Delta t} = \frac{1}{3}(1) + \frac{1}{3}(3) + \frac{1}{3}(1) = \frac{5}{3}$$

Illustrations with $X = 0$ and $K = \Delta t$

$$Q_{j+1}^{(n+1)\Delta t} = \frac{KX + \frac{\Delta t}{2}}{K(1-X) + \frac{\Delta t}{2}} Q_j^{n\Delta t} + \frac{\frac{\Delta t}{2} - KX}{K(1-X) + \frac{\Delta t}{2}} Q_j^{(n+1)\Delta t} + \frac{K(1-X) - \frac{\Delta t}{2}}{K(1-X) + \frac{\Delta t}{2}} Q_{j+1}^{n\Delta t}$$

MUSKINGUM EQUATION

with $K = \Delta t$ and letting $\alpha = 1-2X$ this equation simplifies to the following:

$$Q_{j+1}^{(n+1)\Delta t} = \frac{2-\alpha}{2+\alpha} Q_j^{n\Delta t} + \frac{\alpha}{2+\alpha} Q_j^{(n+1)\Delta t} + \frac{\alpha}{2+\alpha} Q_{j+1}^{n\Delta t} \qquad (11)$$

where: Q = flowrate

$n\Delta t$ or $(n+1)\,\Delta t$ (i.e., the superscript on Q) is the time

j or $j+1$ (i.e., the subscript on Q) represents the upstream and downstream section, respectively

Δt = the chosen time interval

α = a weighting factor which must be between 0 and 2 so that the coefficients of the flow points ($Q_j^{n\Delta t}$, $Q_j^{(n+1)\Delta t}$ and $Q_{j+1}^{n\Delta t}$) are nonnegative.

$K = \frac{\Delta x}{c}$ = the travel time for a flood wave to pass from section j to $j+1$, where Δx = distance from section j to section $j+1$ and c = wave celerity (these values will be used subsequently).

S = bottom slope (to be used subsequently).

b = stream width (to be used subsequently).

In the standard Muskingum method α and K are assumed constant. However, Cunge (16) showed that the Muskingum equation can be derived as a finite difference approximation of the St. Venant equations with the inertia terms of the St. Venant momentum equation neglected. Furthermore, α must equal $\frac{KQ}{S(\Delta x)^2\, b}$ for the approximation to be of second order accuracy. This value of α is used in our model.

A further modification was made so that the chosen time interval, Δt, could be small even though the reach, and therefore K, is long. This modification changes the form of the Muskingum formula to the following:

$$Q_{j+1}^{(n+1)\Delta t} = \frac{2-\alpha}{2+\alpha} Q_j^{(n+1)\Delta t-K} + \frac{\alpha}{2+\alpha} Q_j^{(n+1)\Delta t} + \frac{\alpha}{2+\alpha} Q_{j+1}^{(n+1)\Delta t-K} \qquad (12)$$

E. COMBINATION HYDROLOGIC-HYDRAULIC MODEL

A combined hydrologic-hydraulic model has been developed for the Vicente Basin in San Francisco. The model has been applied to the basin and some preliminary results of that application using synthetic rainstorms have been achieved. Actual rainstorms are available for exercising the model as well.

In order to analyze the control possibilities of storm water retention basins it is necessary to develop models which describe the hydrology of the tributary basins and the hydraulics of the sewage collection and transport system. This model must be capable of: (1) predicting the uncontrolled flow upstream of the retention basins, (2) adjusting these flows to describe the control exercised at the retention basins, and (3) routing the controlled flow downstream. It was for this purpose that the model described in this section was developed.

The model consists of a main program, MAIN, and four subroutines BASIN, REACH, KALFA and TRAPAL. The subroutines are general and can be used for any basin while a simple main program must be written for each basin to be modeled. BASIN is the hydrologic component of the model. It accepts rainfall as input and returns the outflow hydrograph. REACH is the transport or hydraulic component of the model. Input to REACH is the upstream hydrograph. Output is the downstream hydrograph of a defined circular or trapezoidal reach. KALFA and TRAPAL calculate travel time and the "weighting factors" to be used in the Muskingum routing performed in REACH. KALFA is for a circular section while TRAPAL is for a trapezoidal section.

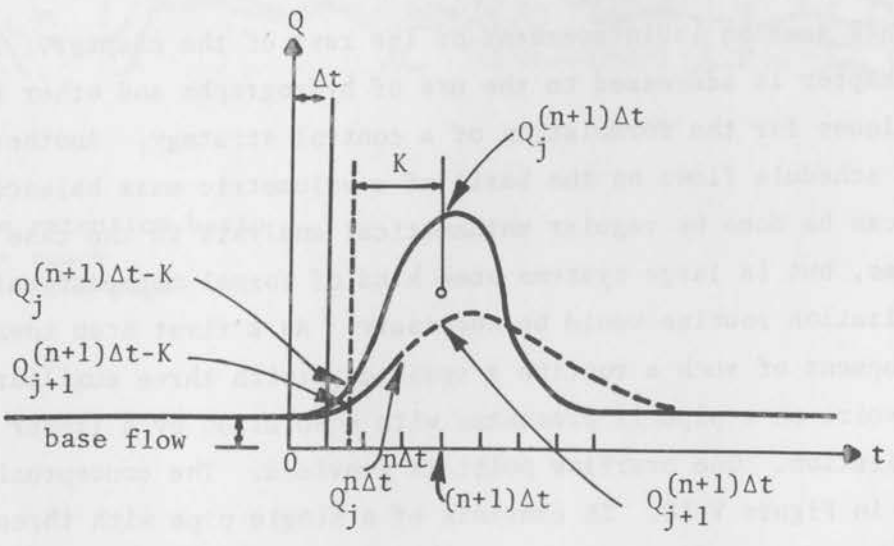
The main program handles the logistics of the particular basin being modeled. It calls subroutines BASIN and REACH, adds the hydrographs of subbasins and branches entering the system, accounts for the control exercised at the retention basins, etc.

Subroutine BASIN predicts the hydrograph of each subbasin in the model. Each subbasin drainage area, runoff coefficient, (C), reservoir routing coefficient (K), base flow and rainfall hyetograph must be specified. The single linear reservoir routing procedure described earlier is used. This is a simple routing model, but its use is justified for the small subbasins under consideration (45).

Subroutine REACH routes a hydrograph through a defined circular or trapezoidal section using the Muskingum routing equation. The routing procedure is described below. The description is based on routing through a circular section. The procedure is similar for a trapezoidal section except subroutine TRAPAL is used instead of KALFA. Also a rectangular or V-shaped section could be routed using TRAPAL as these sections are special cases of a trapezoidal section.

1. Call subroutine REACH from the main program after the upstream hydrograph has been defined.
2. Read the slope (S), radius (R), Manning roughness coefficient (n) and length (Δx) of the reach.
3. To begin the calculation let index $n = 0$ correspond with $t = 0$. Also let $Q^o_{j+1} = Q^o_j$ = base flow.
4. Call KALFA to:
   a. Find the depth of flow (h), which satisfies the Manning equation for $Q^{n\Delta t}_j$ using Newton's Method.
   b. Solve for $C = dQ/dA$
   c. Solve for $K = \Delta x/c$
   d. Solve for $\alpha = KQ/S(\Delta x)^2 b$.
5. Find $Q^{(n+1)\Delta t-K}_j$ and $Q^{(n+1)\Delta t-K}_{j+1}$ by interpolation
6. Solve the Muskingum equation for $Q^{(n+1)\Delta t}_{j+1}$
7. Proceed by incrementing n until $Q^{(n+1)\Delta t}_{j+1}$ approaches base flow.

The modified procedure is illustrated graphically below:



One problem presents itself when a hydrograph is routed through a circular section. When h is approximately 93% of the pipe diameter dQ/dA is zero and K is undefined. At depths from 93% to 100% full K is negative. When this situation occurs the depth is assumed to be slightly less than 93% full and C,K and α are calculated accordingly.

F. APPLICATION OF THE CONTROL MODEL TO A SMALL BASIN

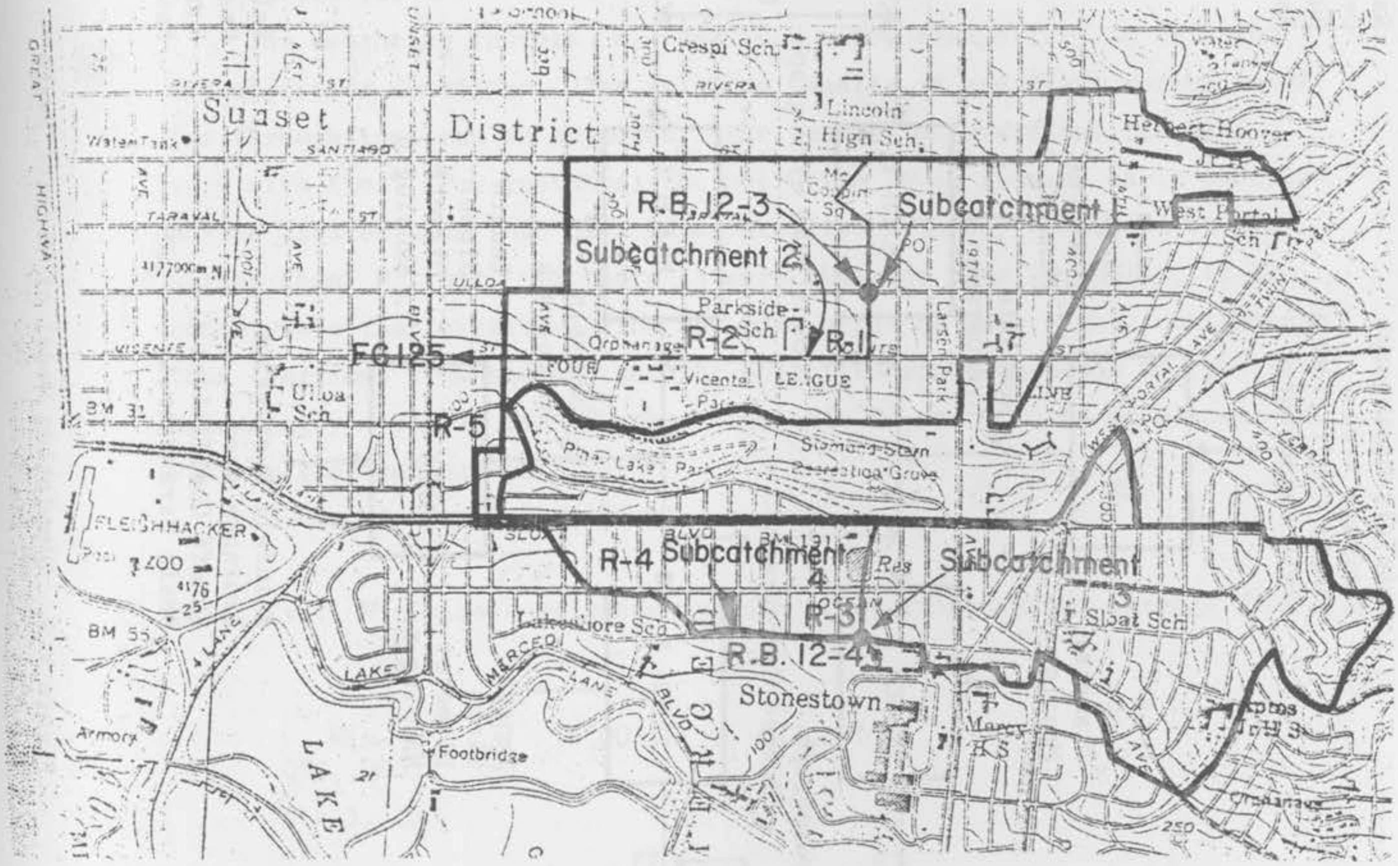
The Vicente St. Basin has been modeled in order to analyze the effects of storm movement and utilization of the proposed retention basins. As shown in Figure V-8, the basin is divided into four subbasins. These four subbasins roughly define the Vicente St. Basin as measured at flow gage 125.

