DISSERTATION

PLANNING WATER QUALITY SURVEILLANCE

Submitted by
Dale H. Vanderholm

In partial fulfillment of the requirements
for the Degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
February, 1972

COLORADO STATE UNIVERSITY

February, 1972

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DALE H. VANDERHOLM ENTITLED PLANNING WATER QUALITY SURVEILLANCE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Robert A. Longenbaugh
E. Gordon Kruse
Ralph W. Hansen
Burns R. Sabey

Adviser

Judson M. Harper
Head of Department

ABSTRACT OF DISSERTATION

PLANNING WATER QUALITY SURVEILLANCE

Two models were developed to evaluate the effectiveness of grab sampling methods in water quality data acquisition. One model was used to predict the detection of significant short term pollution events or quality variations. Several combinations of sampling frequency and location were tested with events of varying magnitude and duration. The second model was primarily used to predict the effectiveness of grab sampling to obtain what can be termed base level type data. For this type of data, the primary concern is the accuracy of observed means, trends, etc., with regard to the true values.

The basic variable evaluated was system effectiveness as a function of sampling frequency. In the first case, system effectiveness was represented by the ability of the sampling combination to detect pollution events generated along a hypothetical stream depicted in a mathematical model. For the second case, effectiveness was measured by the accuracy of observed mean parameter values using various sampling configurations. Each data type was handled separately throughout the study.

As an example for use of the study results, a surveillance system for the South Platte River Basin in Colorado was planned. Networks of primary and secondary sampling stations were proposed for obtaining regulation type and base level type data, respectively. Cost-effectiveness curves for both types of stations were developed for use in planning surveillance levels.

The nature of the problem prevented verification of the models by field studies or similar methods. The sensitivity of the detection model solutions to certain variable changes was tested, with the results indicating negligible effects. However, the results presented are not intended to be taken as absolute values for any stream situation. The extreme variability of natural streams and of pollution sources prevents general solutions from accurately predicting values under individual circumstances.

Dale H. Vanderholm
Department of Agricultural Engineering
Colorado State University
Fort Collins, Colorado 80521
February, 1972

ACKNOWLEDGMENTS

The author wishes to express appreciation to his major professor, Gaylord V. Skogerboe, for the guidance and suggestions given throughout the course of this study and the preparation of this dissertation. The author is also indebted to Dr. Robert Ward for his aid and cooperation as principal investigator for this project. The help and advice of the other members of the Graduate Committee, Ralph W. Hansen, Robert A. Longenbaugh, Dr. Gordon E. Kruse, and Dr. Burns R. Sabey, is also sincerely appreciated. The author wishes to thank Miss Kevin Feigen, who typed this manuscript. Finally, special thanks are due Margaret Vanderholm for her encouragement and understanding throughout this study.

The work upon which this publication is based was supported by funds provided by the Water Quality Office, Environmental Protection Agency. Personal financial support was provided by a N.A.S.A. Traineeship.

TABLE OF CONTENTS

Page

LIST OF TABLES viii
LIST OF FIGURES x

Chapter

1 INTRODUCTION 1
  Background 1
  Problem 2
  Purpose 5
  Scope 5

2 LITERATURE REVIEW 8
  Functional Data Needs 8
  Water Quality Surveillance System Planning 12
  Estuary Sampling 21
  Costs 23

3 PROCEDURE 26
  Experimental Design 26
  Pollution Event Detection 29
  Base Level Data Acquisition 40
    General Description 40
    Statistical Approach 41
    Model Approach 43

4 RESULTS 47
  Detection of Pollution Events 47
    Number of Samples 47
    Location and Frequency of Sampling with Constant Number of Samples . . 52
    Spill Duration and Frequency of Sampling 58
    Multiple Sampling Stations 64
    Sensitivity Tests for Detection Model 73
      Stream velocity 73
      Quantity of pollutant 76
      Channel geometry 76
      Summary of sensitivity tests . . 79

TABLE OF CONTENTS (Continued)

Chapter Page

Base Level Quality Surveillance 80
Statistical Approach 80
Model Approach 89
Multiple Sampling Stations 90
Discussion 97

5 SYSTEM PLANNING 98
Pollution Source Inventory 100
Surveillance System Data Needs 102
Sampling Station Location 103
System Performance Analysis 110
Pollution Event Detection 111
Base Level Data Acquisition 117
Discussion 120

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 124
Summary 124
Conclusions 125
Recommendations for Further Research . 126

BIBLIOGRAPHY 128

APPENDIX A
The Computer Program for Pollution Event Detection 133

APPENDIX B
The Computer Program for Base Level Data Acquisition 143

LIST OF TABLES

Table		Page
1	Effect of sampling frequency on detection probability	49
2	Effect of sampling frequency and number of stations on detection using total surveillance programs of 12 and 24 samples per month	53
3	Analysis of variance for regression of effects of sampling frequency and number of stations with total of 12 samples collected during month	56
4	Analysis of variance for regression of effects of sampling frequency and number of stations with total of 24 samples collected during month	56
5	Hypothetical example of required statewide sampling frequency for 50% detection level for pollution events	71
6	Base level surveillance from model simulation	91
7	Hypothetical example of base level surveillance sampling frequency for a stream having 3 stations	95
8	Proposed primary sampling stations in the South Platte River Basin	107
9	Proposed secondary sampling stations in the South Platte River Basin	107
10	Proposed primary sampling stations in the South Platte River Basin - alternate network	109

LIST OF TABLES (Continued)

Table | Page

11 Summary of proposed primary sampling stations and respective stream relative effectiveness (REF) values 113

12 Summary of primary sampling stations and respective stream relative effectiveness factor (REF) values - alternate network . . 113

13 Stream characterization data for proposed secondary station locations in the South Platte River Basin 119

A.1 Dictionary of fortran symbols - program DEPROB 135

B.1 Dictionary of fortran symbols - program HISDAT 145

LIST OF FIGURES

Figure		Page
1	Simplified flow diagram of pollution event detection model	30
2	Example instantaneous spill dispersion curve	35
3	Example instantaneous and continuous discharge dispersion curves	38
4	Simplified flow diagram of base level surveillance model	45
5	Relationship between sampling frequency and detection probability for one station at lower end of reach with 0-3 day random spill duration	50
6	Pollution event detection using monthly programs of 12 and 24 samples collected along 100 mile reach	55
7	Spill detection by one station at end of 20 mile reach for 1, 2, and 4 samples during 30 day period	60
8	Spill detection by one station at end of 20 mile reach for 8 and 12 samples during 30 day period	61
9	Detection of short duration spills by one station at end of 20 mile reach for 1, 2, 4, 8, and 12 samples during 30 day period	62
10	Detection of instantaneous type spills by one station at end of 20 mile reach . .	63
11	Detection of random duration spills by one station at end of 20 mile reach . .	65
12	Relative effectiveness factor in relation to number of sampling stations per stream	68

LIST OF FIGURES (Continued)

Figure		Page
13	Effect of flow velocity on detection . .	75
14	Effect of spill size on detection . . .	77
15	Effect of channel geometry on detection .	78
16	Allowable error in relation to number of samples for populations with standard deviations of 1 and 2	81
17	Allowable error in relation to number of samples for populations with standard deviations of 3, 5, and 10	82
18	Allowable error in relation to number of samples for populations with standard deviations of 25 and 50	83
19	Allowable error in relation to number of samples for populations with standard deviations of 100 and 500	84
20	Observed deviations from true mean by base level surveillance model	92
21	South Platte River Basin map	99
22	Location of proposed primary and secondary sampling stations in South Platte River Basin	108
23	Relation between detection and sampling frequency for proposed and alternate South Platte River Basin surveillance networks .	114
24	Annual sampling cost at various detection levels for proposed and alternate South Platte River Basin surveillance networks .	115
25	Relation between allowable error and sampling frequency for proposed South Platte River Basin surveillance network .	120

LIST OF FIGURES (Continued)

Figure Page

26 Annual sampling cost in relation to allowable error for proposed South Platte River Basin surveillance network . . . 122

A.1 Flow diagram for program DEPROB . . . 137

A.2 Flow diagram for subroutine SOURCE . . 138

A.3 Flow diagram for subroutine DISPER . . 139

B.1 Flow diagram for program HISDAT . . . 146

B.2 Flow diagram for subroutine NORDIS . . 147

Chapter 1

INTRODUCTION

Background

The enactment of the Water Quality Act of 1965 committed the Federal Government to the attainment of clean water in the United States. The burden of responsibility for achieving this goal was placed on the states by requiring each individual state to establish water quality standards for interstate streams and to develop detailed plans for implementing and enforcing these standards. Most states were ill-prepared for handling this task, resulting in much activity to develop the necessary capabilities. An additional problem was presented by the lack of basic data in many states on which to base an assessment of the water quality situation. In order to obtain basic data and to enforce water quality standards, the states either established or expanded their water quality monitoring networks.

In terms of time and money expended, traditional grab sampling techniques combined with laboratory sample analysis comprise the primary water quality data collection method in many states. In all probability, this will remain true for years to come. The development of more sophisticated surveillance methods such as remote sensing and continuous automatic monitoring is progressing rapidly, but prohibitive costs and other factors will make these methods impractical for many applications in the immediate future.

Problem

For the most part, the water quality monitoring networks in use today have grown rapidly, without careful design and planning. Even with the commitment of a substantial effort, it is apparent that these networks do not meet the overall needs of the water quality management programs. Many waste sources go undetected. Frequently, pollution problems have dissipated before their existence is noted by the surveillance system, or before data is made available for use. Inadequate or nonrepresentative data may be obtained, which compounds rather than helps alleviate water quality problems.

From the foregoing, it must be concluded that water quality sampling and data analysis can consume large amounts of water pollution control agency time and money without providing the information necessary to support water quality management programs. This is not to say that nothing has been gained from these early surveillance networks. In addition to water quality data, much information has been obtained which provided valuable insight for making improvements on existing networks, as well as gaining valuable planning information for designing new surveillance systems. The available guidelines are few, however, and the planner of a surveillance network is usually forced to base his recommendations on generalities and opinions from other experienced personnel. These are not necessarily incorrect, but they may be subject to varying interpretation.

There are several basic considerations involved in planning a surveillance program which act as constraints in establishing the type of data collection system, as well as the number of stations and frequency of sampling. These constraints may include: (1) needs of data users; (2) available resources; (3) legal requirements; (4) available technology; (5) operational criteria (economic, social); and (6) operational responsibility. In a given situation, it is likely that one or another of these will be a primary constraint. More often than not, the greatest limitation will be the available resources. In view of this, it is obvious that thorough planning and design of surveillance networks is necessary to provide for the most effective system under the given constraints. The heavy reliance on grab sampling for all data needs, with little or no knowledge of the effectiveness of the method, is the weak link in many surveillance programs.

In studying a water quality surveillance method, it is necessary to consider the adaptability of the data to its intended use. Some general functional areas using water quality data are planning, research, aid programs, technical assistance, regulation, and legal enforcement. Planning, aid programs, and technical assistance primarily require historic water quality data. Historic water quality data can be defined for the purposes of this study as any biological, chemical, or physical data collected in the past which can be used to characterize the quality of the stream in question. To make valid assessments and projections concerning water quality, historic data must be used to evaluate long term trends and present conditions. Historic data can also be used to identify problem areas for research purposes. Although individual characteristics such as precision, parameters necessary, etc., may vary among these needs, it is felt that the general type of data needed can be grouped into the one broad category, historic or base level water quality data.

For regulation and enforcement purposes, sufficient data must be obtained from a surveillance system to insure compliance with established stream quality standards. To accomplish this, a surveillance method must have a reasonably high probability of detecting pollution events which violate the quality standards. Short term trends, or evidence of impending problem conditions, must be indicated by the chosen surveillance method. This must all be accomplished with minimum lag time so that prevention and/or abatement action can be taken. For the purposes of this study, data requirements of this type will be grouped under the broad category of regulation and enforcement.

Purpose

The primary objective of this research will be to arrive at an estimate of the effectiveness of grab sampling techniques in stream water quality surveillance. Along with this, techniques will be developed to establish the most effective combination of sampling location and sampling frequency to meet surveillance needs for a given situation.

All water quality data requirements have been simplified as to falling under base level type data or regulation type data. It must be emphasized that the division may not be this distinct and that overlapping may occur. However, for this study such a categorization is adequate and practical.

To evaluate the overall effectiveness of grab sampling techniques, the primary characteristics to be considered will be capability with respect to data needs, reliability and cost. The results of this study will aid in quantifying these characteristics and will contribute information valuable in planning and design of surveillance systems.

Scope

For the most part, this study will deal with evaluating the capability of grab sampling techniques in a routine monitoring program with respect to data needs. Data needs must be well understood and defined prior to design and planning of a surveillance program. This study will not attempt to recommend or design any optimum generalized surveillance system, but will provide information which will aid in intelligent decision-making once the data needs and other constraints are defined.

Data needs have already been grouped into two general categories, base level type data and regulation type data. These will be handled separately throughout the study. In evaluating grab sampling techniques for obtaining base level type data, the main consideration will be the ability of the system to provide a representative picture of long term water quality levels. These can be characterized by such statistical parameters as means, standard deviations, and trends. The primary variables affecting the capability of a system to approach the true values of these parameters are sampling location, sampling frequency, and stream quality variability. Being concerned only with routine surveillance systems, the assumption will be made that some knowledge of the stream variability is already available. This information should be a requirement prior to design of a routine surveillance system and will probably be obtained by special stream surveys. Sampling location must be based on a variety of factors which will be discussed fully. This leaves the variable of sampling frequency to be evaluated. The study is designed to define the effect of this variable on the ability of a system to obtain representative long term data.

To evaluate the capability of grab sampling techniques in obtaining regulation type data, the same reasoning is used to arrive at sampling frequency as the primary independent variable to be studied. For this situation, however, the dependent variable of concern will be the ability of the system to detect short term quality variations that are indicative of pollution events and stream standard violations. In other words, extremes are of importance instead of averages. This phase of the study is designed to find the relationship between sampling frequency and probability of detecting pollution events. The effect of sampling location on detection probability will also be evaluated.

Planners of surveillance programs are in need of more specific information and guidelines on which to base their decisions. The information resulting from the analysis described above will enable planners to estimate the performance of a system at a given level of surveillance or conversely, to plan a system for a given level of performance. This will be the main theme of the study. To add to the usefulness of the information, the characteristic of cost will also be considered.

Chapter 2

LITERATURE REVIEW

Water quality surveillance is an activity carried out in support of Federal, state, and local pollution control programs. The objectives of these programs are the abatement and prevention of water pollution. To accomplish this, the groups concerned are involved in planning, research, aid programs, technical assistance, regulation, and legal enforcement. The collection, processing, and dissemination of water quality data are necessary prerequisites to these duties. The data required will vary with the intended use, although in some instances data collected for one purpose may adapt well for another use. This research is concerned only with routine water quality surveillance data acquisition, but it is recognized that many other data types are necessary for the successful operation of a state water pollution control agency.