Results of initial simulation runs on the basin are not included in this report since they have not been checked with actual data yet. A model now exists that can be exercised in the simulation mode to explore practically any scenario desired for the Vicente Basin.

The structure of the simulation model is shown on Figure V-9. From this figure it is clear where parameters can be varied. As an example, note the volumes of retention basins 12-3 and 12-4. The volumes can be easily changed to examine the effect on downstream hydrographs of such changes. As another example, note the hyetographs into the individual subcatchments. These hyetographs can be varied to simulate different rainfall patterns.

G. ANOTHER TECHNIQUE-LINEAR OPTIMIZATION

This section is independent of the rest of the chapter. The rest of the chapter is addressed to the use of hydrographs and other flow prediction techniques for the formulation of a control strategy. Another technique is to schedule flows on the basis of a volumetric mass balance technique. This can be done by regular mathematical analysis in the case of small systems, but in large systems some kind of formal mathematical model, an optimization routine would be necessary. As a first step toward the development of such a routine a small case with three auxiliary storage reservoirs on a pipe is presented with a solution by a linear programming optimization. One overflow point is provided. The conceptual model is shown in Figure V-10. It consists of a single pipe with three inputs,



Notes:

R.B. = retention basin
R = reach
FG = flow gage

Figure V-8

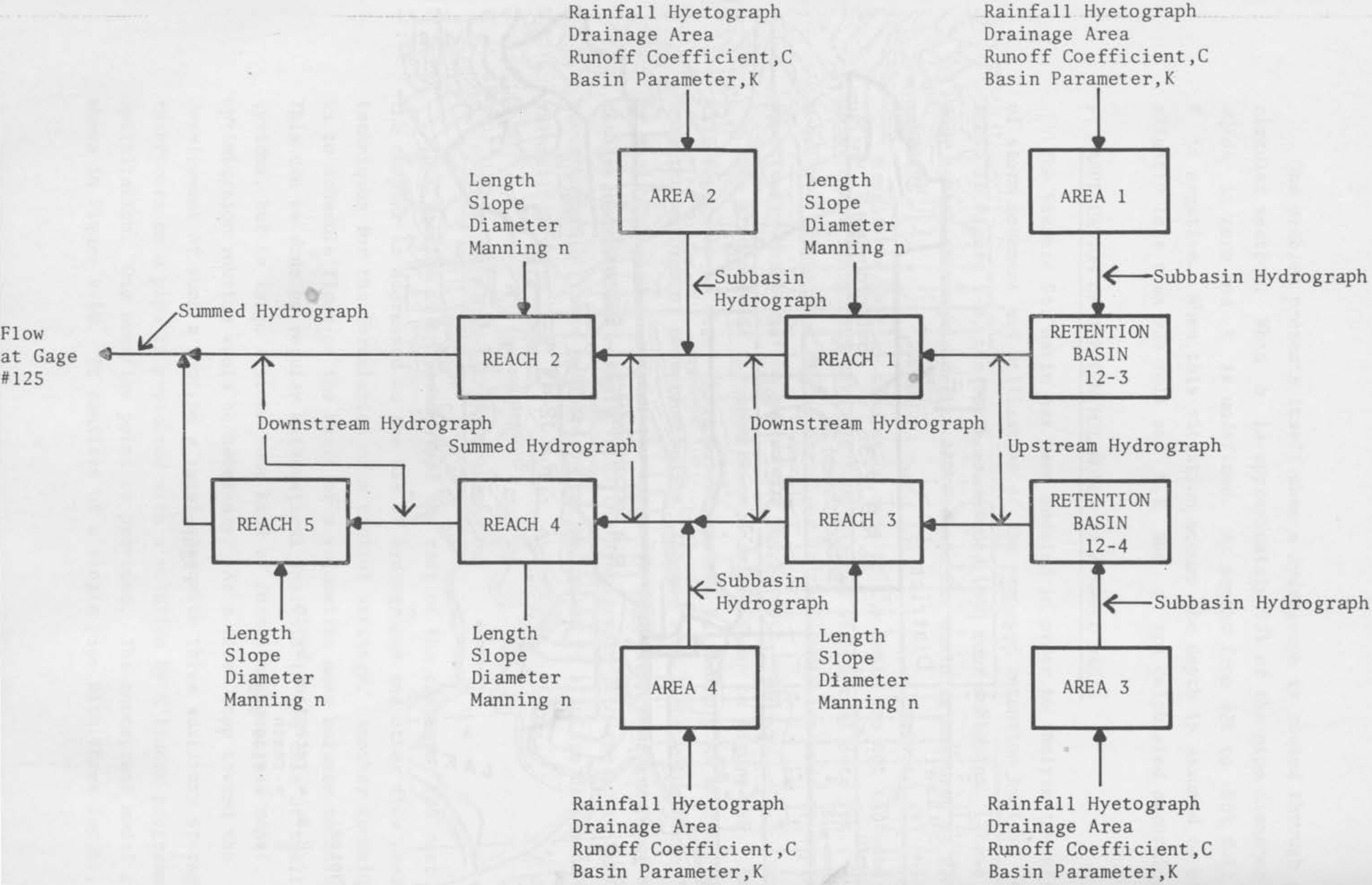


Figure V-9. Simulation Model of Vicente Basin

F1, F2, F3 with a subscript i referring to the particular increment of time being considered. The retention basins are given with volumes V1, V2, and V3 and the units QT1, QT2, and QT3 constitute throughflows past the particular retention basins in question. The quantity QO3 is the single overflow point which is shown as being from reservoir 3. The formulation of the problem is such that we minimize an objective function which consists of a weighted average of overflows minus throughflow. The objective is thus to minimize the objective function shown in Equation 13.

The weighting factors P_i and C_i allow flexibility in defining the objective functions. The relative penalty on overflows versus credit for throughflows can be adjusted. The penalty on overflows can also vary with time. For instance, the pollution level from an early overflow may be greater than that of a later overflow. Thus, P_1 could be set higher than P_2 etc. If there is more than one overflow point, it is conceivable that overflows from one area might be more highly contaminated than overflows from another and the objective function could be specified accordingly. Simply stated, the values of P and C can be allowed to vary in time and/or space.

An example problem follows:

Objective: Minimize a weighted average of overflows minus through flow

$$\min_{\substack{QT3_i,\,QO3_i \\ i = 1 \ldots n}} \sum_{i=1}^{n} \left(P_i QO3_i - C_i\, QT3_i\right) \Delta t_i \qquad (13)$$

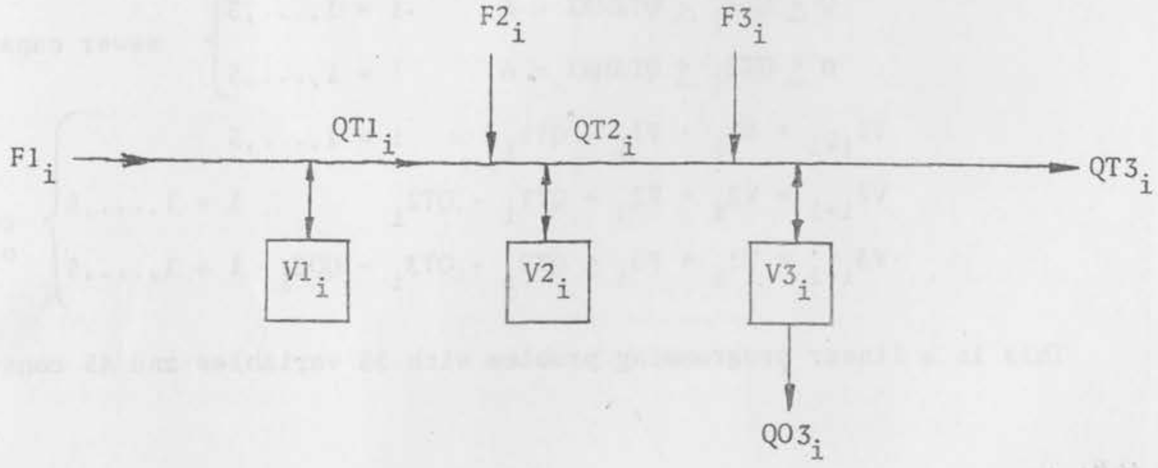


Figure V-10

Example:

$P_i = 1.0,\ C_i = 0.2 \qquad i = 1,\ldots,n = 5$

$F1_1 = F2_1 = F3_1 = 3$

$F1_2 = F2_2 = F3_2 = 4$

$F1_3 = F2_3 = F3_3 = 6$

$F1_4 = F2_4 = F3_4 = 5$

$F1_5 = F2_5 = F3_5 = 4$

$\Delta t_i = 1 \qquad i = 1,\ldots,5$

$V1_1 = V2_1 = V3_1 = 0$

$V1MAX = V2MAX = V3MAX = 7$

$QT1MAX = 4 \qquad QT2MAX = QT3MAX = 6$

Objective

$$\min_{\substack{QT3_i, QO3_i \\ i = 1,\ldots,5}} \sum_{i=1}^{5} (QO3_i - 0.2\ QT3_i)\Delta t_i$$

Constraints

$$\left.\begin{array}{ll} 0 \le V1_i \le V1MAX = 7 & i = 2,\ldots,6 \\ 0 \le V2_i \le V2MAX = 7 & i = 2,\ldots,6 \\ 0 \le V3_i \le V3MAX = 7 & i = 2,\ldots,6 \end{array}\right\} \text{reservoir capacity}$$

$$\left.\begin{array}{ll} 0 \le QT1_i \le QT1MAX = 4 & i = 1,\ldots,5 \\ 0 \le QT2_i \le QT2MAX = 6 & i = 1,\ldots,5 \\ 0 \le QT3_i \le QT3MAX = 6 & i = 1,\ldots,5 \end{array}\right\} \text{sewer capacity}$$

$$\left.\begin{array}{ll} V1_{i+1} = V1_i + F1_i - QT1_i & i = 1,\ldots,5 \\ V2_{i+1} = V2_i + F2_i + QT1_i - QT2_i & i = 1,\ldots,5 \\ V3_{i+1} = V3_i + F3_i + QT2_i - QT3_i - QO3_i & i = 1,\ldots,5 \end{array}\right\} \text{continuity of flow}$$

This is a linear programming problem with 35 variables and 45 constraints

As can be seen from the continuity of flow equations, no time lag between retention basins was considered in the above example. The concept of a constant travel time between retention basins can easily be incorporated. For example, if the travel time between retention basins 1 and 2 was one time interval and the travel time between basins 2 and 3 was also one time interval the continuity equations would be changed as follows:

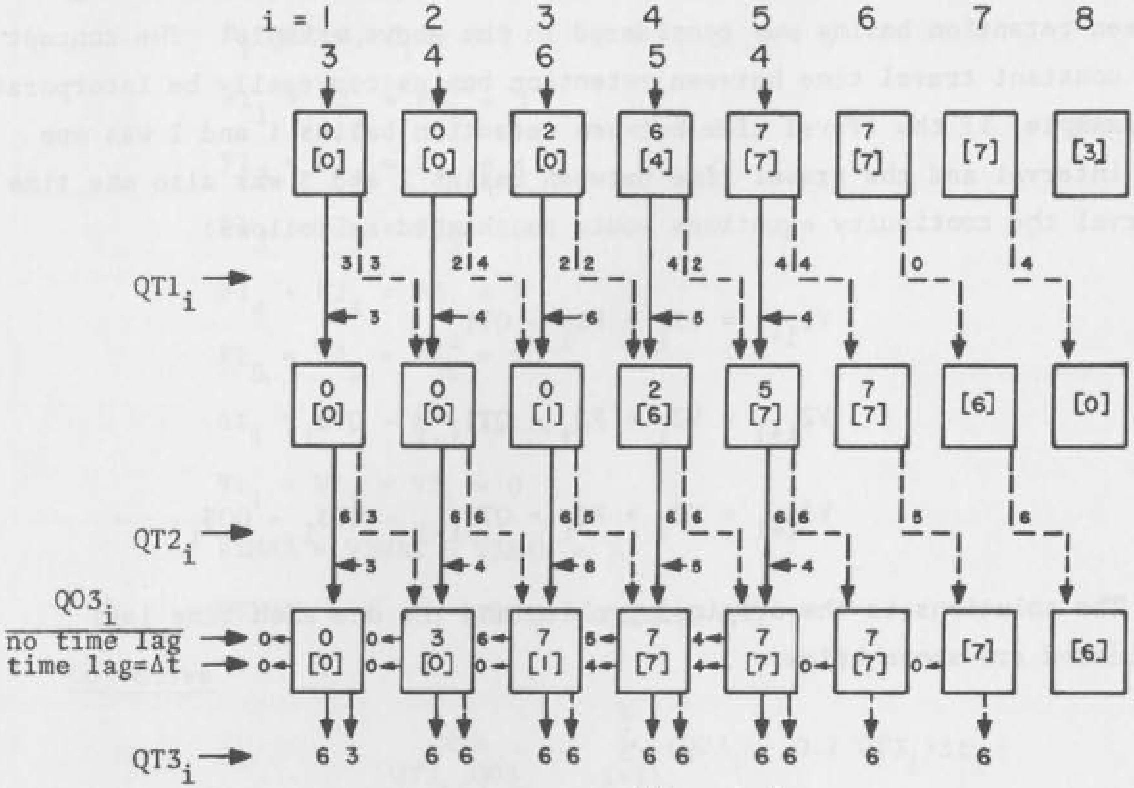
$$V1_{i+1} = V1_i + F1_i - QT1_i$$

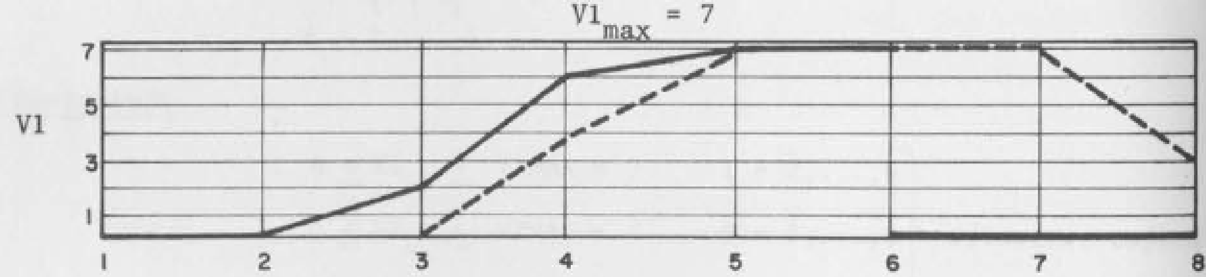
$$V2_{i+1} = V2_i + F2_i + QT1_{i-1} - QT2_i$$

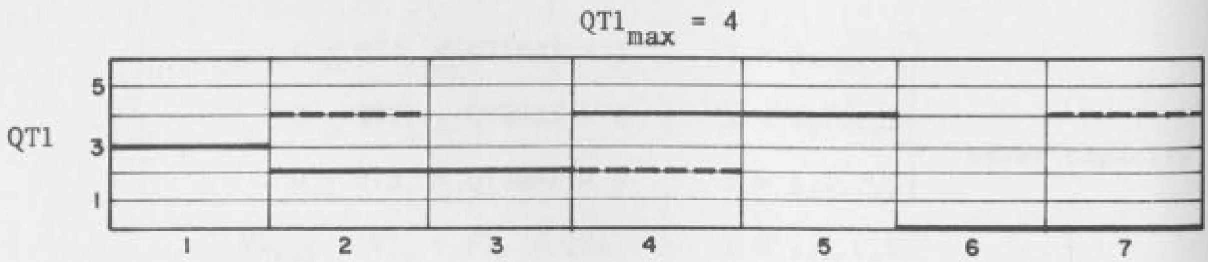
$$V3_{i+1} = V3_i + F3_i + QT2_{i-1} - QT3_i - QO3_i$$

The solutions to the original problem and the one with time lags considered are shown below:

Results: (5.1 sec. comp. time + 6.3 sec. execution time)







NOTE:

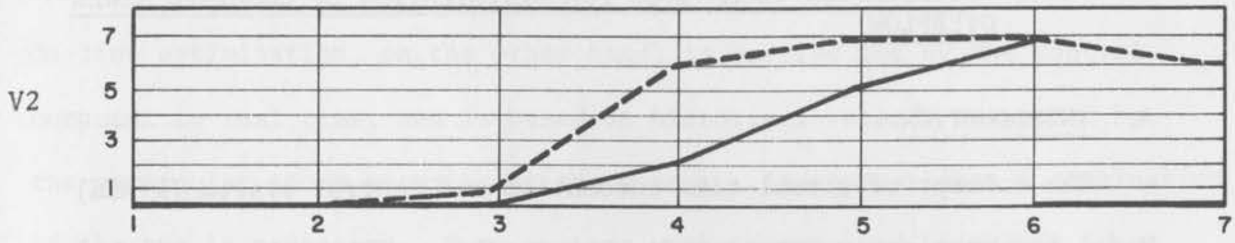
——— No time lag

\- - - - - Time lag between res. 1 & 2 and 2 & 3 is one time interval

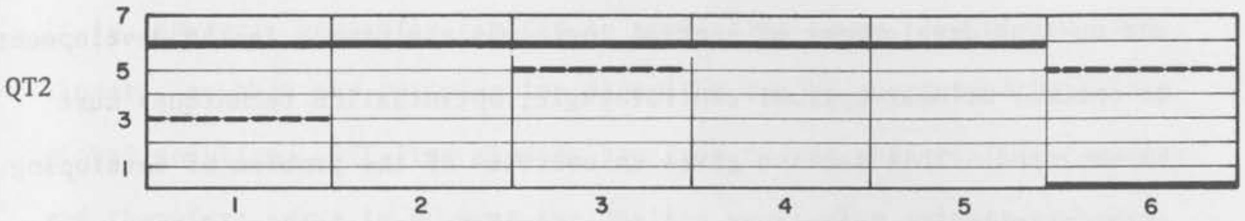
[ ] Storages resulting from the above time lags (at beginning of period)

Seven time intervals were considered for the "time lag" case. This increased the size of the l.p. problem to one of 49 variables and 63 constraints.

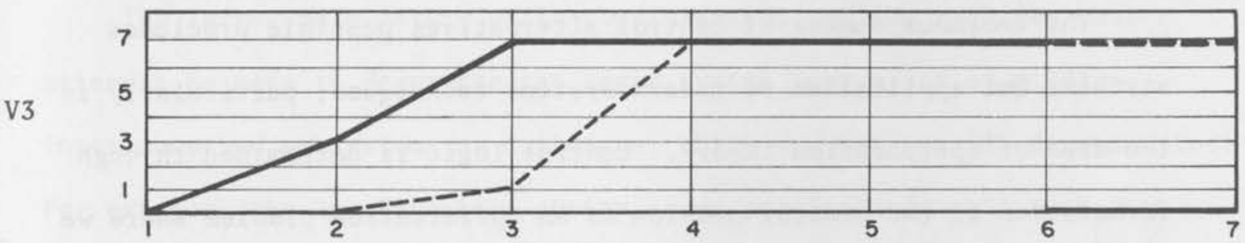
$V2_{max} = 7$



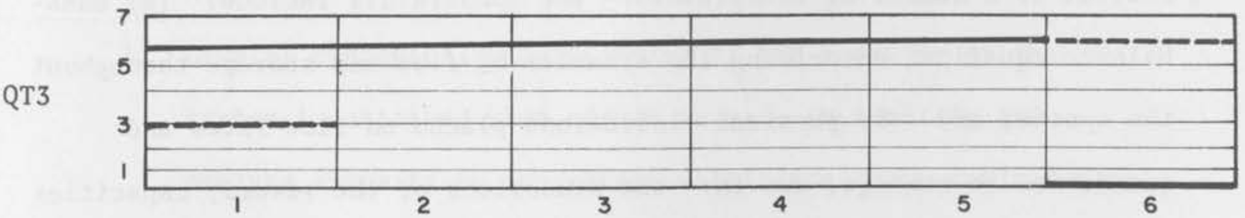
$QT2_{max} = 6$

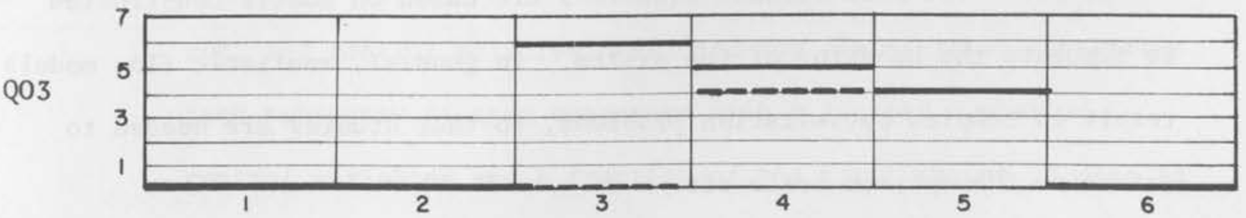


$V3_{max} = 7$



$QT3_{max} = 6$





VI. OPTIMIZATION TECHNIQUES FOR MINIMIZATION OF COMBINED SEWER OVERFLOW

A. INTRODUCTION

The concept of a real-time automation and control system (RTACS) Model was previously introduced. The need for control logic as the heart of the control model was discussed and the question of off-line and on-line development of control logic was explored. In the development of optimal or near-optimal control logic, optimization techniques must be employed. This section gives an overview of the problem of developing such optimization techniques. A more complete description of the problem is provided in a technical report issued separately.

The enormous number of control alternatives possible precludes anything but application of modern systems techniques, particularly in the area of optimization theory. Control logic is determined through formulation of the control problem as an optimization problem where we seek to minimize total weighted overflows from the combined sewer system, subject to a number of constraints. The constraints include: (a) mass-balance equations describing the dynamics of flow and storage throughout the system, and (b) physical limitations placed on flow rates and quantities in storage, due to: the dimensions of the sewers, capacities of ambient and auxiliary storage, and capacities of treatment plant facilities. The mass-balance equations are based on models constructed to simulate the behavior of the system. In general, realistic flow models result in complex optimization problems, so that studies are needed to determine the optimum trade-off.

There is question as to whether optimization should be carried out all off-line, all on-line, or a mixture of the two. Off-line optimization results in general operating policies, based on historical rainfall data, which are programmed into the control computer operating the system. On-line optimization, on the other hand, is carried out by the control computer in real time, and is based on historical records augmented by the particular storm occuring at the moment. It appears that a combination of the two is necessary. Some on-line work is required, since it is impossible to model all possible storm situations in an off-line manner. It is, however, generally limited to simplified sewer flow models (e.g., linear), so that the optimization algorithm can be guaranteed to find a global solution. Off-line studies are free to use more realistic models, and therefore serve to augment the on-line work. The primary emphasis here is on the former.