Functional Data Needs

The planning function is emerging as one of the primary duties of water pollution control organizations. All states are required by Federal law to develop and adopt general comprehensive programs for the prevention and abatement of water pollution. The Water Quality Office of the Environmental Protection Agency (EPA/WQO) issued a set of guidelines in January, 1971 to assist the states in implementing the necessary planning (8). In addition, general data needs from water quality surveillance are discussed by Sayers (35), while Gannon and Wezernak (10) have stressed the importance of collecting water quality information with a definite purpose in mind.

Moody (25) has described the data requirements for planning purposes. These are primarily data for evaluating base level stream quality conditions, along with quality trends, and identifying problem areas. These data are usually then incorporated into a planning model to aid in the decision-making process. Moody points out errors in the data itself, or in its analysis, may cause over or under design and result in loss of economic efficiency for a project. Petri (29) notes that planning data are often insufficient for several reasons, one of which is that data needs are not anticipated far enough in advance. Anderson, et al., (1) point out the lack of water quality trend analysis in the literature and contribute this primarily to a lack of reliable and extensive data of sufficient time length.

Data collected under a routine surveillance program may indicate areas where additional study or research is necessary. Research may then be performed by the agency concerned, or contracted outside. Wisconsin law (54) is an example of the provisions made by states for water quality research. This law states in part: "The department may conduct scientific experiments, investigations, waste treatment demonstrations and research on any matter under its jurisdiction." Data for research will normally be specified and detailed, hence beyond the realm of routine surveillance data.

Federal aid programs involve the states in applying for, accepting, and supervising loans and grants for water pollution control. In most cases, these funds are for the construction of waste-water treatment facilities as discussed by Bramer (4). Since treatment facilities are installed to maintain water quality levels in streams, the basic water quality data requirements are concerned with the nature of the receiving stream and the applicable water quality criteria. These requirements are used to establish effluent requirements and evaluate the proposed treatment facility. Receiving stream data requirements will vary greatly with the stream characteristics and the water usage, according to Bramer.

Technical assistance is a general duty of an agency to advise, consult, and cooperate on technical matters with other agencies and political subdivisions of the state and Federal government and with private enterprises. This duty consists of several activities including pollution abatement recommendations and evaluation of proposed and existing treatment facilities. Bramer (4) includes data needs for this category also, indicating that the data requirements for this duty are almost identical to those of the aid program category.

Regulation can be described as the activity of the state to control the quality of the water in its streams and rivers. This will include the establishment of stream standards and monitoring to insure that the standards are being met. Management of stream quality may also be included in this category. For this study, management is defined as short term adjustments in waste treatment and in streamflow regulation to maintain desired water quality levels. In terms of money and manpower involved, regulation is probably the most important duty of state water pollution control agencies. Data requirements for successful performance of this duty are quite stringent. An effective surveillance system must have a high probability of detecting stream standard violations. McDermott (21) feels that a minimum of sampling stations with a high sampling frequency will provide the best data. He also states that the adequacy of a sampling schedule should be judged by the ninety-five percent confidence interval for correctly defining the stream quality. Obviously, a very high sampling frequency would be necessary to meet this criterion. If action is to be taken on stream standard violations, the data collection, analysis, and dissemination must occur very rapidly. Management of stream quality has similar data requirements to monitoring for stream standard violations. In fact, monitoring for management purposes must permit detection of short term quality trends and allow sufficient reaction time for management decisions to prevent stream standards from being violated. Moody (25) specifies the need for current water quality trends to measure effectiveness of management procedures. Data requirements for regulation purposes, then, can be characterized as timely, reliable estimates of stream quality levels and trends.

Legal enforcement is the function of the state to enforce stream standards by legal means when it cannot do so by persuasion. Data required for this activity must prove that violations have occurred and prove the source responsible. Ballinger (3) indicates that the methods used and the quality control employed are quite important in obtaining data which will withstand vigorous challenges during legal proceedings. An intensive water quality survey with strict quality control measures is necessary to obtain data which will meet these requirements.

Water Quality Surveillance System Planning

Water quality data uses may be grouped by classification systems different from, although similar to, those just mentioned. For example, McDermott (21) states that water quality monitoring is a support activity for three functions: (1) water quality standards enforcement and revision; (2) water quality baseline and trend evaluation; and (3) planning and management programs. Metink (22) categorizes water quality data into three groups: (1) basic data; (2) survey data; and (3) enforcement data. How the purposes are grouped is not important. To realize, however, that the data required varies greatly with the purpose of collection is important. This should be considered in designing a quality surveillance system. Some of the general problems encountered in surveillance system planning are discussed by Pomeroy and Orlob (30). They state that minimum data needs are dependent upon drainage area, length of water course, slope, surveillance cycle, and pollution characteristics, along with other factors. De Falco (5) lists four questions that should be asked before designing a surveillance system: (1) why are the data needed? (2) where should they be collected? (3) when should they be obtained? and (4) what will be done with the information?

McDermott (21) states that if the primary purpose of data collection is to determine standards compliance, then the quality parameters listed in the standards should be given primary consideration in a surveillance system. In most instances, the parameters listed in the standards are far fewer than those available. McDermott has summarized the frequency of parameter usage in state standards. He indicates that only nine of the many available parameters appear in the standards of all states.

Five of the nine parameters appearing in state stream standards are termed the "Five Freedoms:" freedom from the presence of floating solids, settleable solids, unnatural turbidity or color, unnatural taste or odor, and toxic substances. The other four are DO (dissolved oxygen), pH, coliforms, and temperature. McDermott notes that the first four freedoms require use of man's senses and judgment as opposed to determination by analytical methods solely. Morgan (26) discusses parameters of interest for basic water quality data, particularly with respect to water usage. He indicates that selection of parameters for monitoring should be on this basis.

If long term base level data is the data collection purpose, it is desirable to measure a wide range of parameters, according to McDermott (21). Parameters not presently included in water quality standards may be added to standards at some later date, or may be needed for current or future planning purposes. McDermott lists seventy parameters which may be used to quantify stream water quality. Of these, all but four are listed in Standard Methods (37) and can be determined using grab sampling and traditional wet chemistry methods. Obviously, grab sampling has a capability of almost one hundred percent with regard to parameter measurement. Ballinger (3) indicates that only those procedures listed in Standard Methods have been acceptable for obtaining data for use in legal proceedings, so far. This implies that intensive surveillance using grab sampling methods is necessary for obtaining legally acceptable data.

Grab sampling usually refers to the obtaining of a sample at a single point in space and time. Various references (17,34,47) describe procedures such as the compositing of samples and the use of depth integrating samplers to obtain more representative samples. For the purposes of this study, grab sampling will include these methods, also. Ball (2) discusses errors to avoid in sample collection, such as errors in site selection, sample collection and field measurements, and sample preservation and storage. He describes a cross sectional sampling procedure used by the Bureau of Reclamation for determining the most representative sampling sites.

Several studies have been conducted on the use of index parameters for water quality surveillance. The primary purpose of using such indexes is the possible reduction of sample analyses necessary to obtain the needed information. In addition, index parameters may be useful in estimation of missing data points and in determining sampling schedules. Wang and Evans (50) used regression analysis and found good relationships using streamflow as the independent variable and various nutrient concentrations as dependent variables. Durum (6) also used streamflow as the independent, or index, variable with mineral concentrations as the dependent variables. Gunnerson (15) tried both streamflow and TDS (total dissolved solids) as indicator variables on a Columbia River study with fairly good success. Steele (38) used both streamflow and specific conductance as independent variables with various ionic constituents as dependent variables. He found specific conductance to be the best indicator, or index, parameter. Notably, all of these studies have selected a parameter for the independent variable which is easily measured and for which long term records are commonly available.

The frequency of sampling necessary to obtain data satisfactory for their intended purpose is difficult to define. Kittrell (17) says frequency of sampling varies with water use, the urgency of developing a representative record of quality, and the capacity of the responsible agency for sample collection and analysis. He points out that due to logistics, control agencies often sample at monthly or longer intervals, thereby allowing many standards violations to occur without being detected because of such infrequent sampling. Kittrell questions the practice of routine monitoring at regular intervals throughout the year and suggests greater economy might be achieved by limiting the sampling to periods of potential damage.

Stream water quality may exhibit diurnal, seasonal, annual, or other cyclic patterns (9). In addition, stream quality also will show random variation from meteorological and hydrologic events. Pollution occurrences may be random or cyclic in nature. An example of a cyclic event might be the effluent discharge from a seasonal industry such as a food processing plant. An accidental pollutant spill would more likely fall into a random uniform pattern. In other words, accidental spills should exhibit no time pattern of occurrence but, rather, have equal likelihood of occurring at any time throughout the year.

A California study (14) points out that grab sampling will miss, or detect, pollution events by chance. The water quality of an individual stream may range from highly variable to fairly stable depending upon local hydrologic and meteorologic conditions, the nature of the stream itself, and the contributing pollution sources. McDermott (21) states that the variability of the stream quality dictates to a large extent the frequency of sampling necessary to characterize the stream. In designing a surveillance system, it is desirable to use the minimum sampling frequency which will supply the necessary information. In an Ontario study, Rizvi (32) used analysis of variance on historical lake water quality data to determine minimum sampling frequencies. Since lake conditions were relatively stable, he found that previous sampling frequencies could often be significantly reduced with little or no loss of information.

Gunnerson (13) employed power spectra analysis to determine optimum sampling frequency for DO and specific conductance in a tidal estuary. He noted that for study of periodic harmonic motion, observations must be at less than one-half the wave period. His studies showed that the optimum sampling frequency for the parameters studied was about two hours. Moody (25) also discusses the use of power spectra analysis for determining sampling frequency. Thomann (42) used time series analysis to study the periodicity of DO and temperature in a Delaware estuary. All of these studies have been concerned with short term periodic variations (e.g. diurnal) for which very frequent observations are necessary. Obviously, routine surveillance by grab sampling is impractical for this purpose.

Steele (39) investigated the effects of sampling frequency using regression analysis. He simulated short term quality variations by use of their relations to index variables as described earlier. The simulated data was then compared to observed data. He notes that time-dependent variations may be masked by this method.

Pomeroy and Orlob (30) present minimum surveillance requirements for streams. They present recommendations regarding the minimum number of stations and sampling frequencies for given situations based primarily on stream slopes and flow variability. They do not explain how these recommended numbers were obtained. Weisbecker, et al., (53) propose a methodology for planning monitoring programs assuming that preliminary data such as water usage, base level quality and important parameter data are available. They recommend sampling frequencies for various parameters based on the variation expected and the importance of the parameter.

Sample site selection is, in most cases, somewhat arbitrary. Sites should be located at the most representative points, according to Ball (2). Kittrell (17) states that sites should account for present and potential pollution sources, water usage, and physical stream characteristics. Kittrell and West (18) emphasize that stations should be located to obtain the most representative data, rather than for convenience. A general discussion on representative sampling is given by Roskopf (34), who states that there is no ideal time and place for sampling for all purposes. Velz (49) discusses several factors to consider in station location. He notes that stations should not be located immediately below tributary mouths, or pollution sources. Colorado stations are based on water quality standard change points, among other considerations (23). The wording of the Federal program grant application implies, and has been interpreted to mean in some cases, that a station must be located within each reach having a different water quality standard (7). At least one study has been conducted using statistical techniques to analyze station locations. Palmer and Sato (28) used multiple and pair testing on data from lake sampling stations in Ontario to test similarity between station results. They found that stations could be reduced to prevent duplication of data and increase efficiency of data collection.

A few authors have described general procedures for design of water quality surveillance systems. Roche (33) emphasizes the need for cooperative effort among concerned agencies to achieve an effective monitoring program. Kittrell (17) discusses general guidelines for establishing a surveillance system. Haney and Schmidt (16) point out the importance of proper planning and present several points to be considered in sampling program design.

Recommendations were made regarding a complete surveillance system for the Sacramento River in a California study (14), but the basis for some of the recommendations, such as sampling frequencies, was not made clear. A systems analysis approach was used in a study (46) conducted for the Federal Water Quality Administration (FWQA). The objective of this study was to develop a general method for the design of surveillance systems for major river basins. The selection of parameters to be measured was primarily based on the capabilities of automatic monitors and on stream standards at the particular points sampled. A sampling frequency of once or twice monthly, depending upon location, was recommended for those parameters not continuously monitored. The report states that these frequencies are based on the needs to protect water uses, as well as to provide information necessary for future evaluation. However, the report does not explain how the sampling frequencies were selected on this basis. Surveillance stations were located on the basis of their relation to (1) interstate borders, (2) potable water supplies of major population centers, (3) major pollution sources, and (4) tributary streams.

Several papers describe and recommend increased use of the STORET system for data handling and retrieval. A computerized water quality data handling and retrieval system (STORET) was implemented by the Federal Water Pollution Control Administration (FWPCA) in 1964. STORET system use by Federal and state agencies is increasing rapidly. A basic description of the system and its use is found in a publication published by the FWPCA in 1966 (43). Taylor (41) has explained some of the STORET characteristics and mentions some experiences with its use.

Since this dissertation is primarily concerned with grab sampling methods, surveillance using remote sensing and continuous automatic monitoring methods is mentioned only briefly. Literature reviews reflecting current state-of-the-art for these methods can be found in a project report by Ward (51) and in a thesis by Sylvester (40).

Estuary Sampling

Estuaries present very complex problems in terms of water quality. Their hydrologic and hydrodynamic characteristics are complex and the mixing of fresh and saline waters compounds this complexity. Considering that many estuary shores are industrial centers producing a wide variety of pollutants, one sees that the problems can become enormous.

The Delaware River Estuary has been the subject of considerable study. O'Connor, et al., (27) indicate that several agencies sample this estuary regularly, but give no background as to the planning of the sampling program. Thomann (42) used data from the Delaware River Estuary in his study of time series analysis of water quality data.

The problems involved in estuary water quality surveillance are discussed by Pomeroy and Orlob (30). Among the factors which they state should be considered are: (1) type of quality constituents; (2) size of estuary; (3) shape of estuary; (4) relation between runoff, tidal action, and mixing potential; (5) degree of stratification; (6) quality, hydrologic, and hydrodynamic cycles; and (7) periodic vs. random phenomena. They present a set of minimum surveillance requirements for various types of estuaries. These recommendations are based on what the authors term the minimum surveillance to obtain statistically significant data. They do not, however, describe any of the methods used to arrive at these numbers, other than to state that at least six samples per cycle are necessary to characterize a periodic phenomenon.

Gunnerson (13) used time series analysis to determine optimum sampling intervals in tidal estuaries. His study was primarily concerned with short term periodic phenomena, although the method can be applied to any time period for which adequate data is available. The use of spectral analysis for analyzing water quality data from streams and estuaries is described by Wastler (52).

Gibbs and Isaac (11) discuss the water quality monitoring program for the Duwamish Estuary near Seattle, Washington. They state that manual sampling was considered impractical in this situation due to complexities of the estuary system. They also note that manual sampling is used for parameters not available from automatic monitors.

Velz (49) notes that the semi-daily tidal cycle is a major factor controlling estuary quality, necessitating sampling at frequent intervals (one to two hours). He states that the tidal influence tends to prevent sudden changes in water quality, but that random sampling is of little value. Therefore, frequent, controlled sampling is required to properly define estuary quality conditions.

Costs

Costs of water quality data collection vary with the methods used and with locale, but it is generally accepted that costs are high. Petri (29) states that one of the basic reasons for insufficient planning data, in many instances, is the high cost of sample collection, laboratory analysis, and data reporting. Gunnerson (14) feels that four man-days of handling and evaluation are needed for every one man-day of data collection, not including laboratory requirements. Pennsylvania water pollution control authorities feel that routine sampling is too expensive for enforcement purposes and use it only for obtaining long term base level data (31). De Falco (5) gives the cost of manual surveillance as $25 to $50 per sample for sample collection and the same for laboratory analysis. Records of the Ohio River Sanitary Commission (ORSANCO) indicate that the cost of manual sampling and analysis in that region is about $2.20 per data item (19). Maylath (20) states that the costs for manual sampling and analysis in New York State are about $6.00 per data item.

Manual sampling is the only method used presently in Colorado for routine quality monitoring. The actual costs for this program in Colorado during the 1970-71 fiscal year were assembled by Misbach (24) and used to calculate costs per sample. His figures show these values: sample collection, $21.40 per sample; chemical, bacteriological, and radiological analyses, $34.80 per sample; data handling and analysis, $10.18 per sample. Thus, the total cost amounts to $66.38 per sample. The Colorado Water Pollution Control Division shares laboratory facilities with the State Public Health Department and contributes financial support proportional to the work load required for laboratory analysis of water samples. For this reason, Misbach indicates that laboratory analysis costs were based on their contribution rather than on actual compilation of laboratory costs.

There is not enough cost information given by various institutions to allow direct comparison, or to explain reasons for the variation in costs. The point is made by almost all authors that, due to the big costs involved, proper planning of surveillance systems is very important.

Chapter 3

PROCEDURE

Experimental Design

The basic tool used in performing this study is a mathematical model written into a digital computer program. In addition, some simple statistical prediction methods are employed. Numerous models have been developed to simulate water quality regimes and thereby predict actual water quality levels under given conditions. The models used in this study are different in that they were developed to predict the performance of water quality surveillance networks for various water quality conditions. In other words, we are trying to model water quality surveillance systems, not water quality. The data obtained from these models is intended for use in design and evaluation of actual surveillance systems.

Mathematical models were selected because of their characteristic of allowing a large number of trials to be made simulating various conditions using high speed computers. A field study of surveillance systems would require the installation of the necessary facilities or the observation of existing ones. To evaluate many systems under a variety of conditions would be too costly and time consuming for a study of this nature. When using models, however, care must be taken to insure the validity of the models in simulating the system(s) under consideration.

The first model described below was developed to study the effect of sampling location and frequency on the ability of a monitoring system to detect significant short term quality variations, or pollution events. The terms "pollution event" and "spill" are used synonomously in this study and refer to any short term quality variation or extreme value from any cause which may indicate a stream standard violation. The model generates a series of these events at random times and locations on the stream reach under study. Downstream movement and dispersion of the pollutant is calculated. Various combinations of sampling times and locations are read into the program for testing, and if sampling and spill coincide at a certain point in time and space, detection of the spill is assumed. By testing the various sampling combinations with a large number of random spills, predictions of the sampling effectiveness can be made.

To study base level type data acquisition by grab sampling, both a statistical and model approach were used. In this situation, the objective is not to detect extremes, but rather to obtain representative mean values. Statistical theory contains methods for estimating the number of samples necessary to predict a mean within a given range of the true mean for a known confidence level. The method used in this study is described in detail later in this chapter. This method requires only that some estimate of the variability of the parameter under consideration is available. Then, by specifying the allowable error, the number of samples necessary can be estimated. For the time period in question, the number of samples is converted to a sampling frequency at the specified sampling stations.

A model was developed illustrating the statistical approach just described. This model generates a set of water quality data for a hypothetical parameter over a long time period. The characteristics of the generated data, such as the mean and standard deviation, are known. Various sampling schedules are tested by reading them into the program and obtaining a set of observed data points from the generated data. An observed data point is that value occurring in the generated data at the point in time a sample is specified. The characteristics of the observed data can then be compared to the characteristics of the generated data. The model and the statistical presentation provide a means whereby the performance of a surveillance system in acquisition of base level type data can be evaluated.

Pollution Event Detection

The effectiveness of a surveillance system in detecting a pollution event or stream quality standard violation is of primary importance for the regulation function. A literature search did not reveal any information or methods to quantify this characteristic for grab sampling, or even that any attempts had been made to determine the level of effectiveness. Since one of the objectives of this study is to evaluate grab sampling methods for regulation data needs, it was necessary to devise a method whereby a numerical estimate of detection levels could be made.

The method developed involves the use of a simple mathematical stream model. A program was written for the Colorado State University CDC 6400 digital computer. A simplified flow diagram for the program is shown in Fig. 1 and a listing of the program and complete flow diagram are included in the appendices. The basic program inputs are the geometric and hydraulic characteristics of the stream. For the initial analysis, a hypothetical stream was assumed with the following characteristics: average width, 200 feet; average depth, 1.5 feet; average velocity, 2 fps; average flow rate, 600 cfs; Manning "n" value, 0.025. These values are similar to those that can be expected on the lower reaches of the South Platte River in Colorado (12). Time of travel and dispersion of pollutants from a specified pollution event are calculated using these values. By specifying a numerical value for these

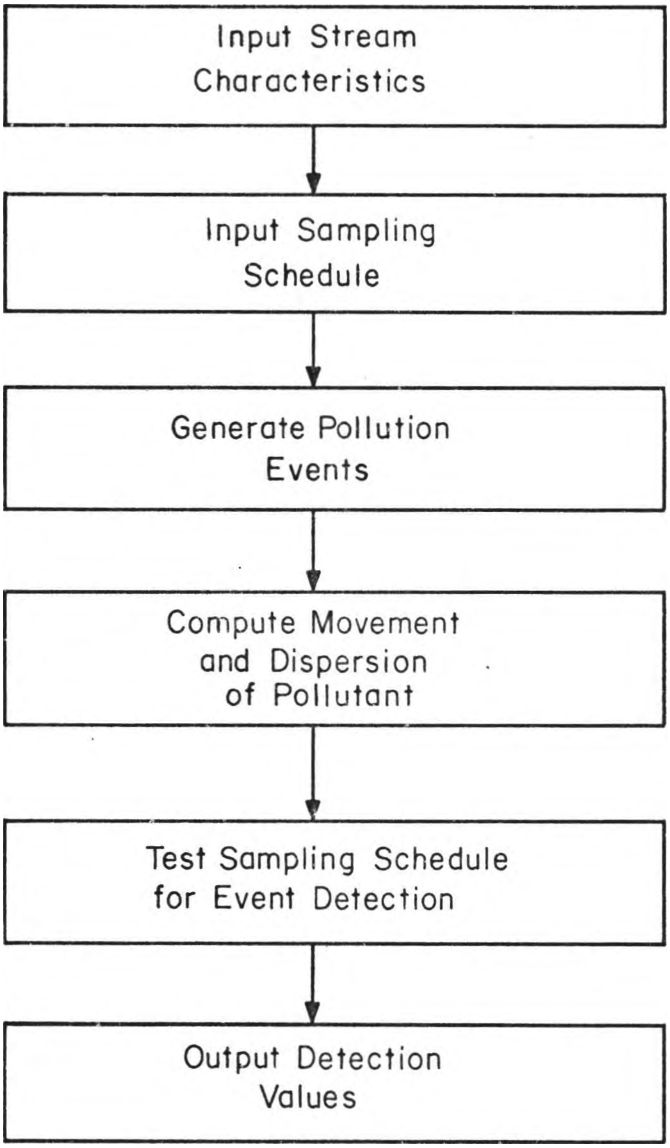

Figure 1. Simplified flow diagram of pollution event detection model.

parameters, the assumptions of uniform channel cross section and steady uniform flow are also implied. The length of the stream reach was varied in the program, depending upon the particular situation under study.

The arbitrary selection and use of a single set of values for stream characteristics is obviously not in accordance with an actual situation. However, sensitivity tests were performed on the model to check the effects of varying these parameters. The results of the sensitivity tests will be reported in the following chapter.

Location and time of pollution events are assumed to be completely random occurrences. A uniform random number generating function is used to select each of these parameters. For all of the analyses reported here, the location was a uniformly distributed random point anywhere along the entire reach under study. The time of pollution event occurrence was allowed to vary within the range of 0 to 30 days. Another pollution event characteristic considered was the length of time discharge occurs, or the spill duration. Since this may vary from an instantaneous spill to a continuous discharge over a long time period under actual conditions, the event time was studied as an independent variable, either specified or random within a specified range.

A method developed by Glover (12) for the U.S. Geological Survey (USGS) was used to compute the longitudinal dispersion curves for pollutants during travel downstream. This method of solution requires the stream geometry and hydraulic characteristics described earlier.

For calculating longitudinal dispersion, Glover developed the following equation, which is also the format of the equation used in the model for detecting pollution events.

$$S = \frac{Q_s}{BD} \frac{e^{-\left(\frac{x-\bar{v}t}{\sqrt{4K_x t}}\right)^2 \cdot}}{\sqrt{4K_x t}} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

In this equation, S is pollutant concentration in lb per 1000 cubic feet of water, Q_s is size of spill in lb, B is average stream width in feet, D is average stream depth in feet, x is distance from spill point to sampling point in feet, $\bar{v}$ is average stream velocity in feet per second, t is elapsed time since spill in seconds, and K_x is the longitudinal diffusion coefficient in square feet per second.

Use of Glover's method requires selection of a longitudinal diffusion coefficient applicable to the situation under consideration. The following approach is used by Glover to arrive at an estimate for the longitudinal diffusion coefficient. The Manning and Chezy expressions for mean stream velocity are equated and solved for the Chezy coefficient, C_1. This results in the following expression:

$$C_1 = \frac{1.486}{n} R^{1/6} \quad \ldots\ldots\ldots (2)$$

In Equation 2, n is the Manning roughness coefficient and R is the hydraulic radius in feet. A value for C_1 is then obtained by substituting values for n and R and then solving the equation. The next step is to calculate a value for shear velocity, v_*, which Glover defines as the square root of the ratio of the friction stress exerted by the stream on its bed, τ_o, to the density of the fluid, (i.e., $v_* = \sqrt{\tau_o/\rho}$). The relation for calculating shear velocity is given in Equation 3, where g is the acceleration of gravity.

$$v_* = \frac{\bar{v}\sqrt{g}}{C_1} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Finally, experimental data obtained by Glover indicates the relation between shear velocity and the longitudinal diffusion coefficient is

$$K_x = CRv_* \quad \ldots\ldots\ldots\ldots\ldots (4)$$

where C is some constant dependent on the characteristics of the stream under consideration. For a natural stream such as assumed in this study, Glover states the value of C should be about 500. Equation 4 is solved to obtain a value for K_x, which is then substituted into Equation 1.

The final dispersion curve for the point along the stream reach in question is calculated by substituting values for t into Equation 1 and solving. The initial t value must be specified to occur just before the leading edge of the dispersion curve reaches the sampling point. By then incrementing t in finite steps until the significant portion of the pollutant has passed the sampling station, a curve such as shown in Fig. 2 is obtained.

Glover's formula calculates the longitudinal dispersion curve for a finite amount of conservative pollutant released instantaneously from a point source. A conservative pollutant can be described as essentially inert, such that no reactions occur which significantly add, remove, or change the form of the pollutant within the time period considered. Complete lateral and vertical mixing was assumed in all cases. If the distance from the spill to sampling point is very small, this assumption is not valid. In addition, this situation does not allow time for development of a dispersion curve from an instantaneous spill. The program contains provisions to compensate for this possibility.

The calculated dispersion curve is in terms of a time history of pollutant concentration at a given location along the reach. Concentration of the assumed conservative pollutant is expressed in units of milligrams per liter (mg/l). The initial quantity of pollutant introduced must be specified. This quantity was specified as 1000 pounds for all trials in the study except when sensitivity of the model solution to this value was being tested. A background concentration of pollutant in the stream is also specified, with the actual concentration curve being

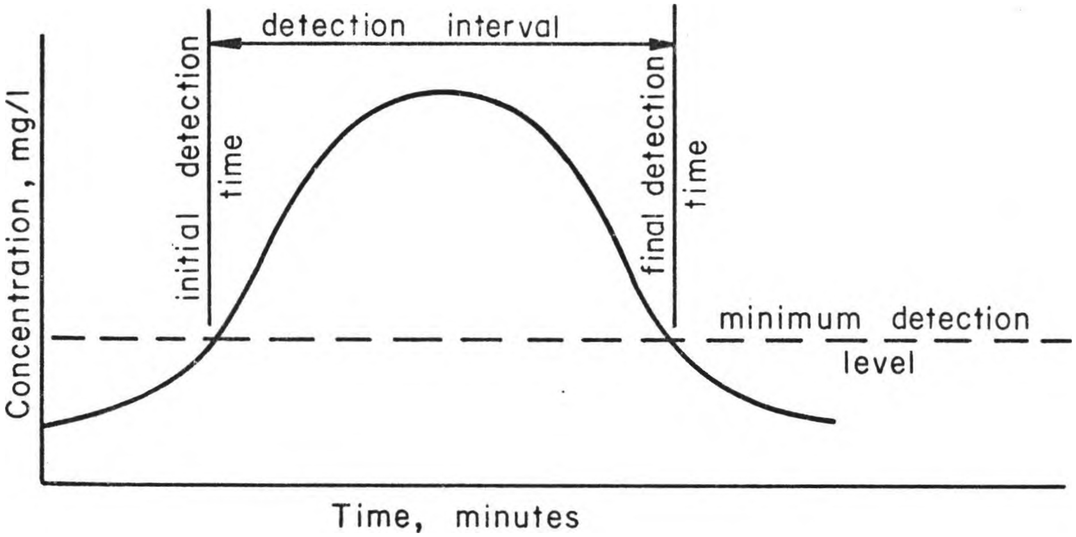

Figure 2. Example instantaneous spill dispersion curve.

computed as the sum of background and pollution event concentrations. The shape of the calculated dispersion curve for an instantaneous spill approximates that of a normal distribution curve. An example curve illustrating this is shown in Fig. 2. Curves calculated for points close to the spill origin will have a very narrow spread and a high peak. As travel distance downstream increases, the curves will tend to widen and flatten.

By specifying a minimum detectable level for detection of a pollution event, a time period is defined during which a sample must be taken for the event to be detected. The term "minimum detectable level," as used here, does not refer to the actual concentration which can be detected by a given analysis technique. Rather, it refers to some concentration indicative of a pollution event due to its value being beyond the range of normal variation. The example dispersion curve shown in Fig. 2 illustrates the time period for detecting the pollution event.