The large-scale nature of the optimization problem requires that attempts be made to decompose the sewer system into a set of mildly interconnected subsystems or *subbasins*, which are temporarily disconnected. For example, the San Francisco system seems particularly well suited to decomposition, as schematically represented in Figure VI-1.

The *advantages* of decomposing a large-scale system are the following:

1. Greater conceptual understanding of the behavior of the system is attained when effort is made to identify and analyze subparts or subsystems within the large-scale system.
2. Mathematical programming techniques are available such that interconnections between the subsystems can be temporarily cut, and control policies developed for the isolated subsystems. Each subsystem is then concerned with a limited number of control variables and a fraction of the total amount of data is necessary to operate the system. The result is considerable increase in system reliability toward achieving the overall system goals. The subsystems can then be recomposed together

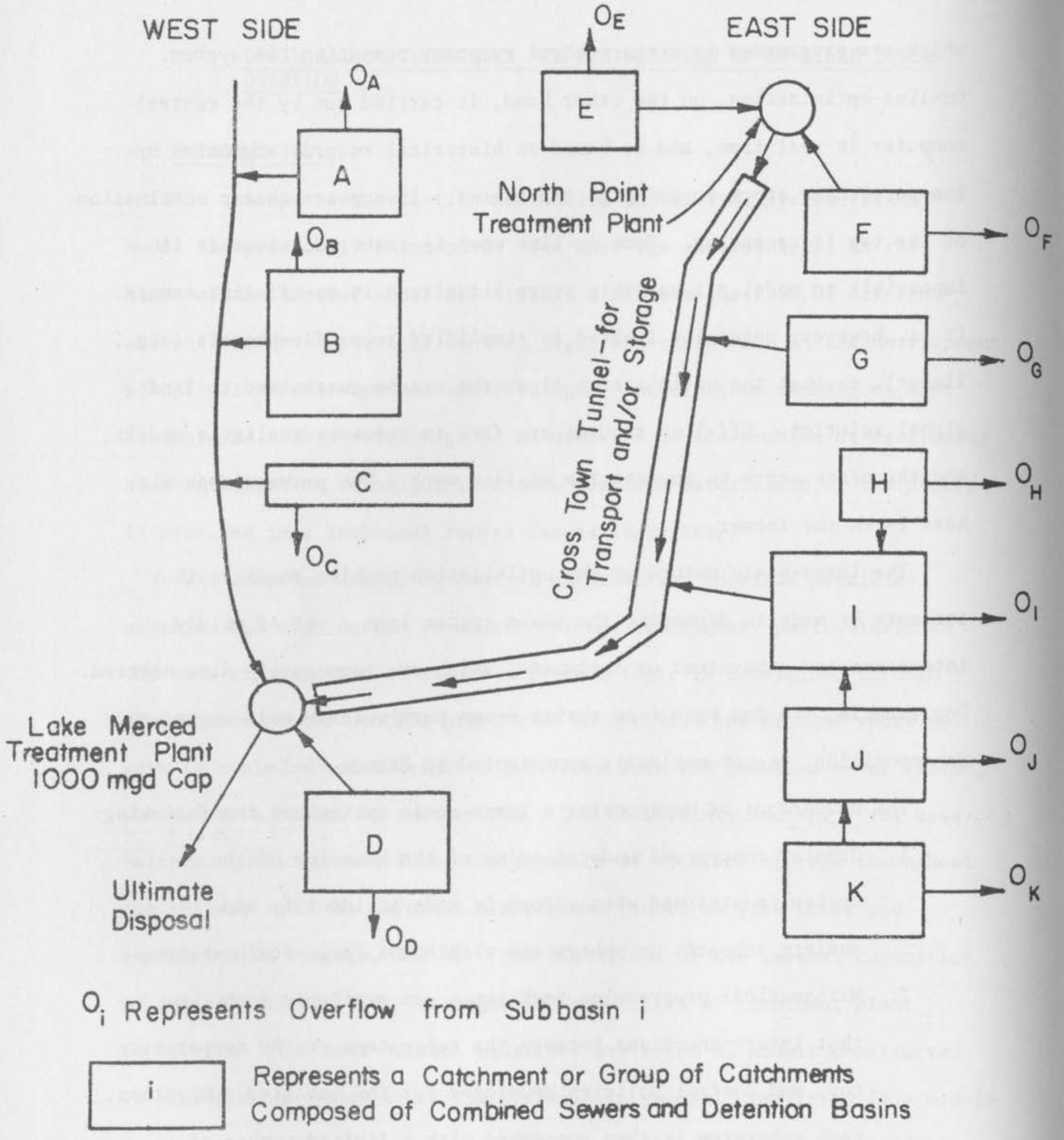


FIGURE VI-1

DECOMPOSITION OF THE PLANNED SAN FRANCISCO
COMBINED SEWER SYSTEM

by a master control which achieves the recomposition in some kind of iterative fashion.

3. Generally, less computer hardware is required for the decomposition approach than for centralized approaches. Essentially, computer storage is replaced by additional computer time. Less required computer hardware may mean greater reliability.

The emphasis in this section is on smaller scale subbasin analysis. Future reports will deal with development of master controllers that tie the subbasins together. With this plan in mind, storage configurations will be used in discussing the various optimization formulations and solution strategies, thus preventing unwieldy notation in the presentation. Extensions to more complicated configurations should be reasonably obvious.

The undertaking of this portion of the study has been motivated by the following:

1. The need for a broad, comprehensive evaluation of the basic optimization methodologies with regard to their specific applicability to solution of the optimal control problem for combined sewers.
2. The need for summarizing and critically analyzing current published attempts at formulating and solving the control problem via particular optimization techniques. As mentioned previously, however, little is available at the present time.
3. The necessity for generating new ideas with regard to specific optimization strategies for dealing with the complexities of the control problem that have so far hindered actual implementation for real time systems.

Detailed description of attempts to satisfy these objectives can be found elsewhere (27). The goal here is to summarize some of the important formulations and assertions. One should decide at an early stage whether to apply finite or infinite-dimensional optimization techniques (i.e., continuous-time optimal control theory). A more complete discussion of the latter can be found in (27). Finite-dimensional techniques are discussed in the following presentation, concluding with some ideas on application of indirect or dual approaches to the control problem. These approaches revolve around the concept of approximate-flow, and they may open the door to dealing with the difficulties that have so far hindered direct application of more conventional optimization techniques.

B. FINITE AND INFINITE-DIMENSIONAL OPTIMIZATION

1. A Reservoir Control Problem

a. Discrete Time Case [finite-dimensional optimization]

Suppose we are concerned with minimizing overflows at a particular control point i (≥ 2).

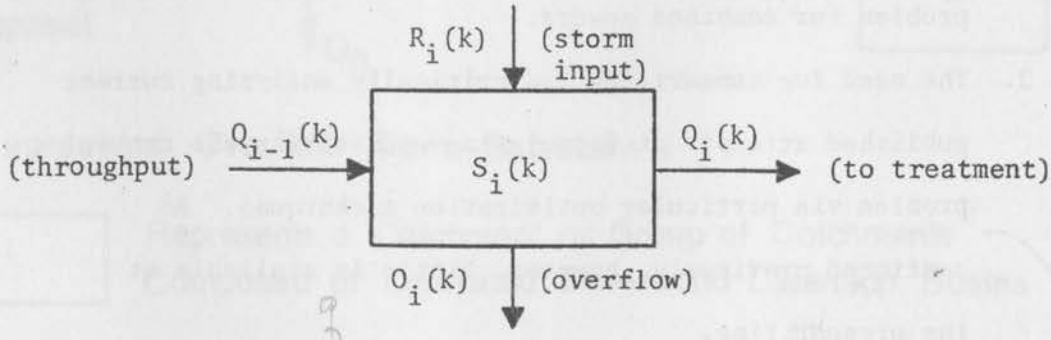


FIGURE VI-2
COMBINED SEWER STORAGE

where the time horizon is broken up into M discrete intervals

$$0 \triangleq t_1 < t_2 < \cdots < t_M < t_{M+1} \triangleq T_f$$

where interval k is defined by $[t_k, t_{k+1}]$, where $\Delta t = t_{k+1} - t_k$ for all $k = 1,\ldots,M$. For this problem

$S_i(k)$ = the storage (i.e., ambient and/or auxiliary) in the sewer at control point i, at the beginning of time period k (i.e., at time t_k)

$R_i(k)$ = the average rate of direct stormflow input to control point i, during time period k

$Q_i(k)$ = the average rate of throughput in the sewer from control point i, during period k

$O_i(k)$ = the average rate of overflow to receiving waters from control point i, during period k

$Q_{i-1}(k)$ = the sewer throughput rate from upstream control point $i - 1$, during period k.

Since our goal is to minimize overflows, an optimization problem can be formulated. In formulating this problem let us assume $Q_{i-1}(k)$ is given for all k, and temporarily drop the subscript i. Therefore, we can lump $Q_{i-1}(k)$ into the term $R(k)$ as given input to control point i [Problem A1]: [the ω_k $(k = 1,\ldots,M)$ are weighting factors]

$$\underset{\substack{S(k),O(k),Q(k),\\ k=1,\ldots,M}}{\text{minimize}} \sum_{k=1}^{M} \omega_k O(k)\Delta t \qquad (1)$$

subject to:

dynamics (or state equation) $\quad S(k+1) = S(k) - [Q(k) + O(k) - R(k)]\Delta t \quad (k = 1,\ldots,M) \qquad$ (1a)

initial condition $\quad S(1) = c$ (given)

state-space constraint $\quad 0 \leq S(k) \leq S_{max},\ k = 2,\ldots,M \qquad$ (1c) final condition $S_{M+1} = S_{final}$ (specified) (1d)

control constraint $0 \leq Q(k) \leq Q_{max}$, $k = 1,\ldots,M$ (1e)

where S_{max} and Q_{max} are upper bounds on storage and throughput, respectively. If $S(k)$ represents ambient storage, then S_{max} can be considered as a variable $S_{max}(k)$, where some kind of adjustable weir is utilized in the sewer. Then we would add the constraint

$$S_{max}(k) \leq \overline{S}_{max} \quad \text{for all } k$$

where $\overline{S}_{max}$ is the upper bound on storage obtained when the weir height is maximized.

Definitions

$S(k)$ $\triangleq$ the state variable, or the state of the system at any time k. It is a dependent variable, since it is a function of $Q(k')$, $O(k')$, $k' = 1,\ldots,k-1$

$Q(k)$, $O(k)$ $\triangleq$ the *control* or *decision variables*, since they are independent variables and directly controllable

k $\triangleq$ the particular *stage* of the dynamic process.