The actual value of the concentration at any point in time is not important to the final desired solution, but is just a tool to arrive at the detection time interval. In other words, the pollution event will be detected if a sample is collected at a point in time when the concentration is greater than the minimum detection level. Thus, the possibility of detection is only concerned with whether or not the concentration is greater than, or less than, the minimum detection level. At some finite distance below the point of origin of a spill, the calculated dispersion curve will flatten to the extent that the detection interval will decrease. Eventually, the entire curve will fall below the minimum detectable level. The implications of this will be discussed further in the following chapter.

A hypothetical pollutant that meets the requirements of this method is assumed throughout the study. Fortunately, many common pollutants very nearly meet these requirements and the methods reported herein should be applicable in a majority of situations.

In the case of a continuous discharge, no practical method of calculating longitudinal dispersion was found. For the present model setup, if a continuous discharge occurs, its duration is simply added to the detection interval for an instantaneous spill occurring at the same time and location, thereby increasing the detection interval by the duration of the spill. The waste discharge diluted by stream flow is assumed to produce a concentration equal to that at the peak of the calculated dispersion curve. As the spill duration increases, the dispersion curve begins to approximate a square wave and the calculated dispersion becomes less influential on the detection interval length. This situation is illustrated by the sample curves in Fig. 3.

Sampling locations along a reach and sampling times at these locations are read into the program. Sampling

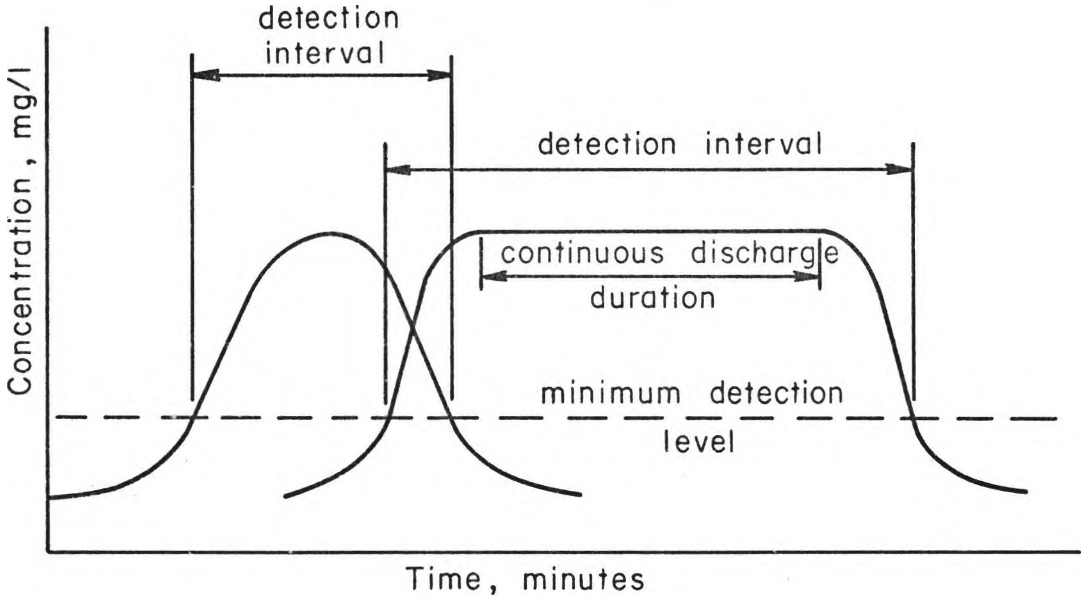

Figure 3. Example instantaneous and continuous discharge dispersion curves.

times are specified within the same 0 to 30 day range as pollution event occurrence. Any sampling frequency from once to many times during this period may be selected. The model thus permits any combination of sampling location and frequency to be studied.

A brief explanation of the computation procedure is provided below. All necessary stream characteristics, sampling times and locations, and spill durations are read into the computer program. Uniform random numbers are generated to select the time and location of the pollution event. For each sampling location downstream from the spill location, a dispersion curve is calculated and the time interval for detection is determined. The given times of sampling at each station are tested against the calculated detection time interval and a determination made as to whether or not detection occurs. Each pollution event is tested at each sampling location for all sampling times, if necessary. If detection occurs, no further locations and times are tested for that event, so that detection will not be counted more than once for the same event. When this procedure is completed, a new pollution event is generated and the process repeated.

Presently, the program generates 50 events and outputs the number of events detected out of this total. The program repeats this 20 times, thereby producing 20 sets of 50 events, or a total of 1000 random pollution events. The results are used to calculate the detection probability for the specified sampling configuration and spill duration. The results from different combinations are compared and estimates made of quantitative values for detection probability.

There are several inputs, such as channel geometry and flow characteristics, for which arbitrary values must be assigned. For most cases where this has been done, sensitivity checks were performed on the model by individually varying these parameters. This analysis is included in the following chapter.

Base Level Data Acquisition

General Description

For planning and other related functions, it is necessary to have data that are representative of the ranges in stream quality that may occur in time and space. Short term variations such as diurnal are not considered here, but seasonal and annual variations, as well as long term trends, are important. The literature reviewed indicated that grab sampling was well suited to obtaining this type of data due to less stringent sampling frequency requirements, along with the wide range of parameters measurable by this method. In most instances, however, these observations were based on opinion and experience, rather than experimental evaluation. This phase of the study was designed to develop a method whereby the effectiveness of grab sampling in meeting data needs of this type can be evaluated.

Data of this type can probably be best presented in terms of some simple statistical parameters, such as means and standard deviations. This suggested that a theoretical statistical approach might be applicable. At the same time, it was felt that the evaluation could also be accomplished using simulation techniques. The end result was to use both approaches. Therefore, the statistical theory was used as the basic evaluation procedure and a mathematical model was developed for illustrative and comparative purposes.

Statistical Approach

A primary objective for employing statistics is to determine the sampling frequency necessary for obtaining representative base level data. As was the case throughout this study, the assumption is made that sufficient data is already available for designing the surveillance system. Using the known data, it was desired to establish a routine surveillance program which would adequately perform at a given level. Snedecor and Cochran (36) present a simple method for answering the question, "How large a sample do I need?" This method was easily adapted to the problem at hand to answer the question, "What sampling frequency do I need?"

The first assumption to be made in developing the statistical approach is that a normally distributed population is being sampled. Since the population in this case is mean annual concentrations, and since the "Central Limit Theorem" states that sample averages tend to become normal even if the original population is not, this assumption is easily justified. Next, an estimate is desired to be correct to within some limit, ±L. Snedecor and Cochran state that when the standard deviation of the population, σ, is not known, but must be estimated by the sample standard deviation, S, the 95% confidence limits are given by the expression

$$\mu - t_{0.05}\, S/\sqrt{n} \leq \bar{X} \leq \mu + t_{0.05}\, S/\sqrt{n} \quad \ldots(5)$$

where μ is the mean, $\bar{X}$ is the observed mean, t is a value from the student's t distribution, and n is the sample size or number of observations. For water quality data, values for S can be calculated for the specific time period under consideration from historical data. The value of the limit, L, or allowable error, can then be expressed as

$$L = t_{0.05}\, S/\sqrt{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

By substituting a value for $t_{0.05}$ with n-1 degrees of freedom and values for S and L, the number of samples necessary to estimate the annual mean with 95% probability that the error of the estimate will be equal to, or less than, the limit, L, can be calculated. This relationship was used to develop a series of curves which are presented in the following chapter.

This procedure cannot be applied to situations in which the mean, μ, is very small. An example of this might be a trace metal for which many zero concentrations are observed and most concentrations observed are very close to zero. In this case, unless the number of observations, n, is very high (probably in the range of several thousands), the normal distribution curve of the means will extend significantly into the negative range. This implies that $\bar{X}$ can take on negative values, which is impossible. For this reason, use of the method must be confined to those quality parameters for which it can be demonstrated that no significant portion of the normal distribution curve of the means extends into the negative range.

Model Approach

The model approach uses a simple mathematical model of a stream and surveillance system as the basic tool. Although actual water quality data for an existing stream could be used, the initial approach was to use hypothetical data. The advantage of this procedure was that the hypothetical data can be generated with known variations and trends. This study was not intended to become involved in data analysis or in methods of data analysis. In addition, use of hypothetical data avoided the problem of having to work with incomplete or inadequate data, with consequent difficulties in interpreting results, which is often the case in real situations. The evaluation of the surveillance system will be accomplished by observing its effectiveness in detecting the known data characteristics.

A computer program was written incorporating this model. The initial function of the program is to generate a set of long term water quality data for a given point in space along a stream. The data include known seasonal and annual variations, long term trend variation, and random variation. The surveillance system characteristic of concern is the sampling frequency, which is handled as an independent variable. This is an input variable and can easily be changed to study various combinations. A simplified flow diagram of the program used is shown in Fig. 4, while a copy of the program and a complete flow diagram are included in the appendices. The model does not consider the effect of sampling locations, since it deals with only one point in space. In actual design of a surveillance system, it is anticipated that sampling station locations will be established on the basis of known river and pollution source characteristics. After these locations are established, it will be necessary to study the variability of the desired quality parameters to arrive at a sampling frequency adequate to obtain the representative data.

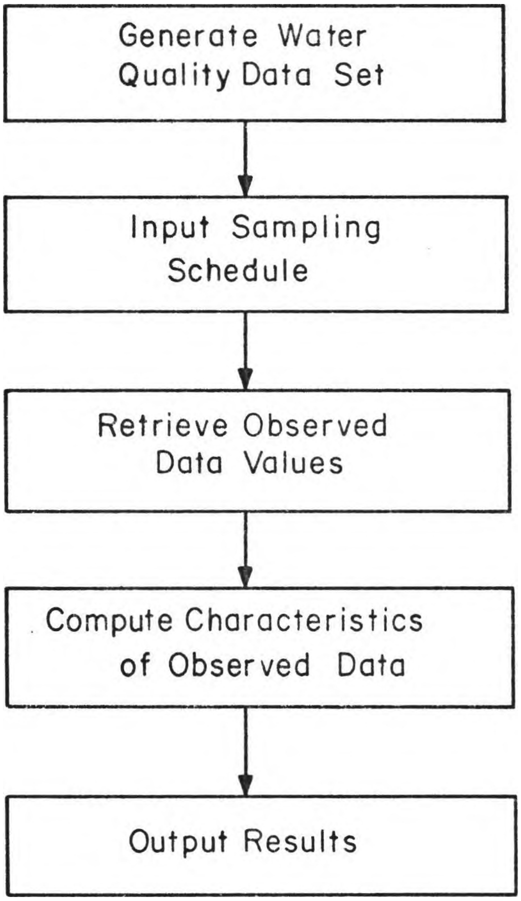

Figure 4. Simplified flow diagram of base level surveillance model.

A brief description of the computation procedure employed by this program is as follows. A hypothetical historical data set for a desired parameter is generated for a sampling location. For example, this data set could consist of weekly observations for ten years of a particular water quality parameter. The known data characteristics could include annual means, a cyclic seasonal variation and a random normal error term with a specified standard deviation. A proposed sampling schedule is read into the program for evaluation. Data values and the sampling schedule have time subscripts so that a sample taken at any time will fall on a single data value, or between two values. An observed data value is obtained either by interpolation or by direct reading, if sampling and data time correspond. These observed values are retained and the characteristics of the observed data compared to the characteristics of the hypothetical data. By varying sampling frequency, it is possible to estimate a frequency which will result in data of accuracy predictable by confidence intervals.

Data obtained from this model are compared to that predicted by the previously described statistical approach. While it is realized that many trials should be made to obtain values that are statistically valid, it is felt that the model data serves as a useful illustration of what may be happening in an actual situation.

Chapter 4

RESULTS

Detection of Pollution Events

The model used for estimating the detection of pollution events is described in the previous chapter. This section summarizes the results of the analysis of the data obtained from the model. The term "pollution event" is used throughout this study to refer to any significant short term quality variation resulting from any cause. The predicted values should not be taken as absolute, but rather as relative for comparison of various sampling combinations. Sensitivity analyses are included to indicate the effect of changing some variables on the model solution. Physical situations are different in every case, however, and these cannot possibly all be considered.

Number of Samples

Initially, data were generated to evaluate the effect of the number of samples taken on pollution event detection. Stream reach lengths of 20 and 100 miles were selected and a single sampling point was specified at the downstream end of the reach under consideration. Spill location was completely random along the entire reach and time of occurrence random in the range 0 to 30 days. A random spill duration from 0 to 3 days was used. A random 0 to 3 day pollution event was felt to exemplify most of the common events that occur. Sampling times were uniformly spaced over the 30 day period and the number of samples varied from 2 to 30. Due to the very low detection level resulting from a sampling frequency of twice monthly, it was not felt that inclusion of data for a sampling frequency of once monthly would be worthwhile. The results of this trial are shown in Table 1. As explained in the chapter on procedures, the total number of samples can also be described as the total number of chances to detect each pollution event. The data indicates that detection probability, the dependent variable, is proportional to the number of samples taken. This is illustrated graphically in Fig. 5. However, the relationship is obviously not linear. Since a random spill duration is used, a certain number of short duration spills will remain undetected until the time interval between samples is smaller than the detection interval of the smallest spills. This accounts for the decreasing change in detection with change in sampling frequency. To obtain a detection level of 100 percent under these conditions would require a very high sampling frequency. The use of grab sampling as a routine monitoring method would probably not be feasible if detection levels near 100 percent were necessary.

The difference in detection between the two situations considered is very slight, indicating that spacing of

Table 1. Effect of sampling frequency on detection probability.

	Run										
	1	2	3	4	5	6	7	8	9	10	11
Total Number of Samples per Month	2	4	8	12	16	20	25	30	50	75	100
Total Number of Events Tested per Month	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Average Detection, Per Cent											
Case 1*	6.2	16.7	39.2	52.1	60.0	71.3	75.1	83.9	92.8	95.2	97.8
Case 2+	7.6	17.1	37.8	56.5	63.4	72.5	77.5	80.1	90.9	94.5	97.2

*Case 1 - one station at lower end of 100 mile reach

+Case 2 - one station at lower end of 20 mile reach

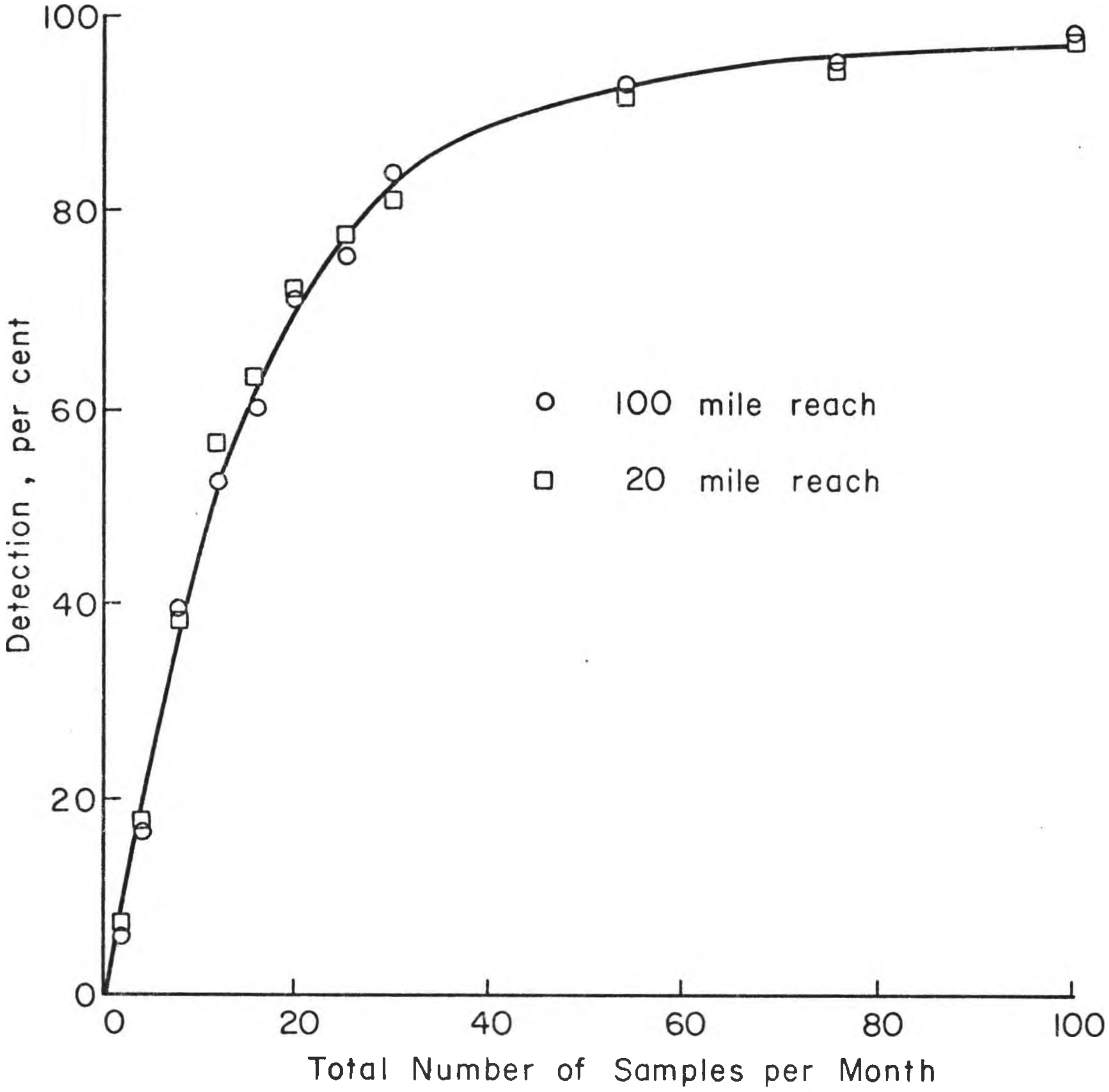

Figure 5. Relationship between sampling frequency and detection probability for one station at lower end of reach with 0-3 day random spill duration.

stations has little effect. This is probably not entirely correct, since a station must be located within a reasonable distance of a pollution source to prevent dispersion, dilution, or other activity from rendering an event unrecognizable. Since the model assumes a conservative pollutant and no dilution effects, it is unable to account for attenuation from these causes.

Using only the model solutions, it would be possible to establish distances where detection starts to decrease and where detection is impossible due to flattening of the dispersion curves. The results indicate that these points were not reached by the distances considered in the trial just described. Two additional tests were made with events originating along the upper 20 miles of the reach and a single sampling station at 500 miles downstream for one test and 1000 miles downstream for the other. Detection for the sampling frequencies tested was slightly higher for the 500 mile station than for the 20 mile and 100 mile stations as shown in Fig. 5. No events were detected at the 1000 mile station, indicating that the points of detection decrease and disappearance occur between 500 and 1000 miles. Since, even in 500 miles, factors not considered in the model, such as tributary inflow, become too significant to ignore, more detailed analysis was not conducted on this point.

Location and Frequency of Sampling with Constant Number of Samples

The next investigation was undertaken to evaluate the effect of varying the number of sampling stations and sampling frequency, while holding the total number of samples constant. The stream reach under consideration was set at 100 miles and the spill characteristics were the same as in the previous section. In this case, however, the number of sampling stations and the sampling frequency at each station were varied to hold the total number of samples constant at 12 and 24 per month. From the plot in Fig. 5, detection values of around 50% and 80% respectively should be achieved for sampling frequencies of 12 and 24 per month.

Sample locations were uniformly spaced along the 100 mile reach. For example, when 4 stations are specified, they were located at 25, 50, 75 and 100 miles. Where only one station location was used, it was specified at the lower end of the 100 mile reach. Sampling times were selected at uniform time intervals over a 30 day period. The very last sampling times at the lower end of the reach were selected to allow for the travel time required for a pollution event occurring at the upstream end of the reach. This procedure was used to prevent events from going undetected in the model due to use of a finite time period. The data output from this evaluation is listed in Table 2.

Table 2. Effect of sampling frequency and number of stations on detection using total surveillance programs of 12 and 24 samples per month.

	Run											
	1	2	3	4	5	6	7	8	9	10	11	12
Number of Sampling Stations	12	6	4	3	2	1	24	12	6	4	2	1
Number of Samples per Station per Month	1	2	3	4	6	12	1	2	4	6	12	24
Total Number of Samples per Month	12	12	12	12	12	12	24	24	24	24	24	24
Total Number of Events Tested per Month	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Average Detection, Per Cent	30.4	32.9	30.6	31.8	38.0	55.1	43.5	45.8	44.3	50.5	69.7	81.6

The plots in Fig. 6, which were developed from the data in Table 2, illustrate that there is some effect on detection due to the combination of sampling locations and frequency. The dependent variable, detection, increases almost linearly as the number of samples per station were increased. An analysis of variance for the calculated regression lines has been included in Tables 3 and 4. The fitted lines are only valid in the ranges of 1 to 12 and 1 to 24 samples per station as no sampling frequencies outside these ranges were considered. Initially, a mathematical model of the form

$$Y = b_0 + b_1X + b_2X^2 + b_3X^3 + e \quad ....(7)$$

was assumed for both lines. In Equation 7, Y is detection, X is the number of samples per station, b values are the regression coefficients, and e is a random error term. The combined improvement in terms of sums of squares due to quadratic and cubic effects after removal of first order linear contribution was used to test the null hypothesis H_0: $b_2 = b_3 = 0$. This F value was not significant at the 0.05 level for either line and the null hypothesis was not rejected. The F value for first order linear contribution was significant at the 0.01 level for both lines, so a null hypothesis of H_0: $b_1 = 0$ is rejected. The first order model

$$Y = b_0 + b_1X + e \quad ....(8)$$

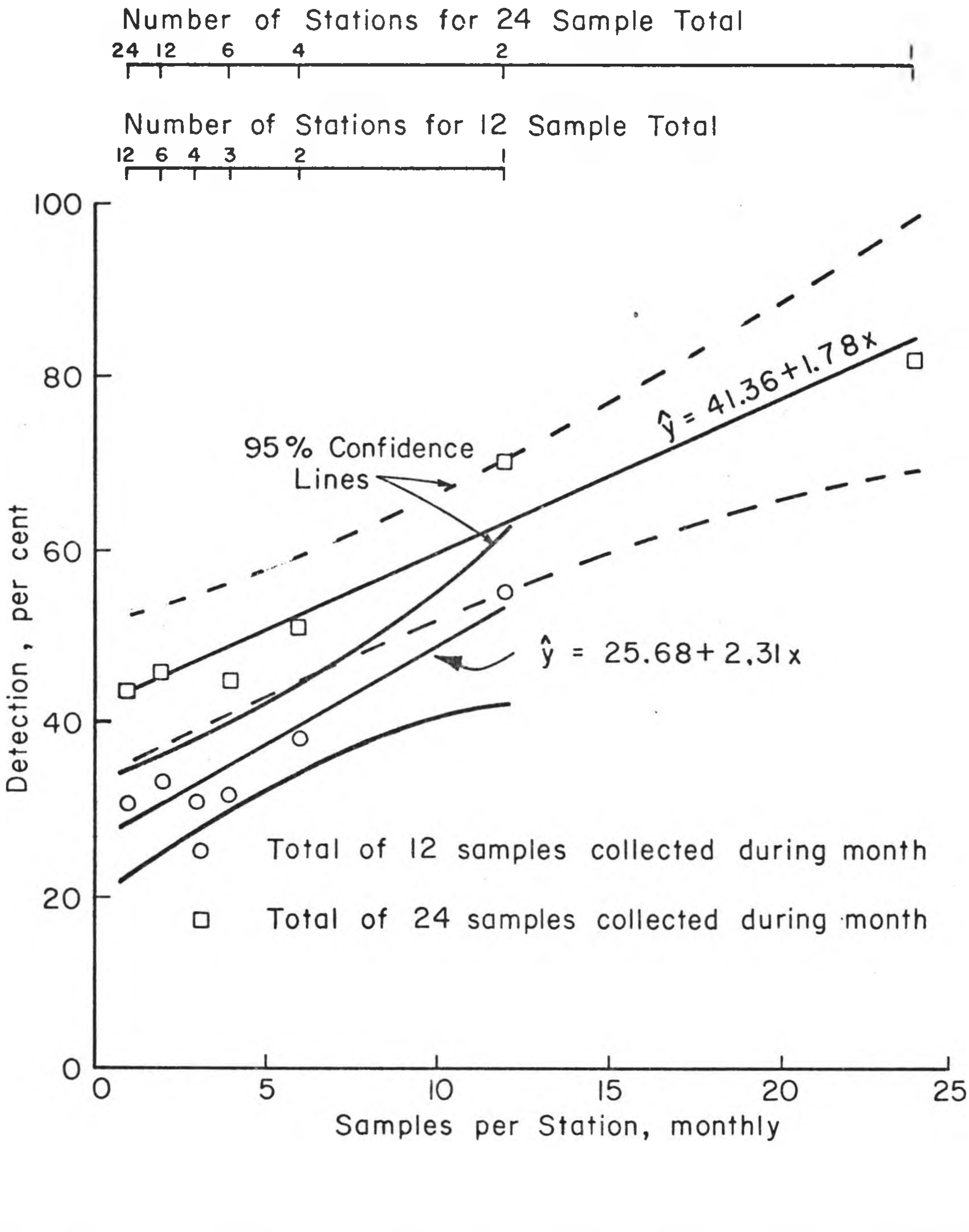

Figure 6. Pollution event detection using monthly programs of 12 and 24 samples collected along 100 mile reach.

Table 3. Analysis of variance for regression of effects of sampling frequency and number of stations with total of 12 samples collected during month.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Total	5	455.27		
First Order	1	423.67	423.67	122.45**
Quadratic and Cubic	2	24.69	12.35	3.57
Deviations	2	6.91	3.46	

**significant at 0.01 level

Table 4. Analysis of variance for regression of effects of sampling frequency and number of stations with total of 24 samples collected during month.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Total	5	1270.42		
First Order	1	1194.80	1194.80	382.95**
Quadratic and Cubic	2	69.42	34.71	11.13
Deviations	2	6.24	3.12	

**significant at 0.01 level

was then used for both regression lines. The equations for the predicted values of detection $(\hat{Y})$ are shown in Fig. 6.

The 95% confidence bands for the mean value of Y for a given value of sampling frequency, X, were calculated using the expression

$$\hat{Y} - \sqrt{2F(2, \text{error d.f.})}\ S\hat{Y} \leq \mu \leq$$
$$\leq \hat{Y} + \sqrt{2F(2, \text{error d.f.})}\ S\hat{Y} \qquad \text{.....(9)}$$

In this equation, $S\hat{Y}$ is the estimated standard error of $\hat{Y}$, μ is the mean, and F is a value from the F distribution with degrees of freedom as shown. Equation 9 is the form recommended by Draper and Smith (55) for obtaining a joint confidence region for all the b parameters. These confidence bands have been plotted in Fig. 6.

To explain the effect of station location and sampling frequency, the point of origin of the pollution events must be considered. As the number of stations is reduced, a greater number of samples are taken towards the lower end of the reach. This causes a greater number of events to originate above the sampling points and thus accounts partially for the increase in detection with a decrease in sampling stations. When only one station is used, all events originating along the 100 mile reach will be above the station, since it is located at the lower end of the reach. In addition, when only one station is used, average travel distance by each event before reaching a sampling station is larger, causing wider dispersion curves and longer detection intervals.

The data in this section can be summarized by stating that the highest detection level will be obtained by having a minimum number of sampling points with a maximum sampling frequency. Having a large number of sampling stations would be advantageous in locating the origin of those events that were detected. However, the other disadvantages of having a large number of stations with low sampling frequency outweigh the advantages. The minimum number of sampling points needed must be decided on the basis of location and number of significant pollution sources, among other factors, since it has already been noted that distance from source to sampling point should not be too great.

Spill Duration and Frequency of Sampling

A pollution event may be partially characterized by its duration and, in some instances, knowledge may be available as to spill durations that can be commonly expected. This trial was designed to study the relation of spill duration and sampling frequency to event detection. For this trial, as well as for most of the trials that follow, a stream reach length of 20 miles was used with one sampling station specified at the lower end of the reach. Spill location was allowed to vary randomly throughout the reach and the time of spill occurrence varied within a 0 to 30 day range.

The results obtained from the model for this trial are shown in Figs. 7, 8, and 9. Each plotted point represents the percent of events detected from a total of 1000 events. For example, 1000 events with a spill duration of 24 hours were generated occurring at random times and locations. When a sampling frequency of twice monthly was used, a detection value of 5.9 percent resulted. This process was repeated many times to obtain the plots shown. The scales used on Figs. 7, 8, and 9 do not permit zero duration, or instantaneous spills, to be shown well, so Fig. 10 has been included to show these results. The 100 percent detection point in Figs. 7 and 8 was assumed to exist when spill duration was equal to the time interval between samples. In all cases, this point plotted almost exactly on the observed line.

A first order linear mathematical model of the form given in Equation 8 was assumed for each fitted line in Figs. 6 through 10. The F test for significance of regression was used for each line and in all cases was significant at the 0.01 level.

If information is available as to spill durations that can reasonably be expected in an actual situation, Figs. 7, 8, 9, and 10 can be used to estimate the surveillance schedule necessary for a desired detection level. Again, it must be stressed that these values are approximations for the physical situations used in the model, but they can be useful even considering this limitation.