Problem A1 is a straightforward linear programming problem. There are several other ways of formulating this single reservoir problem, but they involve introduction of some degree of nonlinearity. For example, suppose we let $\overline{Q}(k)$ represent total outflow from the reservoir (including overflows). The objective function then becomes

$$\min_{\substack{S(k),\overline{Q}(k),\\ k=1,\ldots,M}} \sum_{k\epsilon K} [S(k) - S_{max}]$$

where

$$K = \{k \mid S(k) - S_{max} \geq 0\}$$

and the state equation is

$$S(k+1) = S(k) - \overline{Q}(k) + R(k), \quad k = 1,\ldots,M$$

Even though we now have only one decision variable $\overline{Q}(k)$, the objective function is discontinuous and no longer linear. This problem, however, is solveable by dynamic programming, which will be discussed further in a subsequent section.

b. Continuous-Time Case [infinite-dimensional optimization]

Suppose we let $\Delta t \to 0$, or equivalently, let $M \to \infty$. That is, Equation (1a) can be written as

$$\frac{S(t_k + \Delta t) - S(t_k)}{\Delta t} = -[Q(t_k) + O(t_k) - R(t_k)]$$

Taking the limit $\Delta t \to 0$ of both sides yields

$$\frac{dS(t)}{dt} = -[Q(t) + O(t) - R(t)]$$

$$\text{(for all } 0 \le t \le T_f\text{)}$$

Therefore, the continuous-time version of Problem A1 is [Problem A2]:

$$\underset{\substack{S(t),O(t),Q(t),\\ \text{for all } t\varepsilon[0,T_f]}}{\text{minimize}} \int_0^{T_f} \omega(t)O(t)dt$$

subject to:

dynamics (or state equation)	$\frac{dS(t)}{dt} = -[Q(t) + O(t) - R(t)], \quad t \;\varepsilon\; [0,T_f]$
initial condition	$S(0) = c$ (given)
state-space constraint	$0 \le S(t) \le S_{max}$, for all $t\varepsilon[0,T_f]$
final condition	$S(T_f) = S_{final}$ (specified)
control constraint	$0 \le Q(t) \le Q_{max}$, for all $t\varepsilon[0,T_f]$

c. Discussion

For the practical problem of optimally controlling combined sewer overflows via storage regulation, it is safe to assume that controls will be carried out in discrete time intervals. This is due to the following factors associated with on-line, automated control:

1. There is a finite amount of time required to actually effect control. That is, time is required for passage of information, the opening and closing of valves and regulators, the inflation and deflation of adjustable weirs, etc.
2. On-line control requires the processing of rainfall and sewer flow data, which is sampled at discrete-time [e.g., for the San Francisco system, data is collected every 15 seconds (23)].
3. Sufficient data must be collected in order to make a reasonable prediction of future storm input so that the next control can be effected. There is an interesting trade-off here:
   (a) Large intervals between control would allow the processing of more data, resulting in more accurate prediction. Though the individual controls are more optimal in the sense that they are based on more accurate data, the system is less controllable due to the large intervals.
   (b) Small intervals between control would result in less accurate storm prediction. Though the system is more controllable than in case (a), there is greater question as to the optimality of the controls.

Suppose it is decided that actual control of the system must occur between a discrete interval Δt_{actual} (which may be variable). Then there are two basic ways of determining the optimal controls $Q^*(k)$ and $O^*(k)$, where $\Delta t_{actual} = t_{k+1} - t_k$:

(i) Finite-Dimensional Optimization: Solve Problem A1, letting $\Delta t = \Delta t_{actual}/m$, where m is some integer ≥ 1, and determine $Q^*(k), O^*(k)$ from these results.

(ii) Infinite-Dimensional Optimization: Solve Problem A2, and determine $Q^*(t), O^*(t)$ for all $0 \leq t \leq T_f$, from which $Q^*(t_k)$ and $O^*(t_k)$ can be easily found for all k.

We are ultimately interested in considering the very general control problem involving many reservoirs in a complex of interraction. There is the need, then, to utilize realistic flow routing methods, which will unfortunately introduce nonlinearities into the state equation. In addressing ourselves to the general, complex control problems, we must decide which of these two solution approaches [(i) or (ii)] is most appropriate for the particular problem at hand. In attempting to answer this question, we will utilize a very general formulation of the control problem.

d. Generalization

The reservoir control problem can be generalized as follows, for $\Delta t = 1$ [Problem B]:

$$\min_{x,u} \sum_{k=1}^{M} f(x(k),u(k)) + \phi(x(M+1))$$

[where $x = (x(1),\ldots,x(M+1))$, $u = (u(1),\ldots,u(M))$ and $\phi(\cdot)$ is an added term associated with the final state.]

subject to:

dynamics $\qquad x(k+1) = x(k) + g(x(k),u(k)) \quad (k = 1,\ldots,M)$

initial condition $\qquad x(1) = c$ (given)

state-space constraint $\qquad q(x(k)) \leq 0, \quad k = 1,\ldots,M$

final condition $p(x(M+1)) = 0$

control constraint $h(x(k),u(k)) \leq 0, \quad k = 1,\ldots,M$

which is equivalent to Problem A1 if we define

$$u(k) \triangleq (Q(k),O(k))$$

$$x(k) \triangleq S(k)$$

$$f(\cdot,u(k)) \triangleq O(k)$$

$$\phi(\cdot) \triangleq 0$$

$$g(\cdot,u(k)) \triangleq Q(k) - O(k) + R(k)$$

$$p(x(M+1)) \triangleq S(M+1) - S_{final}$$

$$q(x(k)) \triangleq \underset{\text{(a)}}{\begin{bmatrix} S(k) - S_{max} \\ -S(k) \end{bmatrix}} \quad \text{or} \quad \underset{\text{(b)}}{S(k)[S(k) - S_{max}]}$$

$$h(\cdot,u(k)) \triangleq \begin{bmatrix} Q(k) - Q_{max} \\ -Q(k) \end{bmatrix} \quad \text{or} \quad Q(k)[Q(k) - Q_{max}]$$

{notice that (a) and (b) are exactly equivalent}

In general, then, $u(k), x(k), g(\cdot,\cdot), q(\cdot), p(\cdot)$, and $h(\cdot,\cdot)$ can themselves be vectors, for all k. For generality, let us specify that $u(k) \varepsilon E^m$, $x(k) \varepsilon E^n$, $g(\cdot,\cdot) \varepsilon E^n$, $q(\cdot) \varepsilon E^{2n}$ [for case (a)], $q(\cdot) \varepsilon E^n$ [for case (b)], $p(\cdot) \varepsilon E^n$, and $h(\cdot,\cdot) \varepsilon E^{\ell}$, for all k. For Problem A1, then, $m = 2$, $n = 1$, and $\ell = 2$.

For the discrete-time problem (Problem B), a nominal time increment of $\Delta t = 1$ was assumed. As we let $\Delta t \to 0$ (or $M \to \infty$), we obtain the continuous-time version of Problem B [<u>Problem C</u>]:

$$\min_{\substack{x(t),u(t) \\ \text{for all } t \varepsilon [0,T_f]}} \int_0^{T_f} f(x(t),u(t))dt + \phi(x(T_f))$$

subject to:

dynamics (or state equation) $\dot{x}(t) = g(x(t),u(t))$, for all $t \epsilon [0,T_f]$

initial condition $x(0) = c$

state-space constraint $q(x(t)) \leq 0$, for all $t \epsilon [0,T_f]$

final condition $p(x(T_f)) = 0$

control constraint $h(x(t),u(t))$, for all $t \epsilon [0,T_f]$

d. Discussion

Let us summarize some of the conclusions presented in (27):

1. There are two basic approaches to solving the optimal control problem of minimizing overflows from combined sewer systems:
   (a) Solve the finite-dimensional problem [Problem B], where the time horizon has been discretized, and determine the optimal controls for each interval.
   (b) Solve the infinite-dimensional problem [Problem C] and discretize the resulting continuous-time optimal control† according to the interval Δt_{actual}
2. The necessary conditions for the continuous-time optimal control problem can be derived as limiting versions (as $\Delta t \rightarrow 0$) of the Kuhn-Tucker necessary conditions for the discrete-time problem.
3. Infinite-dimensional optimization is more heavily dependent upon utilizing necessary conditions for determining optimal controls than is finite-dimensional optimization. Since necessary conditions are generally applicable at local minima, maxima, saddle-points, etc., solution results can be deceiving for nonlinear problems (unless certain convexity conditions hold, thus assuring that the Kuhn-Tucker conditions are both necessary and sufficient).

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†Note: Since integration must be carried out numerically on a digital computer, then this control will actually be discretized, though the time intervals used for integration $\delta t << \Delta t_{actual}$.

4. The necessary conditions for infinite-dimensional problems are difficult to solve simultaneously (for x^*, u^*) because:
   (a) Large numbers of constraints (on control and state variables) tend to create large numbers of necessary conditions (corner conditions) and the control logic becomes increasingly complex.
   (b) Computational inefficiency arises in solution of the two-point boundary-value problem, and the possibility of divergence is ever-present for nonlinear problems, due to instability.
5. Data for the combined sewer problem are taken in discrete-time. But notice, for example, that Problem A2 requires that continuous data $R(t)$ (for all $t \in [0,T_f]$) be given. Thus, a continuous curve must be approximated from the discrete data. Since there are an infinite number of such approximations (based on whatever fitting criteria are used), the uniqueness of the resulting optimal control $u^*(t)$ may be questionable.

These statements seem to suggest that finite-dimensional optimization is superior, at least for our problem. Notice, however, that if M is large (which may be necessary for accurate control), then the number of variables involved in Problem B would quickly tax the rapid-access storage capacity of even the largest digital computers. If this is the case, there may be no other alternative but to apply continuous-time control theory. On the other hand, we could arbitrarily decrease M (i.e., increase Δt) so that Problem B becomes solveable, with a resulting decrease in the accuracy of the control. Though the resulting u^* is optimal with respect to these coarser intervals, it will probably be suboptimal with respect to the more realistic finer intervals.

For the combined sewer problem, it appears that M can be kept to a reasonable size (allowing solution by finite-dimensional methods), due to statements 1, 2, and 3 in subsection c of this section. In addition, control policies can probably be developed storm by storm, so that a problem need not be defined over several storms. As Canon, et. al. (8),[†] have succinctly stated, the "...main reason for attaching so much importance to discrete optimal control is technical and stems from the constantly increasing use of digital computers in the control of dynamical systems. In any computation carried out on a digital computer, we can do no better than obtain a finite set of real numbers. Thus, in solving a continuous optimal control problem... we are forced to resort to some form of discretization." The question, then, is whether to discretize prior to computation (as in finite-dimensional optimization) or during the subsequent to computation (as in infinite-dimensional optimization). For the combined sewer problem, it appears that the former should be stressed.

The following section will concentrate on finite dimensional optimization techniques and their applicability to the combined sewer problem. A more detailed discussion can be found in (27)[*].

C. MATHEMATICAL PROGRAMMING APPROACHES

Methods used to solve finite-dimensional optimization problems are lumped under the term *mathematical programming*. That is, linear, nonlinear and dynamic programming are all mathematical programming techniques. The variety of techniques is large, particularly under the category of nonlinear

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[†][pgs. 1 and 2]

[*]As an additional reference for calculation time intervals and sequences, the reader is referred to reference (21) for the Seattle experience.

programming. Again, mathematical programming methods usually are not based upon solution of necessary conditions, as in continuous-time control theory. Necessary conditions may be used, however, for checking the optimality of solutions determined by other means.

Evaluation of mathematical techniques are based on answers to the following questions:

1. How realistic a model concerning the flow dynamics of the system can be utilized?
2. Can the method tolerate a large number of variables? That is, is it conducive to decomposition, since the large-scale problem must eventually be dealt with?
3. Will the method guarantee convergence to global or just local solutions?

The particular technique to be applied depends upon [referring to the general control problem (Problem B)]:

(i) the nature of $f(\cdot,\cdot)$ and $\phi(\cdot)$ (i.e., their linearity, nonlinearity, nonconvexity, continuity, etc.)