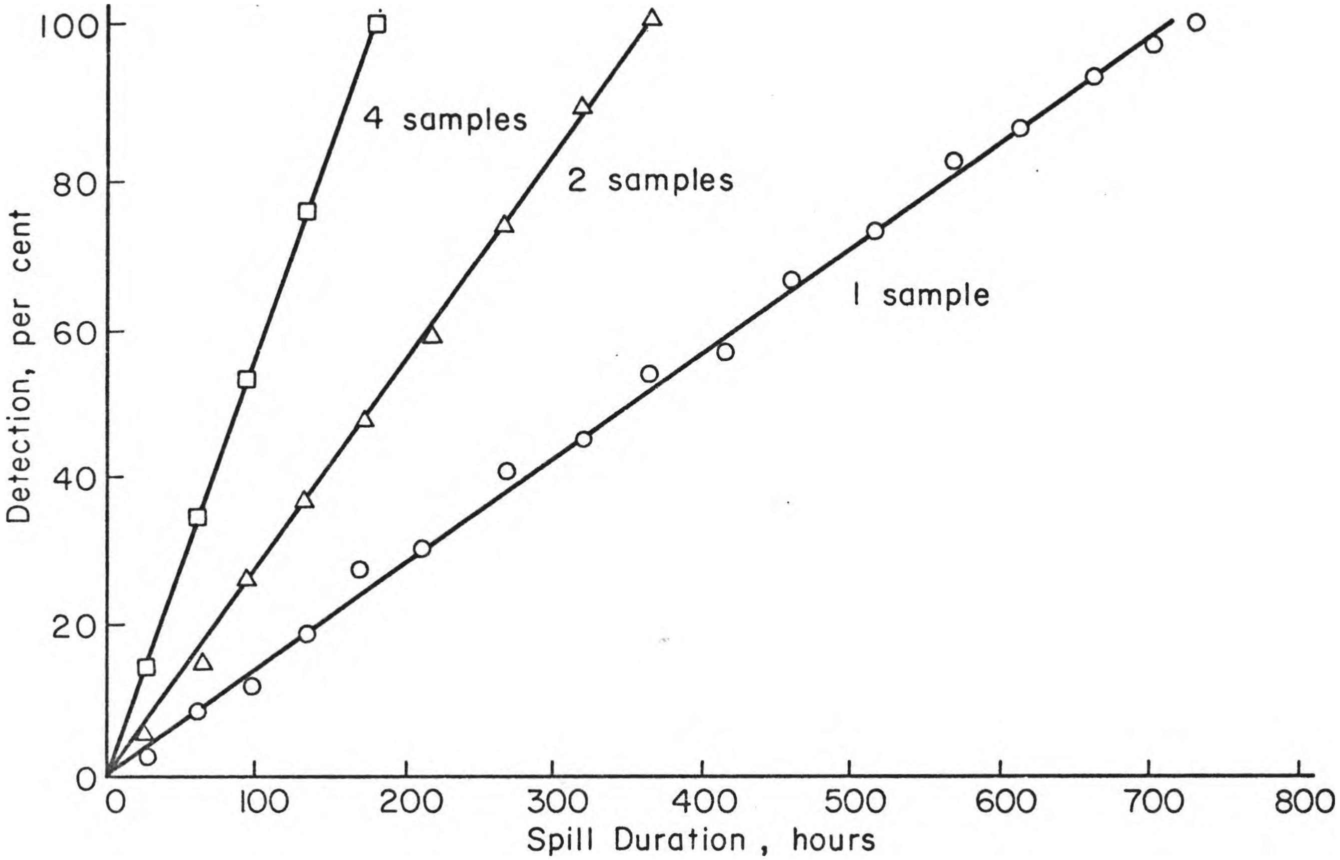

Figure 7. Spill detection by one station at end of 20 mile reach for 1, 2, and 4 samples during 30 day period.

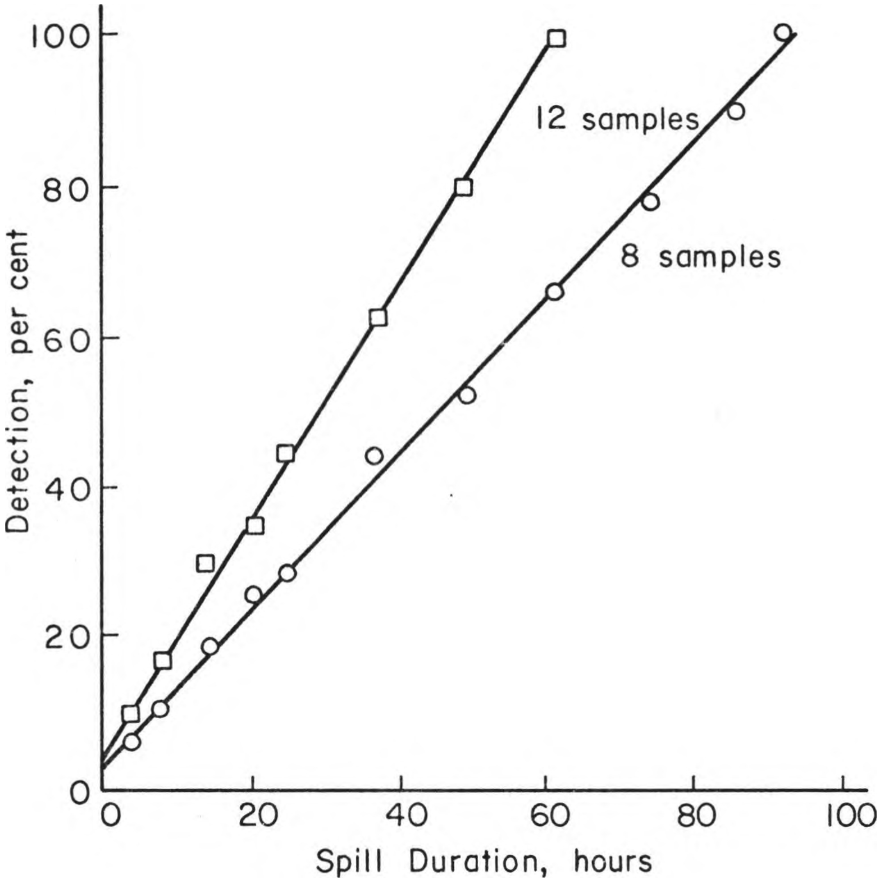

Figure 8. Spill detection by one station at end of 20 mile reach for 8 and 12 samples during 30 day period.

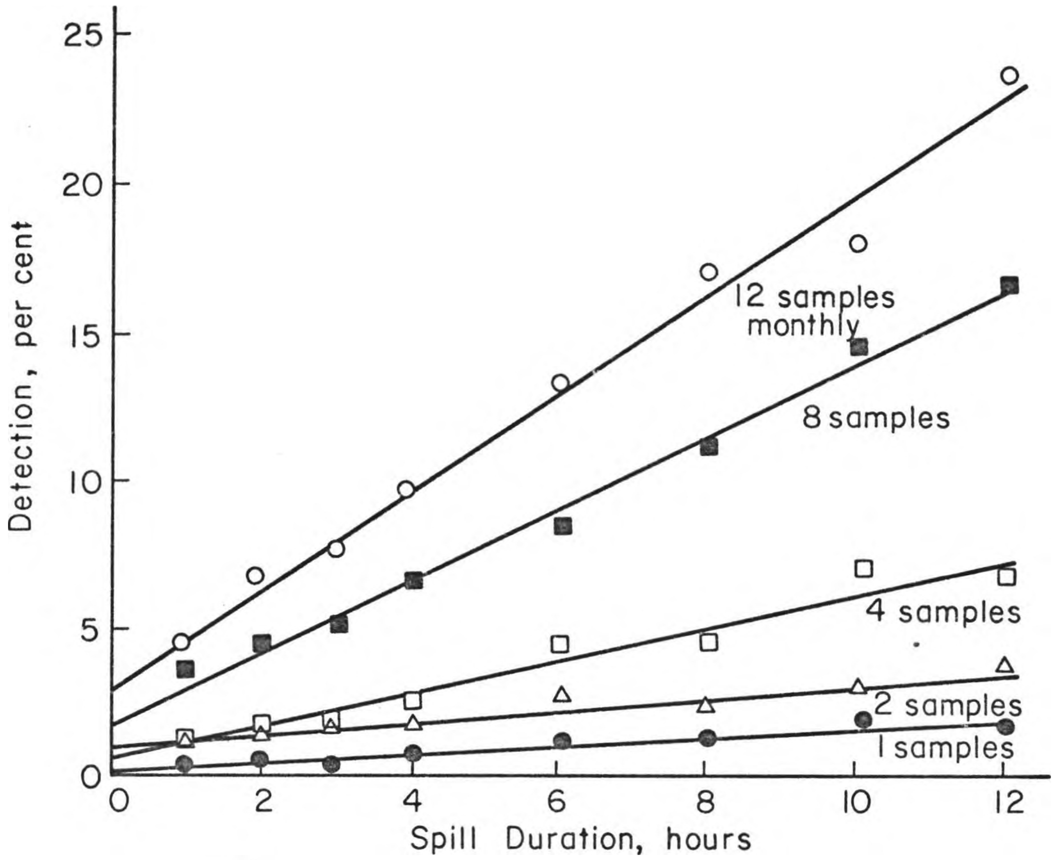

Figure 9. Detection of short duration spills by one station at end of 20 mile reach for 1, 2, 4, 8, and 12 samples during 30 day period.

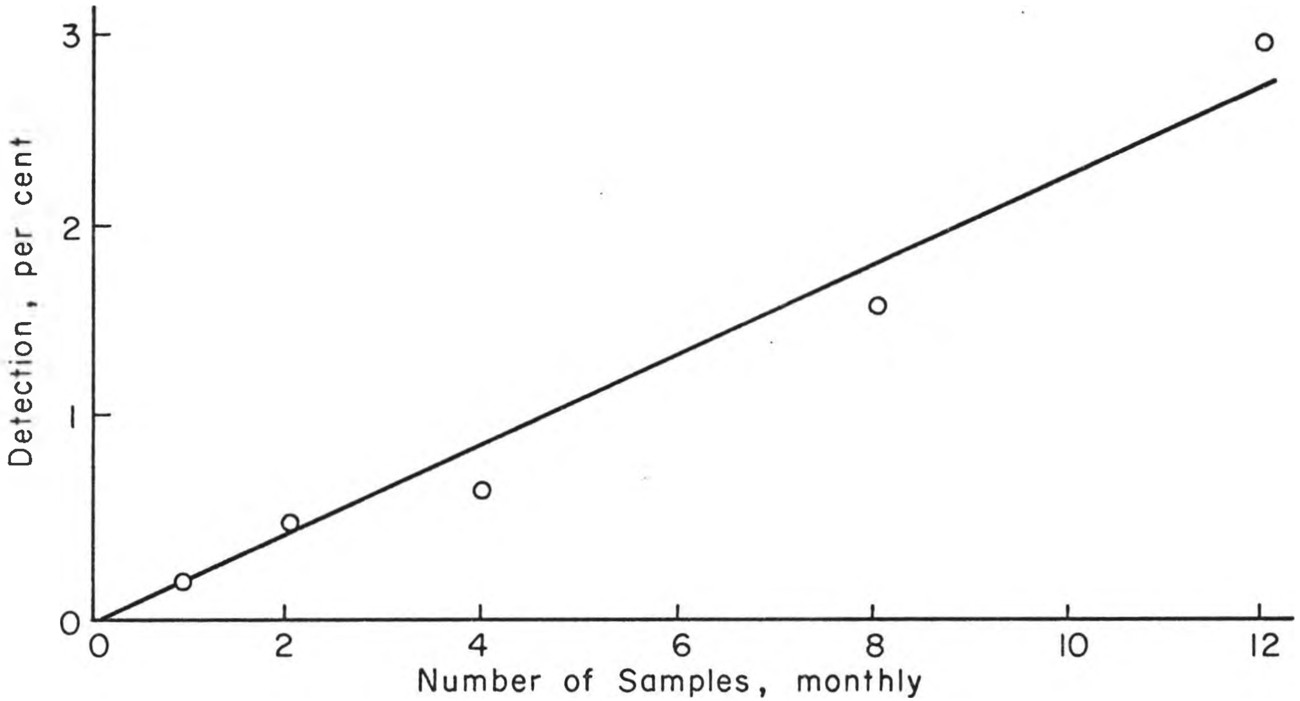

Figure 10. Detection of instantaneous type spills by one station at end of 20 mile reach.

The sensitivity analyses described later in this chapter will elaborate on this point.

Another approach was also used to consider the relation of spill duration and sampling frequency to detection. In this trial, spill duration was allowed to vary randomly in several ranges rather than specified as in the preceding trial. All other factors were the same. The results of the trial are shown in Fig. 11. This plot can be used in the same way as Figs. 7, 8, and 9, but it is not necessary to specify an exact spill duration in this case. If some knowledge of the range of spill durations to be expected is available, a detection level can be estimated. The results in Fig. 11 indicate, as did Fig. 5, that there is a decreasing rate of information return as sampling frequency increases. This is due to the very short, or instantaneous, type spills which will not be detected unless the time between samples is very low, i.e., in terms of minutes or hours instead of days.

Multiple Sampling Stations

With the exception of the section discussing detection with a constant number of samples, all results presented so far have been for situations in which a single sampling point was used. Since multiple sampling points will be necessary or desirable for most streams, these results must be adapted to apply in situations where two or more stations are used. The fact that detection effectiveness decreases

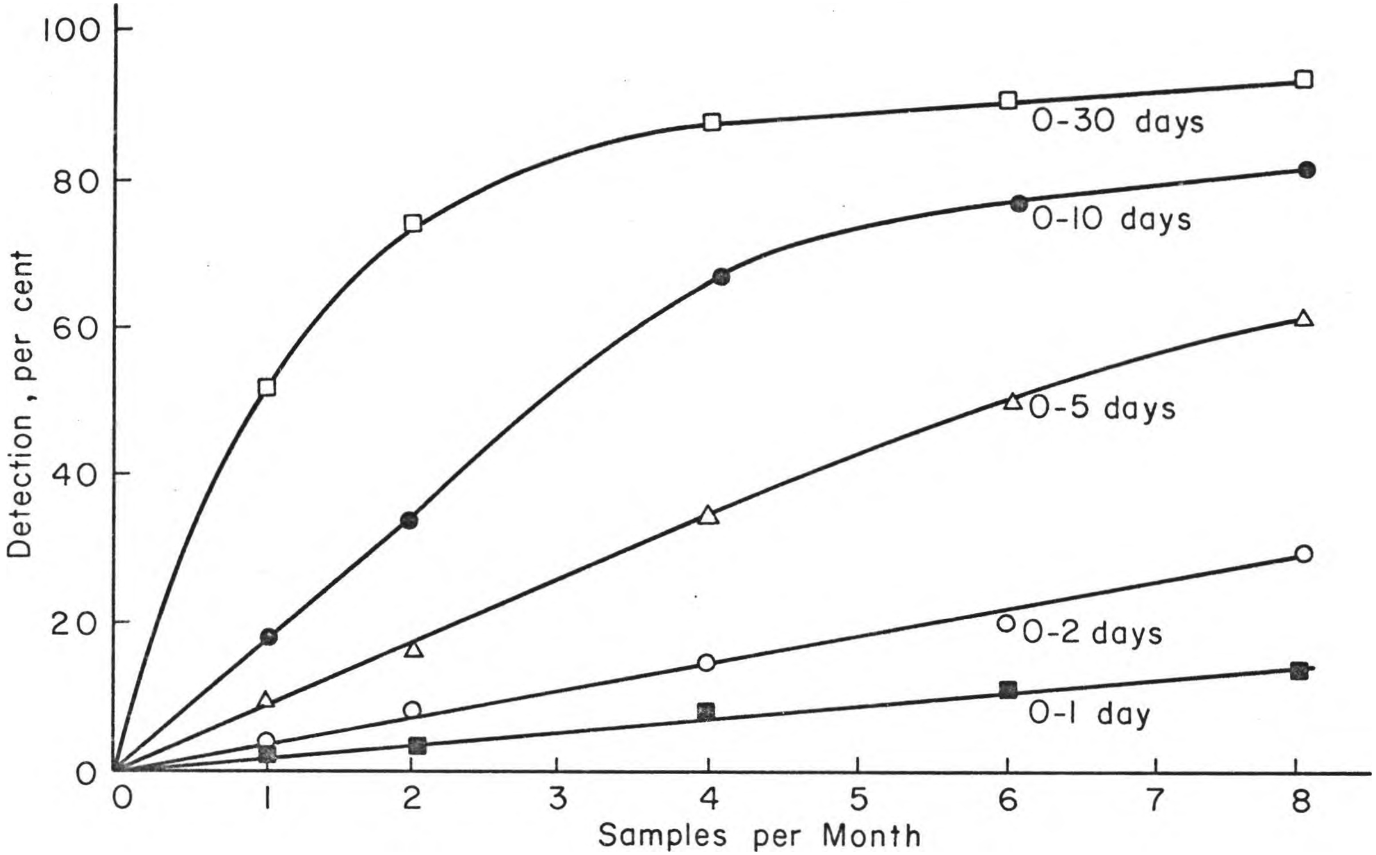

Figure 11. Detection of random duration spills by one station at end of 20 mile reach.

as the number of sampling points increases with a constant total number of samples was pointed out previously. However, if sampling points are increased with a corresponding increase in total number of samples, an increase in detection would be expected. This relation would not be linear, however, since the relation of detection to total number of samples was not linear when random spill durations were used (Fig. 5).

Since all results presented are on a per stream basis, this basis must still be used when considering multiple sampling stations. The predicted detection levels for a stream must be modified according to the number of stations used and to the total number of samples taken. Due to non-linearity of the relationships involved, direct addition or multiplication of predicted detection values as station numbers increase is not possible. For example, if one station sampled twice monthly should result in a 5% detection level, 4 stations sampled twice monthly will not result in a detection level of 20%. Each station as one moves downstream is a little more effective than the one just above it since the probability of more spills occurring above the downstream station is greater.

For the case where events originate randomly at any point along a reach, Fig. 6 indicates that the highest detection value occurs when one station (within a reasonable distance of the pollution sources) is sampled very frequently. This arrangement is assumed to have the peak effectiveness that can be expected. At this point, it is necessary to coin a term referring to the relative effectiveness of a system as compared to the ideal situation. This term is the "relative effectiveness factor" (REF).

For the situation with peak effectiveness, a value of 1.0 will be assigned to the REF and for all other situations it will be less than 1.0.

The results shown in Fig. 6 were used to compute REF values, which have been plotted in Fig. 12. These REF values are simply ratios of the detection level corresponding with the number of stations to the peak detection level, which is the detection probability for a single station. Fig. 12 can be used in conjunction with Fig. 5 to estimate the detection for a multi-station network along a given stream. The equation of the predicted REF value ($\hat{Y}$) in relation to the number of sampling stations (X) is given in the figure. In addition, 95% confidence bands were calculated for the prediction line using Equation 9 and have been plotted in Fig. 12.

The following examples are presented to illustrate the procedures involved. In each example, it is assumed that a minimum number of sampling points to adequately monitor a stream can be selected.

For the first example, a hypothetical stream is assumed for which six sampling points are deemed necessary. For a sampling frequency of twice monthly per station, it is desired to estimate the detection level to be expected.

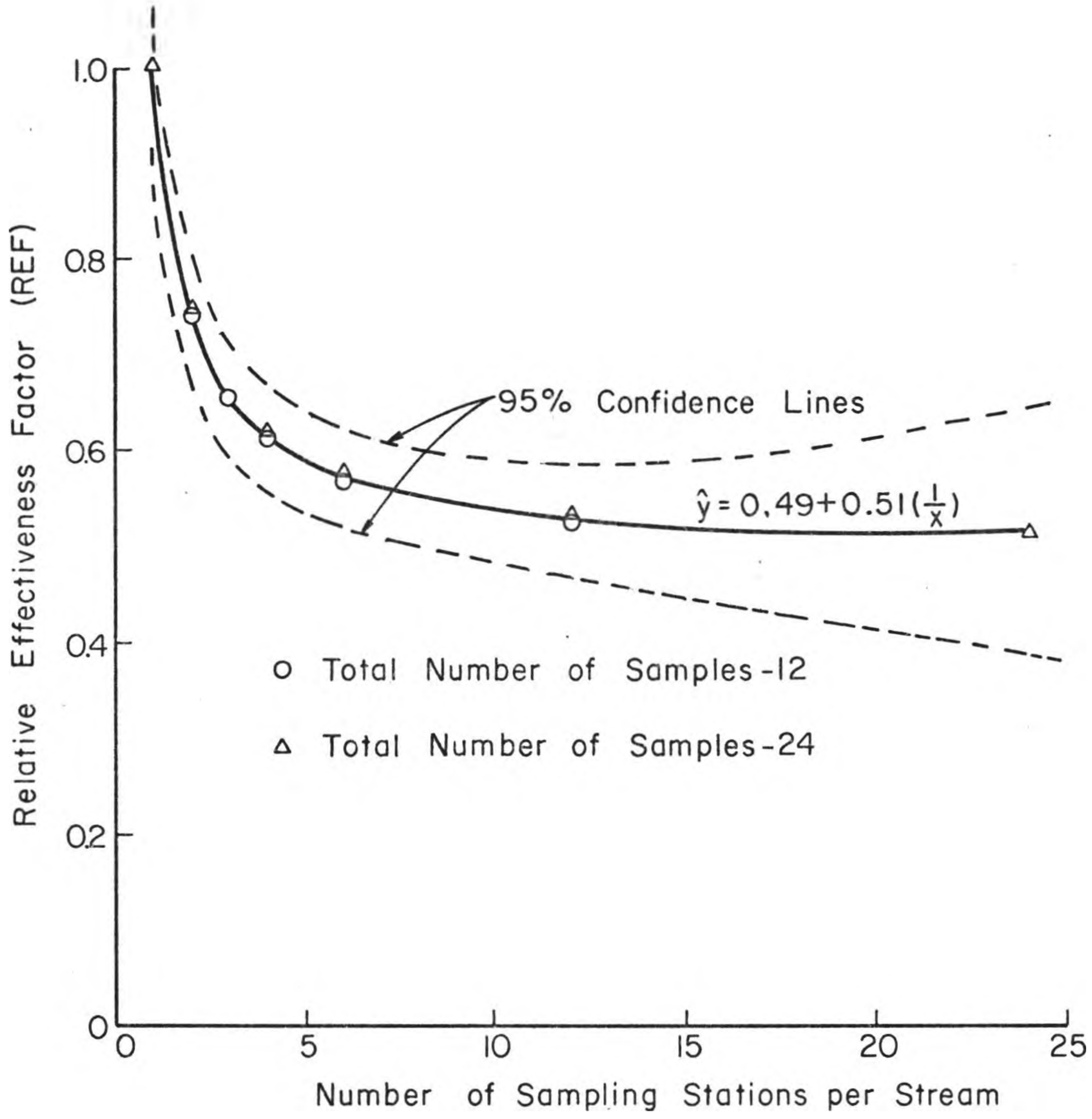

Figure 12. Relative effectiveness factor in relation to number of sampling stations per stream.

From Fig. 5, for a total of 12 samples monthly, a detection level of about 52% could be expected. However, Fig. 5 is based on the ideal situation of one station and 12 samples per month at that station. For this particular example, the detection level for 1 station, with 12 samples collected each month, can also be obtained from Fig. 6. Since 6 stations are used in this example, the effectiveness of each station is reduced and the 52% detection value must be modified accordingly. From Fig. 12, an REF value of about 0.58 is read for 6 stations. Multiplying 52% by the REF value of 0.58 results in an estimated detection level for the proposed system of about 30% for spills in the 0-3 day random duration range. This same result can be obtained from Fig. 6 by reading the detection level for a frequency of 2 samples per station. If spills of durations different than these were expected, this detection value would have to be further modified using Figs. 7 through 11 as guidelines.

Approaching the same situation from a different viewpoint, in the second example it is desired to estimate how often the 6 designated stations should be sampled to obtain an approximate detection level of 50% for 0-3 day random duration spills. Since the REF value again is 0.58, the desired 50% detection value must be divided by 0.58, resulting in a value of 89%. Entering Fig. 5 with a 89% detection value, it is found that about 45 samples monthly are necessary. Each of the 6 stations should be sampled almost 8 times monthly to obtain the desired detection level. A comparison of the two examples shows that it was necessary to quadruple the sampling frequency to increase detection from 30% to 50%.

When desirable to estimate sampling requirements on a statewide basis, the problem must still be approached stream-by-stream. For example, assume that a state has 8 major streams that must be monitored. Table 5 lists the streams and number of sampling stations on each stream for this hypothetical example. A 50% detection level is desired. Using the same procedures as in the two previous examples, the number of samples per stream per month is calculated. From the totals, it is seen that 168 samples monthly are needed from 20 stations. This averages to 8.4 samples per station monthly. On a statewide basis, then, about 8.4 samples monthly per station are needed to achieve a detection level of about 50%. Obviously, some streams will be above and some below the desired level if an average figure such as this is used. However, those streams with a large number of stations will have the highest detection levels and this may not be undesirable, since they are likely the streams experiencing the most serious water quality problems. If actual monitoring schedules are established on a stream-by-stream basis, the overall average should still be useful in fiscal and work load planning.

Table 5. Hypothetical example of required statewide sampling frequency for 50% detection level for pollution events.

Stream	No. of Sampling Stations	Absolute Detection Desired, per cent	REF (Fig. 12)	Required Single Station Detection Level, per cent (50%/REF)	Total Samples Per Month (Fig. 5)
1	2	50	0.74	67.5	20
2	1	50	1.0	50.0	12
3	4	50	0.62	80.6	27
4	4	50	0.61	80.6	27
5	3	50	0.66	75.7	25
6	1	50	1.0	50.0	12
7	2	50	0.74	67.5	20
8	3	50	0.66	75.7	25
Total	20				168

A qualifying note on the use of the procedures just presented should be inserted here. Some quick mental arithmetic will show that, if a 75% detection level is desired on a stream with a station combination resulting in a 0.7 REF value, the absolute detection level necessary for a single station would be greater than 100%. A contradiction seems to exist, since even a 100% detection level is essentially impossible to attain. Actually, this example points out a limitation of the evaluation method and also reflects on the limitations of grab sampling itself for use in detection of pollution events.

To consider the limitations on the use of the method proposed, note that it was earlier stated that a stream-by-stream approach must be used. If all streams or tributaries in a system are considered together, the combined total number of sampling stations may result in an unrealistic REF value. For this reason, each stream and tributary must be considered separately. In addition, the use of a certain amount of judgment is necessary if it is obvious that unrealistic REF values are obtained by use of this approach.

The other point to be made is that high detection levels require very high sampling frequencies. These high sampling frequencies may not be practical using grab sampling techniques and the evaluation procedures proposed may not be applicable for very high detection levels. However, when used along with good judgment, as noted in the previous paragraph, these procedures can aid in the planning and evaluation of water quality surveillance systems.

Sensitivity Tests for Detection Model

The series of trials described in the remainder of this section were designed to evaluate the effects on the model solution by changing some of the parameters for which arbitrary values were chosen. The parameters tested were stream velocity, channel geometry, and quantity of pollutant discharged. The main effect of varying these quantities is to change the shape of the calculated dispersion curve, thereby changing the length of the detection interval. As explained in the previous chapter, this effect becomes relatively less important as spill duration increases. For this reason, the tests were made using fairly short spill durations where the effects would be more pronounced. In all tests, a 20 mile reach with one sampling station sampled twice monthly at the lower end was used.

Stream velocity. The effect of varying stream velocity on the model solution was tested in two ways. In one test, the streamflow, Q, was allowed to vary proportionally to stream velocity, while the channel cross section was held constant. In the other test, the streamflow was held constant and the cross sectional area was varied, along with velocity. Spills of the instantaneous type and of

24 hour duration were used. The results of these tests are shown in Fig. 13 with the solid line representing the run using a constant cross-sectional area and the dashed line for the constant streamflow run. The standard flow velocity used throughout the remainder of the study was 2 fps (feet per second).

As the velocity was increased, it was anticipated that detection would decrease for both tests. This is borne out by the results shown in Fig. 13. In the case of the constant cross-sectional area, this decrease can be attributed to the increased pollutant dilution accompanying the increase in streamflow. This causes a greater portion of the dispersion curve to lie below the established minimum detectable level and thus shortens the detection interval. In extreme cases, the entire curve may lie below the detectable level, allowing no chance of detection.