(ii) the nature of $g(\cdot,\cdot)$, $q(\cdot)$, $p(\cdot)$, and $h(\cdot,\cdot)$

(iii) the number of state variables (n) and decision or control variables (m) at each stage

1. An Example Three Reservoir Problem

As explained previously, we are primarily interested in subbasin analysis here. Future work will concentrate on fitting the subsystems into a large-scale framework. Let us then consider an example subbasin configuration composed of three auxiliary reservoirs in series, with overflow possible from each reservoir,

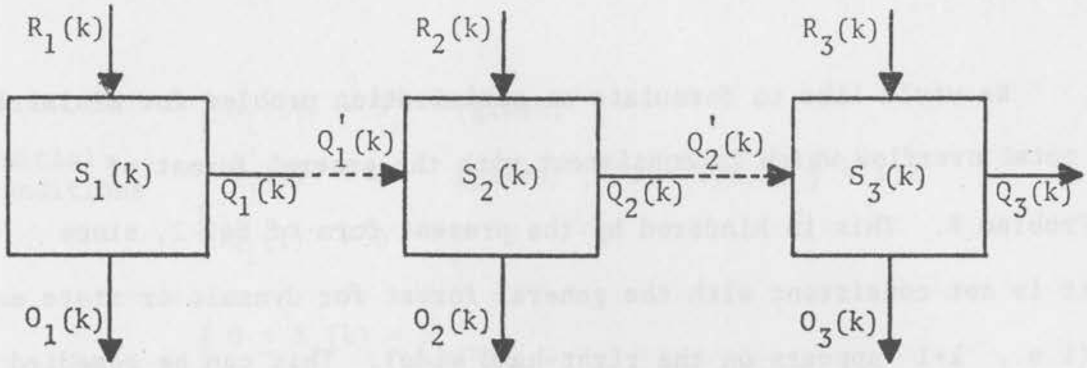

FIGURE VI-3

EXAMPLE THREE RESERVOIR PROBLEM

where

$R_i(k)$ = average rate during period k of lumped direct stormflow input which is translated from the near vicinity of reservoir i [Note: assume that all direct input can be lumped, as shown in Figure VI-3, with negligible direct input occuring between reservoirs]

$Q_i(k)$ = average rate of throughput during period k, from reservoir i, with $Q_3(k)$ going to treatment [$i = 1,2$]

$Q_i'(k)$ = the routed or translated throughput from reservoir i, entering reservoir $i+1$ [$i = 1,2$]

$S_i(k)$ = storage in reservoir i, at the beginning of period k.

$O_i(k)$ = average rate of overflow to receiving waters from reservoir i, during period k.

A common method of flow routing is the Muskingum method (15), where

$$Q_i'(k+1) = Q_i'(k) + T_i(Q_i'(k), Q_i(k), Q_i(k+1)) \qquad (2)$$
$$(k = 1,\ldots,M-1)$$

The transformation T_i may be linear or nonlinear, depending upon whether or not the coefficients associated with the Muskingum method are considered to be functions of flow rate. Backwater effects are not properly considered here, as in more realistic methods (15), but Eq. 2 will suffice for now.

We would like to formulate an optimization problem for minimizing total overflow which is consistent with the general format of Problem B. This is hindered by the present form of Eq. 2, since it is not consistent with the general format for dynamic or state equations (i.e., k+1 appears on the right-hand side). This can be remedied by defining a new state variable $V_i(k)$, and replacing Eq. 2 with [assuming $\Delta t = 1$]:

$$Q_i'(k+1) = Q_i'(k) + T_i(Q_i'(k), Q_i(k), V_i(k)) \tag{3}$$

$$Q_i(k+1) = Q_i(k) + [V_i(k) - Q_i(k)] \tag{4}$$

$$(k = 1,\ldots,M-1)$$

We see that Eq. 2 <=> Eqs. 3,4; $Q_i(k)$ is now regarded as a state variable, and $V_i(k)$ as a control variable, since $Q_i(k+1)$ is dependent upon $V_i(k)$.

We can now formulate the optimization problem [<u>Problem D</u>]:

$$\min_{\substack{S,Q,Q', \\ V,O_3}} \sum_{k=1}^{M} \omega_k \cdot O(k) \tag{5}$$

[where $S,Q \in E^{3(M+1)}, V \in E^{3M}, O \in E^{3M}$ and $Q' \in E^{2M}$]

<u>subject to</u>:

dynamic equations

$$\begin{cases} S_1(k+1) = S_1(k) + R_1'(k) - Q_1(k) - O_1(k) & (6) \\ S_2(k+1) = S_2(k) + R_2(k) + Q_1'(k) - Q_2(k) - O_2(k) & (7) \\ S_3(k+1) = S_3(k) + R_3(k) + Q_2'(k) - Q_3(k) - O_3(k) & (8) \\ Q_i'(k+1) = Q_i'(k) + T_i(Q_i'(k), Q_i(k), V_i(k)) & (9) \\ Q_i(k+1) = Q_i(k) + [V_i(k) - Q_i(k)] & (10) \\ (i = 1,2 \quad k = 1,\ldots,M) & \end{cases}$$

$$\text{initial conditions} \begin{cases} S_i(1) = S_i^o \quad \text{(given)} \\ Q_j'(1) = 0 \quad \text{(given)} \qquad i = 1,2,3;\ j = 1,2 \\ Q_i(1) = 0 \end{cases}$$

$$\text{state-space constraints} \begin{cases} 0 \le S_i(k) \le S_{i,max} & (11) \\ 0 \le Q_j'(k) \le Q_{j,max}' \qquad i = 1,2,3;\ j = 1,2 & (12) \\ 0 \le Q_i(k) \le Q_{i,max} \qquad k = 2,\dots,M & (13) \end{cases}$$

$$\text{final conditions} \begin{cases} S_i(M+1) = 0 & (14) \\ Q_j'(M+1) = 0 \qquad i = 1,2,3;\ j = 1,2 & (15) \\ Q_i(M+1) = 0 & (16) \end{cases}$$

$$\text{control constraints} \begin{cases} 0 \le V_i(k) \le Q_{i,max} \qquad i = 1,2,3 & (17) \\ O(k) \ge 0 \qquad k = 1,\dots,M & (18) \end{cases}$$

Physically speaking, Q_i and Q_i' are only defined for $k = 1,\dots,M$. In order to be consistent with the general format, we are defining $Q_i(M+1) = Q_i'(M+1) \triangleq 0$, and expressing them as final conditions. Notice that Eq. 13 is arbitrary, and we could simply specify

$$S_i(M+1) \ge 0 \qquad (19)$$

as a more realistic final condition. This is, however, not consistent with the general format of Problem B. The transversality conditions for this situation are the same, however, with the exception that the multiplier ρ is now nonnegative.

$$u(k) \triangleq (V(k), O(k)) \qquad \Rightarrow m = 6$$

$$x(k) \triangleq (S(k), Q(k), Q'(k)) \qquad \Rightarrow n = 9$$

$$f(\cdot, u(k)) \triangleq \omega_k \cdot O(k)$$

$$\phi(x(M+1)) \triangleq 0$$

For this problem, then, there are a total of 15M variables (state and control) and 22M constraints, not including nonnegativity restrictions. Suppose, for example, that a storm lasts for about an hour, and control is exercised every 5 minutes. Then M = 12, the number of variables is 180, and there are 264 constraints. Therefore, optimization techniques applied to Problem D must involve some kind of decomposition strategy, where the original problem is replaced by several smaller problems. Note that:

1. Most nonlinear programming codes require that T_i be at least continuous, in order for a solution to be obtained. Usually, stronger assumptions of differentiability are required for the algorithms to operate properly. These assumptions do not seem restrictive for utilization of realistic flow routing procedures.
2. The nonlinearity of T_i, and hence the nonconvexity of Problem D, limits the possible decomposition methods that could be applied. The two most important methods would probably be (i) Geoffrion's resource directive approach and (ii) application of generalized duality theory [see Appendix].
3. In general, all standard nonlinear programming codes, that are not based on grid search methods operating over the entire constraint region of a problem, can at most guarantee convergence to local solutions.

2. Solution Techniques

In addressing ourselves to the most general combined sewer problem for a particular subbasin, where

(i) there are several interconnected storage basins

(ii) realistic routing procedures are utilized, thus introducing nonlinearities into the state equations, and therefore resulting in nonconvexity of the control problem,

it has been concluded in (27) that direct application of

1. linear programming is not possible, unless some kind of linearization procedure is carried out. In general, though, global solution of the original nonlinear problem is difficult to attain by these methods
2. standard dynamic programming, though being a global solution technique, is not feasible, due to dimensionality difficulties caused by interconnection of several reservoirs. Incremental dynamic programming is applicable, but can only guarantee local solutions.
3. nonlinear programming methods can only assure convergence to local solutions.

In order to deal particularly with the problem of finding global solutions, an *approximate-flow technique* is presented in (27) which, in conjunction with generalized duality theory and the projection theorem, results in one-dimensional dynamic programming problems imbedded in constrained nonlinear programming problems of limited dimension, which in turn are imbedded in a dual problem for which global solution is assured as long as global solutions can be obtained for the interior subproblems. The dual problem solves (globally) the original control problem if and only if a saddle-point exists. If a saddle-point does not exist (which is not determinable *a priori* for nonconvex problems), an infeasible solution to the control problem results. If the infeasibility is of tolerable magnitude, then this solution will be adequate. Otherwise, the infeasible solution may be used to generate accurate initial approximations for direct application of constrained nonlinear programming algorithms.

Considerable computational experience is necessary in order to verify the applicability of the approximate-flow technique. It appears, though, that this method opens the way for finding global solutions to the nonconvex control problems resulting from realistic flow routing procedures. The goal is to obtain considerable off-line optimization results based on a large variety of historical and synthetically generated storm situations, so that optimal rule curves and operating policies can be programmed into the on-line computer system. These policies can perhaps be utilized in conjunction with on-line optimization by linear programming. Though simplified linear flow models are required for the latter, on-line optimization has the advantage of being able to respond to the uniqueness of the particular storm event occurring in real time, which is not possible if all optimization is carried out off-line.

D. SUMMARY AND CONCLUSIONS

The optimal control problem associated with automated operation of ambient and/or auxiliary storage capabilities within combined sewer systems can be formulated as either a finite-dimensional (discrete-time) or infinite-dimensional (continuous-time) optimization problem. Both involve discretization at some stage, since digital computers can only deal with finite quantities of real numbers. For the former, discretization is carried out prior to problem solution, whereas for the latter it is effected during and subsequent to computation, since actual control of the system is carried out in discrete-time.

It was concluded that finite-dimensional optimization (FDO) is preferable to infinite-dimensional optimization (IDO) for the combined sewer problem, due to the following factors:

1. Actual operation of the system is carried out in discrete real-time. The size of FDO problems can be unwieldy if the time intervals are too small, so that IDO may be the only alternative. It appears, however, that intervals will be of moderate size, due mainly to the need for collecting and analyzing adequate quantities of sensor data in these intervals, for reasonable storm and flow prediction.
2. IDO is based on solving necessary conditions for optimality, which apply at solutions other than the desired global solution. FDO relies less on necessary conditions.
3. In general, for nonlinear problems, it is easier to obtain at least local solutions by FDO than IDO. It was shown that the necessary conditions for IDO can be derived as limiting cases of the necessary conditions for FDO. But there are difficulties in solving the former that do not arise in the latter.
4. In applying IDO, a continuous curve must be fitted to discrete rainfall data. Since there are an infinite number of such curves, the question of uniqueness of solutions arises.

These conclusions seem to be supported by computational experience. Applications of IDO to ambient storage models failed to give solutions in most cases (27), even though the flow model and system configuration was extremely idealized. This can be contrasted with the ease of obtaining results by linear programming for a comparably simple flow model and auxiliary storage configuration, as reported in Section V. There is some question, however, about the validity of comparing these results, since the ambient storage model required solution of more complicated equations, even though the flow routing assumptions were of comparable simplicity. As discussed in Chapter III, however, it seems possible to treat the ambient case from an auxiliary storage viewpoint, though no computational results are available as yet.

Turning to FDO, it was shown that linear flow routing models (e.g., the Muskingum method with constant coefficients) resulted in a large-scale linear programming problem, for which there are a number of efficient decomposition strategies available. If the error introduced by linear routing is tolerable, linear programming may be feasible for effective on-line optimization, since global solutions to linear problems are assured (under mild assumptions) in a finite number of iterations, by the simplex method.

Introduction of any degree of nonlinearity in the flow routing method (e.g., the Muskingum method with variable coefficients) results in a nonconvex FDO problem. Dynamic programming can deal with the nonconvexity problem, but the so-called curse-of-dimensionality precludes its applicability. Incremental dynamic programming is a possibility, but can only give local solutions, in general. Nonlinear programming algorithms also suffer from the fact that convergence is generally to local solutions. Even if a global solution happens to be determined, there is no known way of verifying its globality, other than by inefficient direct enumeration. These obstacles led to the development of an approximate-flow technique, which appears to have potential in dealing with the problem of finding global solutions, and is discussed in detail in (27).

REFERENCES

1. American Public Works Association, "Combined Sewer Regulator Overflow Facilities Report," a report for the U. S. FWQA, July 1970.

2. American Public Works Association, "Feasibility of Computer Control of Wastewater Treatment," a report for the U. S. EPA, December 1970, pp. 43-44.

3. American Public Works Association, "Public Works Computer Applications," Special Report #38, August 1970.

4. American Public Works Association, "Public Works Information Systems," Special Report #36, October 1970.

5. American Society of Civil Engineers, "Basic Information Needs in Urban Hydrology," a study for the U. S. Geological Survey, April 1969.

6. Blank, D., and J. W. Delleur, "A Program for Estimating Runoff from Indiana Watersheds, Part I Linear Systems Analysis in Surface Water Hydrology and Its Applications to Indiana Watersheds," Technical Report No. 4, Purdue University, Water Resources Research Center, Lafayette, Ind., August 1968.

7. "Can All Americans be Made Equal?" U. S. News and World Report, April 9, 1973.

8. Canon, M. D., C. D. Callum, and E. Polak, THEORY OF OPTIMAL CONTROL AND MATHEMATICAL PROGRAMMING, McGraw-Hill, 1970.

9. Carley, Robert L., Wastewater Reuse and Public Opinion, Unpublished M. S. Thesis, University of Colorado, 1972.

10. Clark, C. O., "Storage and the Unit Hydrograph," Transactions, American Society of Civil Engineers, Vol. 110, 1945.

11. Condon, F. J., "Treatment of Urban Runoff," APWA Reporter, March 1973.

12. "Control Engineers are Stick-in-the-Muds," editorial in the March 1973 edition of Control Engineering.

13. Crawford, Norman H., "Computer Simulation for Design Criteria for Urban Flow Storage Systems," Hydrocomp International, 1973.

14. Crawford, Norman H., "Studies in the Application of Digital Simulation to Urban Hydrology," Hydrocomp International, 1971.

15. Cunge, J. A., "Mathematical Modeling of Open Channel Flow," unpublished lecture notes, Department of Civil Engineering, Colorado State University, 1973.

16. Cunge, J. A., "On the Subject of a Flood Propagation Computation Method (Muskingum Method)," Journal of Hydraulic Research 7, No. 2, 1969.

17. Cunge, J. A., "Use of Transport Models for Wastewater Management Strategy Planning," unpublished manuscript, 1973.

18. Denver Regional Council of Governments, "Final Report - Project REUSE," 1972.

19. Field, Richard, "Management and Control of Combined Sewer Overflows: Program Overview," A Paper Presented at the 44th Annual Meeting of the New York Water Pollution Control Association, January 26-28, 1972.

20. Franklin Institute Research Laboratory, "Selected Storm Water Abstracts," A continuing series of reports issued by the U. S. EPA.

21. Gibbs, Charles V., Alexander, S. M. and Leiser, Curtis P., "System for Regulation of Combined Sewage Flows," Journal of the Sanitary Engineering Division, ASCE, December 1972.

22. Gibson, Harry L., "The Study of Critical Factors to Predict the Outcome of the Information Systems Effort," a paper presented to the American Institute for Decision Science, Atlanta, Georgia, March 1973.

23. Grigg, Neil S., et. al., "Planning and Wastewater Management of a Combined Sewer System in San Francisco," MWIS Project, Technical Report No. 10, CSU, May 1973.

24. Hall, F. R., "Base Flow Recessions-Review," Water Resources Research, Vol. 4, No. 3, pp. 973-983, October 1968.

25. Harris, Garth S., "Real-Time Estimation of Runoff in the Minneapolis-St. Paul Metropolitan Area," University of Minnesota, Memorandum No. M-118, December 1968.

26. Knapp, G. L. and Glasby, J. P., "Urban Hydrology - A Selected Bibliography with Abstracts," U.S.G.S. Water Resources Investigations, March 1972.

27. Labadie, J. W., "Optimization Techniques for Minimization of Combined Sewer Overflow," Technical Report No. 11, MWIS Project (in press).

28. Linsley, Ray K., "A Critical Review of Currently Available Hydrologic Models for Analysis of Urban Stormwater Runoff," Hydrocomp International, 1971.

29. Linsley, R. K. Jr., M. A. Kohler, and J. L. H. Paulhus, "Applied Hydrology," McGraw-Hill Book Company, Inc., New York, N.Y., 1949.

30. Lippmann, Walter, Public Opinion.

31. Lyon Steven A., Letter of Review of MWIS Project 1972.

32. McPherson, Murray B., "Feasibility of the Metropolitan Water Intelligence System Concept," Technical Memorandum #15, ASCE Urban Water Resources Research Program, December 1971.

33. Metcalf and Eddy, Inc., et. al., Stormwater Management Model, 4 Volumes, Report to the U. S. EPA, 1971.

34. Minneapolis-St. Paul Sanitary District, "Dispatching System for Control of Combined Sewer Losses," Report to the EPA, March 1971.

35. Municipality of Metropolitan Seattle, "Maximizing Storage in Combined Sewer Systems," Report for the U. S. EPA, December 1971.

36. Murdick, Robert G. and Ross, Joel E., Information Systems for Modern Management, Prentice-Hall, Inc., 1971.

37. Osgood, Charles, et. al., The Measurement of Meaning, University of Illinois Press, Urbana, 1956.

38. Pateman, Carole, Participation and Democratic Theory, Cambridge: The University Press, 1970.

39. Pew, K. A., Callery, R. L., Brandstetter, A. and Anderson, J. J., "The Design and Operation of a Real-Time Data Acquisiton System and Combined Sewer Controls in the City of Cleveland, Ohio," Paper presented at the 45th Annual WPCF Meeting, Atlanta, October 1972.

40. Rademacher, Robert A., "Construction of a Model for Predicting the Outcome of the Information Systems Effort," Paper presented to the American Institute for Decision Science, MSU, East Lansing, Michigan, April 1973.

41. Rao, A. R., et. al., "Conceptual Hydrologic Models for Urbanizing Basins," Journal of the Hydraulics Division, ASCE, July 1972.

42. San Francisco Department of Public Works, "San Francisco Master Plan for Wastewater Management," 1971.

43. San Francisco Department of Public Works, "San Francisco Master Plan for Wastewater Management - 3 Volumes plus Appendices," 1971.

44. Sarma, P.B.S., et. al., "An Evaluation of Rainfall-Runoff Models for Small Urbanized Watersheds and the Effect of Urbanization on Runoff," Purdue University, October 1969.

45. Sarma, P.B.S., et. al., "A Program in Urban Hydrology, Part II," Purdue University, October 1969.

46. Smith, George L., et. al., "Metropolitan Water Intelligence Systems Project, Completion Report, Phase I," Colorado State University, June 1972.

47. Technical Report No. 1 from MWIS Project - "Existing Automation, Control and Intelligence Systems of Metropolitan Water Facilities" by H. G. Poertner.

48. Technical Report No. 2 from MWIS Project - "Computer and Control Equipment" by Ken Medearis.

49. Technical Report No. 3 from MWIS Project - "Control of Combined Sewer Overflows in Minneapolis-St. Paul" by L. S. Tucker.

50. Technical Report No. 4 from MWIS Project - "Task 3 - Investigation of the Evaluation of Automation and Control Schemes for Combined Sewer Systems" by J. J. Anderson, R. L. Callery, and D. J. Anderson.

51. Technical Report No. 5 from MWIS Project - "Social and Political Feasibility of Automated Urban Sewer Systems" by D. W. Hill and L. S. Tucker.

52. Technical Report No. 6 from MWIS Project - "Urban Size and Its Relation to Need for Automation and Control" by Bruce Bradford and D. C. Taylor.

53. Technical Report No. 7 from MWIS Project - "Model of Real-Time Automation and Control Systems for Combined Sewers" by Warren Bell, C. B. Winn, and G. L. Smith.

54. Technical Report No. 8 from MWIS Project - "Guidelines for the Consideration of Automation and Control Systems" by L. S. Tucker, and D. W. Hill.

55. Technical Report No. 9 from MWIS Project - "Research and Development Needs in Automation and Control of Urban Water Systems" by H. G. Poertner.

56. Toffler, Alvin, Future Shock, Random House, 1970.

57. U. S. Department of Housing and Urban Development, "RFP H-2-70, Municipal Information Systems," Washington, D. C., 1969.

58. U. S. HUD Department, Urban Systems Advisory Committee (USAC), Miscellaneous Notes, August 25, 1972.

59. Forrester, Jay W., Urban Dynamics, MIT Press, 1969.

60. Likert, Rensis, The Human Organization, Its Management and Its Value, McGraw-Hill Book Company, New York, 1967.

61. Skinner, B. F., Up from Freedom, (New York: Knopf, 1971).

APPENDIX

EVALUATION PROBLEM OF STORM WATER ROUTING MODELS

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There is no need to demonstrate the importance of storm water management mathematical models for sewer systems. There exists by now a voluminous literature concerning such models and few of them are available on the market.

When an agency, municipal service or a consultant wishes to use this important and often costly tool the problem of its evaluation is involved. Indeed, even when the authors of a model claim that it is "comprehensive, general, flexible" etc., it is often either an over optimistic view of the real situation or, when true, such a model might be too expensive to apply. Consequently for each particular case an assessment of different models should be made and a decision, based on this evaluation, taken so as to eliminate certain models or methods and to retain others.

Typically a storm water management model deals with equations such as surface runoff computation, flood routing through the sewer network, quality of water simulation, treatment of sewage simulation and cost-effectiveness of the system computations.

This paper is concerned with the flood routing problem only because, as explained below, this part of the model is usually the most important and often decisive for its evaluation. It is felt that the success of application of a general management model depends closely upon the value of the flood propagation (routing) model.

Routing Model Requirements

The following points show why it is so and what should be in consequence the basic characteristics of a good routing model.

1. Hydrology and runoff from the modeled area
   Good simulation of the wave propagation within the sewer system is often more important than is a method of rainfall to runoff transformation. Indeed, the time of propagation may be of an order of magnitude of an hour while the variations of runoff from the elementary basin are of an order of minutes. Thus, a good prediction of the

coincidence of peaks coming from different sewers might be more important than an improvement of rainfall/runoff formulae.

The importance of the hydrological part of a model depends upon the propagation part. If the latter is well developed and consists of a considerable number of computational points, the dimensions of elementary drainage basins are small. Thus, simpler hydrological methods can be applied.

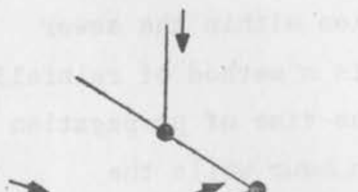
Sewer systems have an important storage capacity when there is a free-surface unsteady flow. This capacity should be taken into account by a model if the final runoff is to be predicted correctly. This is only possible if the routing method allows for the backwater effect in the unsteady flow.

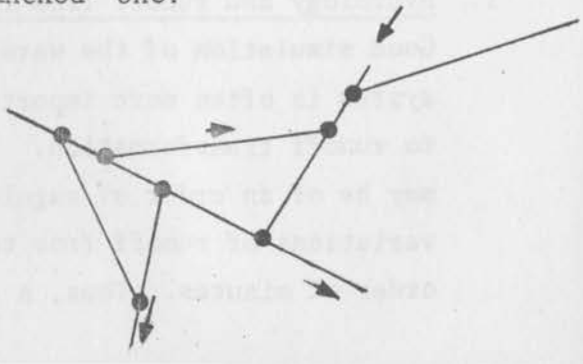
Sometimes a part of a system may be filled up. The sewers are then under pressure and the propagation model should be able to reproduce this situation, i.e., not only to indicate when and where a given sewer becomes pressurized, but also to compute the resulting flow in it.

Finally, from the user's point of view, a model should be able to simulate the sewer network even if its characteristics vary. Which means that the propagation model should reproduce the flow in different parts of a network where the slopes and the cross-sections are different. Within the same network one often finds slopes varying from nearly zero to 1% or more. Often the shape of the sewer varies from circular to oval to trapezoidal to an open channel of natural arbitrary form. The user should not be hampered because of that.

2. <u>Management of a sewer system</u>

A propagation model should be able to simulate a "looped" network of sewers or a "branched" one:





This enables one to simulate the "relief operations" consisting of a transfer of water from one city district to another.

The model should be able to incorporate easily any structure which is normally used to control the flow. Structures such as gates, weirs, pumping stations, have to be simulated, i.e., their backwater influence in unsteady flow must be simulated as well as possible maneuvers. Thus, the model should be able to simulate controlled overflows to storage areas, diversion of flow, interception of discharge, etc. These controls may work on the basis of an automatic feedback defined by certain characteristics (water levels at certain points) or on the basis of time-dependent decisions. The model must be able to simulate them.

The model may be used to simulate short-term phenomena (such as storms) or, on the contrary, long-term situations (such as dry-weather flow). Thus, from the computational point of view it should not be limited to small time steps which might lead to very long computation times when the dry-weather period is simulated.

3. The pollution problem

A good simulation of water propagation in the system is most important for the simulation of water quality. There are two main reasons for that:

(i) It is extremely difficult to simulate well the water quality because the data are sparse and the theories are often not verified enough. Thus, there is always a danger that the errors entailed by using very approximative methods to simulate the water propagation might hamper the good understanding and simulation of the pollution transport. The most accurate available method of flood routing should be used to eliminate all doubts as to how the water propagation is reproduced. Thus, the only possible sources of inaccuracy are in the pollution simulation.

(ii) When simulating the pollutant propagation through the sewers the convection is most important. Indeed, as the time spent by the pollutants in the network is short and as there is no (or hardly any) oxygen, the decay terms in the equations are small. Hence, the convective speed, i.e., the water mean velocity, should be computed as well as possible because the transport of pollutants depends on it. It is important that the velocity variations due to the backwater effect be well simulated.

Basic Hypotheses and Methods

Thus, with the above requirements, one has to consider the problem of hypotheses and methods. Namely, what equations should be taken as the basis of a model and what are the techniques which should be used to solve them.

To answer this question one should know what the purpose of the model is, e.g., when it is to be used to monitor the actual flood propagation through the complicated network in real time, or when one is looking for a maximum internal storage obtained when the dynamic backwater effect is important, the full flow equations (continuity and momentum equations with all inertia terms) should be used. This is one at least for the part of a network which has small longitudinal slopes or is submitted to the tidal influence. When modelling steep basins with backwater effect negligible the storage routing methods may be used (such as MUSKINGUM method). They require less computer time and are more convenient as they permit to route the flood from one section (upstream) to another (downstream) instead of taking into account the backwater effects.

When looking for a general management strategy planning for a given network of sewers the simplest method should be used (storage routing method) because the optimization problems are complicated and when combined with the numerical solution of the full flow equations, might be impossible to solve. This means, however, that once the strategy is chosen, its application must be verified with a model using the full equations.

It may be concluded that there is no general recipe to solve this problem, but that the equations and the numerical method to solve them must be chosen as a function of the problem and the network to be simulated.

One often forgets that the high speed computers now available and the continuous progress in Numerical Analysis permit to employ methods which were considered too costly a few years ago, e.g., it was stated (1) that the numerical solutions of full flow equations were usually obtained by using the method of characteristics and that this technique had been found to be too consumptive of computer time for general applications. Now this statement was based on Reference (2) published in 1968. Nowadays models are available which are based on the numerical integration of full flow equations by finite difference implicit schemes. These models have been used for years to route the floods in rivers (3,4,5,6,7) but only recently were applied to sewer networks. They take into account all inertia terms and, being based on implicit schemes of finite differences, they permit to use any time step Δt without endangering the numerical stability of the solution. The computer time needed for a "branched" model of this type, when using an IBM 360-65 computer is of the order of 0.0025 seconds/computational point/time step, (8). Thus, for a network of 1000 points and for a flood represented by 100 time steps (of, say, one minute) the required computer time is of 0.0025 x 1000 x 100 = 250 seconds which surely is not prohibitive, even for a real time monitoring of the sewer flow during a storm.

Model Validation (Calibrating)

Another problem is the validation of a model. Under normal conditions, when the sewer network is at least partially in operation, a routing model should be validated by calibration. Past observed floods should be computed, the results compared with observations and empirical coefficients in equations such as resistance and singular head losses coefficients adjusted till the computed and the deserved results are the same within admitted accuracy limits.

Actually there always will be some differences between the computed and the observed results. There are several reasons why the computer and observed hydrographs might be different.

1. Basic equations are correct, but numerical method of their integration is inaccurate, e.g., model reaches between the computational points are too long.

   This kind of error may be detected *a priori* either by mathematical analysis or by comparative computations, varying the space step (or interval length between points) ΔX, and repeating computations.

However, for complicated network of sewers comparative runs with different values of ΔX are probably too costly. Consequently, when the new method is developed, the influence of the parameter ΔX should be systematically tested using simplified models. This should be done while other parameters of the model such as rapidity of the discharge fluctuations, average slope of the sewer, etc., are varied. One should be certain, at the end of this testing stage, that the errors due to the schematization are smaller than admissible inaccuracies.

2. Basic equations are simplified abusively, e.g., storage routing method (such as MUSKINGUM) is used for reaches having very small longitudinal slope. Or "diffusion analogy" method, which neglects inertia terms in the flow equations, is used to route rather rapidly varying floods (for instance within that part of a system influenced by the tide).

   The consequences of such an error are usually very costly since there is a tendency to "improve" the method where it is not satisfactory instead to abandon it and use another one. Thus, one can see very complicated procedures superimposed on very simple equations in order to cope with some factors for which provisions had not been made in the original hypotheses.

   A typical example is an attempt to represent the dynamic backwater storage effect with the aid of a storage routing method. As this is inherently impossible, the original simple method is usually replaced by a hybrid one, applicable only for the given case and usually unstable or impracticable for any other.

3. The differences between computed and observed results are caused by inadequate measuring techniques. Sometimes one comes across errors of measurements, such as a bad definition of the zero level of stage recorder. Sometimes the point where the measure is taken may not be representative for the considered cross-section (e.g., a stage recorder installed on a bend, within the backwater effect of a local constriction). On the other hand measures of discharge are usually difficult and inevitably more or less erroneous. Thus, the costly model calibration should not always be carried very far. This sometimes happens, nevertheless, when the contract requires

an absolute accuracy in calibration (defined, for example, as 0.10 meter). Such a requirement may often be met only by choosing flow resistance coefficients which are obviously improbable from a physical point of view. If the basic equations and the method of their solution are correct, such a situation indicates an error of measurement and the requirement should be changed.

4. The differences between computed and observed values may be caused by the lack of data such as lateral inflow or infiltration. Sometimes the lack of such data is masked by choosing physically absurd coefficients in equations. Thus, the model is "calibrated" to reproduce an observed flood within an accuracy required by the contract, but it will surely produce bad results when used to predict future situations.

5. Certain phenomena may not be taken into account by the flow equations or may imply a modification of their coefficients with time, e.g., resistance variations of sewers with time, or bottom level variations due to the sediment transport. These variations may result from a flow evaluation or, on the contrary, may be very rapid and influence the flow during a flood.

All these reasons should be taken into account when evaluating a model or comparing calibration results of two different models. Better calibration fit does not necessarily mean that the model is better.

Evaluation Criteria

It may be thought that the easiest way to evaluate different models is to compare their results for a test case. Actually this is the only way, but not at all an easy one. It was shown above that each model corresponds to certain hypothesis. It is likely that if the criteria of comparison correspond to one particular hypothesis, a particular model based on the same hypothesis might be better off when evaluated according to these criteria.

Thus, criteria such as complexity (or simplicity) of model operating, computational speed, simplicity of output, are very important, but they are not most important.

The first criterion is the certainty that a given model can reproduce the flow for different operating cases such as: small or negligible longitudinal slope, important longitudinal slope, free surface <u>and</u> pressure flow in the same reach of sewers, automatic gates maneuvers, influence of the receiving area (tide) etc.

Besides, the model must be consistent: basic equations and continuity conditions must be satisfied. Thus, to assess the value of a model, intermediate results of computations might be necessary and should be available. This requires some special provisions in the program.

As was stressed before the difficulty of measurements and the often arbitrary definition of singular head losses might hamper the reproduction of observed phenomena within the required accuracy limit, yet this does not necessarily disqualify a model.

Finally there is a factor of competition among different agencies and private firms developing such models. Indeed, when comparing different models it is often necessary, in order to explain or interpret the results, to know the details of employed methods and even programs. It is clear that a private consultant firm would hesitate before making such details available to its competitors. This also means that an agency using a model should be able to operate it in full knowledge of all its details. It is extremely important to understand the dangers of buying a "program package" without knowing what is inside the bag. The ideal for an agency would be to have its own data processing staff not only trained in model operation, but also understanding its premises and knowing the program. Or at least to ensure constant technical assistance of the people who developed it. The availability of these informations and/or of this assistance is one of most important criteria of model evaluation.

REFERENCES FOR APPENDIX

1. Metcalf & Eddy, Inc., University of Florida, Gainesville, Florida, and Water Resources Engineers, Inc., "Storm Water Management Model", Vol. I, Final Report to the EPA, July 1971.

2. Harris, G., "Development of a Computer Program to Route Runoff in the Minneapolis-St. Paul Interceptor Sewers", University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Memorandum No. M-121, December 1968.

3. Preissmann, A., "Propagation of Translatory Waves in Channels and Rivers", (in French), 1st Congress of the French Association for Computing, AFCALTI, Grenoble, 1960.

4. Cunge, J. and Wegner, M., "Numerical Integration of Barre de Saint Venant's Flow Equation by Means of an Implicit Scheme of Finite Differences", (in French, English summary), La Houille Blanche, No. 1, 1964.

5. Abbott, M. B. and Ionescu, F., "On the Numerical Computation of Nearly Horizontal Flows", Journal of the Hydraulics Res., 5, 1967, No. 2.

6. Zanobetti, D., Lorgere H., Preissmann A. and Cunge J. A., "Mekong Delta Mathematical Model Program Construction", Journal of the Waterways and Harbors Division, Proc. of the ASCE, Vol. 96, No. WW2, May 1970.

7. Vasiliev, O. F., "Numerical Solution of the Nonlinear Problems of Unsteady Flow in Open Channels", Proc. of the 2nd International Conference on Numerical Methods in Fluid Dynamics, Berkeley, 1970.

8. SOGREAH, Grenoble, France - Results of Tests Run with the Model Developed by SOGREAH, written unpublished communication.