When the streamflow is held constant and the velocity increased, the effect upon detection is the same as increasing streamflow due to the increase in dispersion. As more dispersion occurs, even though the dispersion curve is widened, the curve also flattens and after a certain time, less of the curve will fall above the detectable limit and the detection interval decreases. For the instantaneous type spill (Fig. 13), it is seen that the detection approaches zero as the velocity increases for both tests, indicating that dispersion and dilution

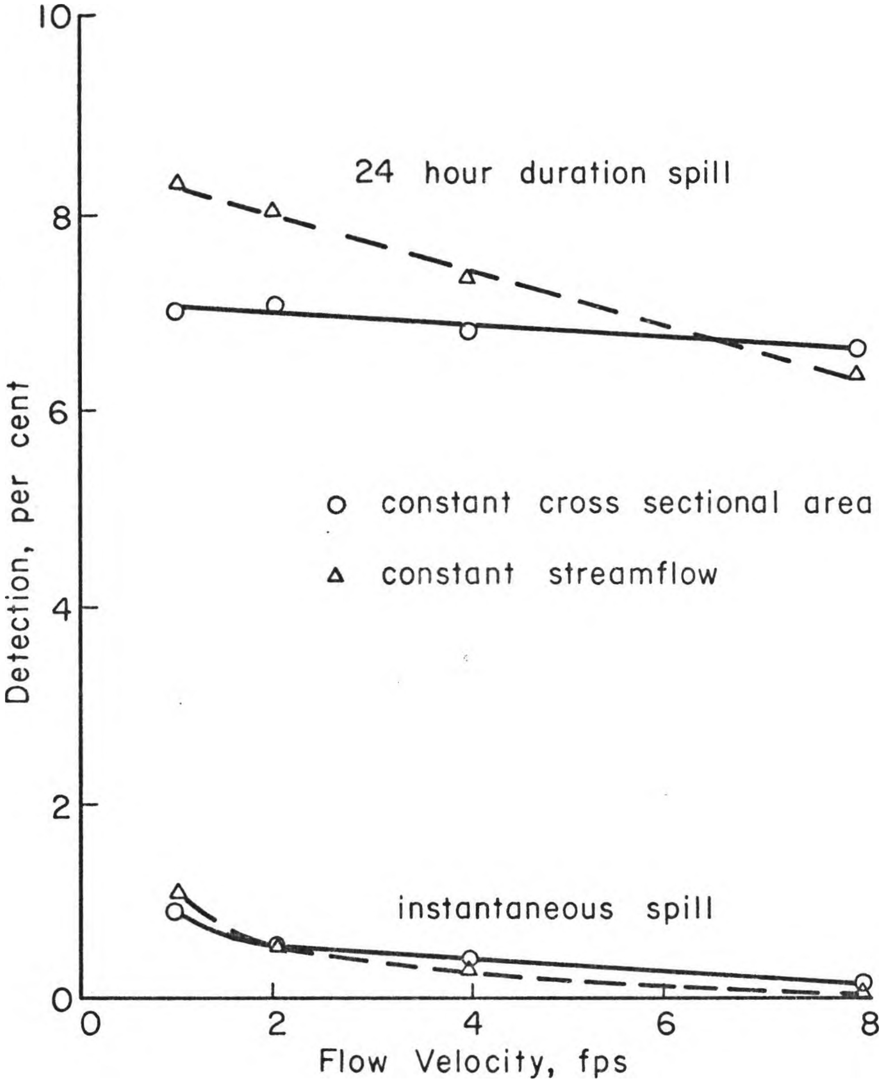

Figure 13. Effect of flow velocity on detection for one station at end of 20 mile reach sampled twice monthly.

effects have flattened the curve almost to a degree where no detection is possible.

Quantity of pollutant. An arbitrary value of 1000 lb was used in the computation procedures for the previous trials described in this study. Early trials indicated that this was about the minimum quantity of pollutant which would produce adequate dispersion curves over the distances under consideration. In this trial, the quantity of pollutant was varied to test its effects upon the model solution. The results of the trial shown in Fig. 14 indicate that the magnitude of this quantity is not critical to the solution. As long as the value used in the model computations is sufficient to produce an adequate dispersion curve, the actual value has little effect.

Channel geometry. In this test, the cross-sectional flow area and the velocity of flow were held constant. The shape of the cross section was changed to vary the hydraulic radius, which is used in computing the longitudinal diffusion coefficient. An average depth of 1.5 feet and an average width of 200 feet were used in the other trials. In this trial, the depth was increased in 1.5 foot steps and the width correspondingly decreased to keep a constant area. The results are shown in Fig. 15 with detection plotted as a function of hydraulic radius. The hydraulic radius of 1.48 corresponds to the standard shape used in the model, while the increasing values of hydraulic radius correspond to increasing flow depths. Hydraulic

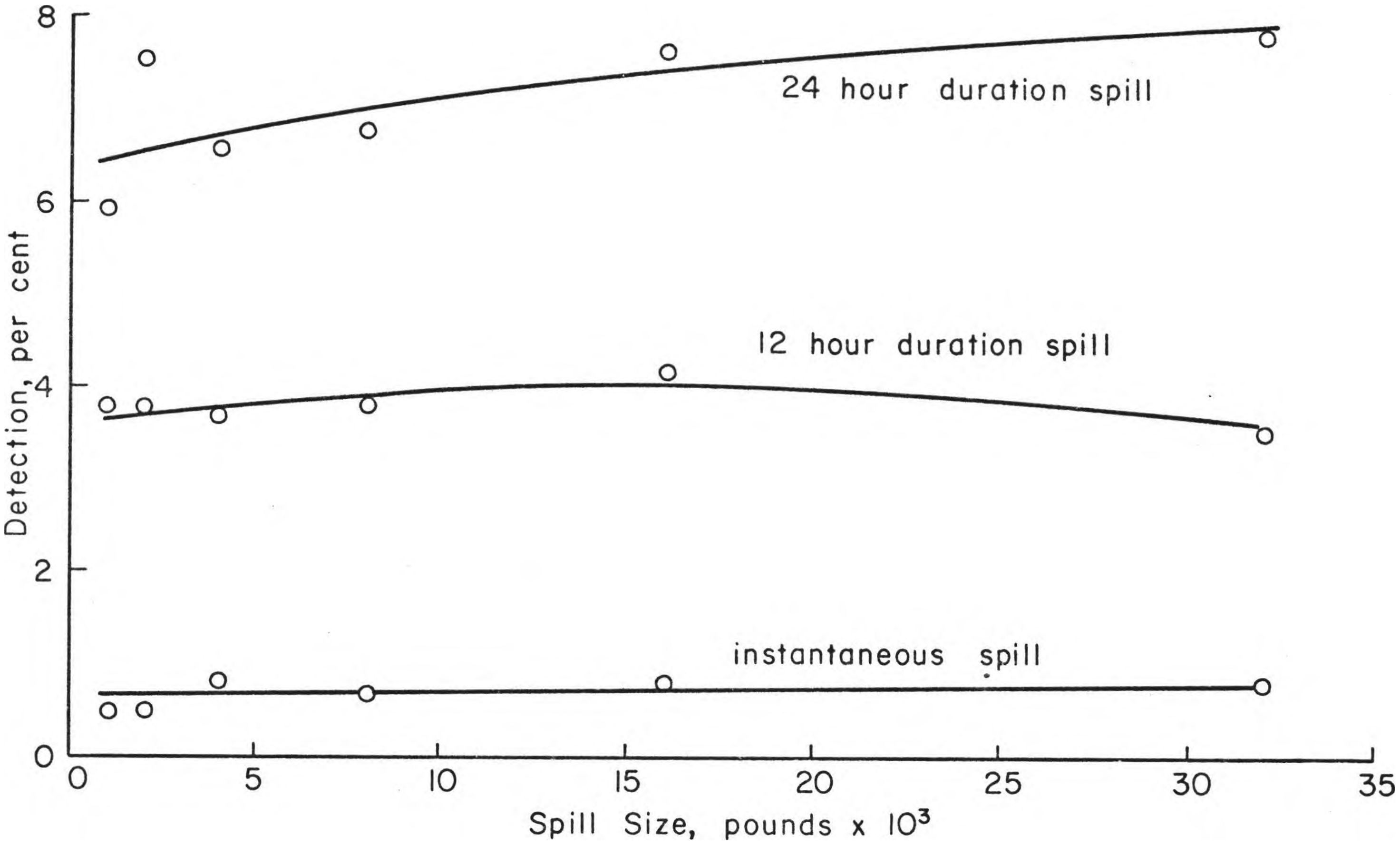

Figure 14. Effect of spill size on detection for one station at end of 20 mile reach sampled twice monthly.

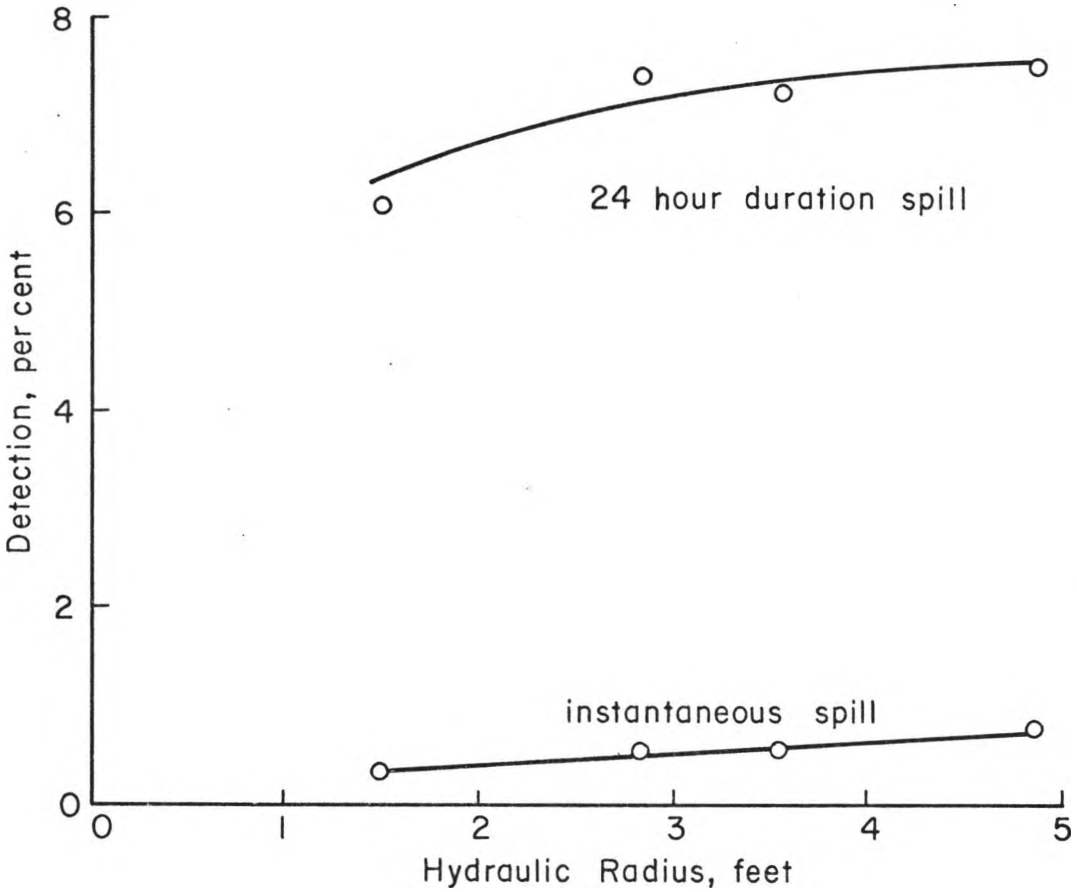

Figure 15. Effect of channel geometry on detection for one station at end of 20 mile reach sampled twice monthly.

radius values of less than 1.48 were not considered, since smaller values are unlikely to occur in natural streams of significant size.

These results indicate a general trend of increased detection with increased hydraulic radius. The increased detection is more pronounced for the 24 hour spill duration as compared with instantaneous spills.

Summary of sensitivity tests. The tests just described were performed to check the model solution sensitivity to the selection of various physical characteristics. The results show that the effects are varied, with both increased and decreased detection resulting, depending upon the variable changed. In all cases, the change in detection was small, never exceeding a change in detection of 2 percent for the ranges tested. Considering the fact that the model arrives at approximations using random number processes, these effects are relatively small. Also, taking into account the nature of the problem at hand, namely planning water quality surveillance systems, the effects of stream velocity, pollutant load, and channel geometry are minor in comparison with the accuracy of the information that must be used in designing a monitoring network. In view of this, it can be said that the model solutions are fairly insensitive to changes in the characteristic parameters tested and that the effects can be considered negligible unless conditions are significantly different from the ranges tested.

Base Level Quality Surveillance

The results of the study presented to this point have been concerned with the detection of what were termed pollution events or significant short term quality variations. The results described in the following sections of this chapter apply to surveillance for base level or long term type data acquisition.

Statistical Approach

The parameter selected as the representative characteristic for base level quality data was the annual mean. Actually, any time period could have been selected and there is much justification for using seasonal means as a basis for comparison rather than annual means. The methods used in this phase of the study could be applied to any time period, but the annual mean was deemed adequate for example purposes.

Figs. 16, 17, 18, and 19 have been prepared as graphical representations of Equation 6 as presented in the procedures chapter. As in the preceding sections, the results shown do not refer to any specific parameter, but are generalized to permit broad application. Use of the curves requires some knowledge of the variability of the data to be expected. For those situations where

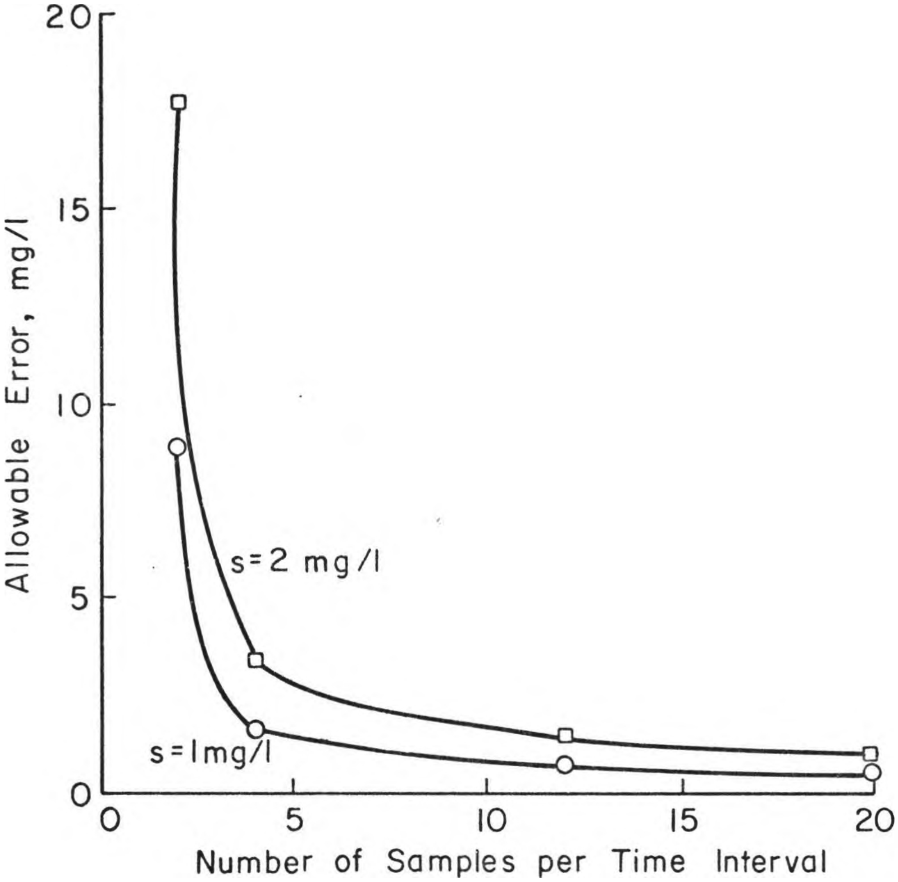

Figure 16. Allowable error in relation to number of samples for populations with standard deviations of 1 and 2.

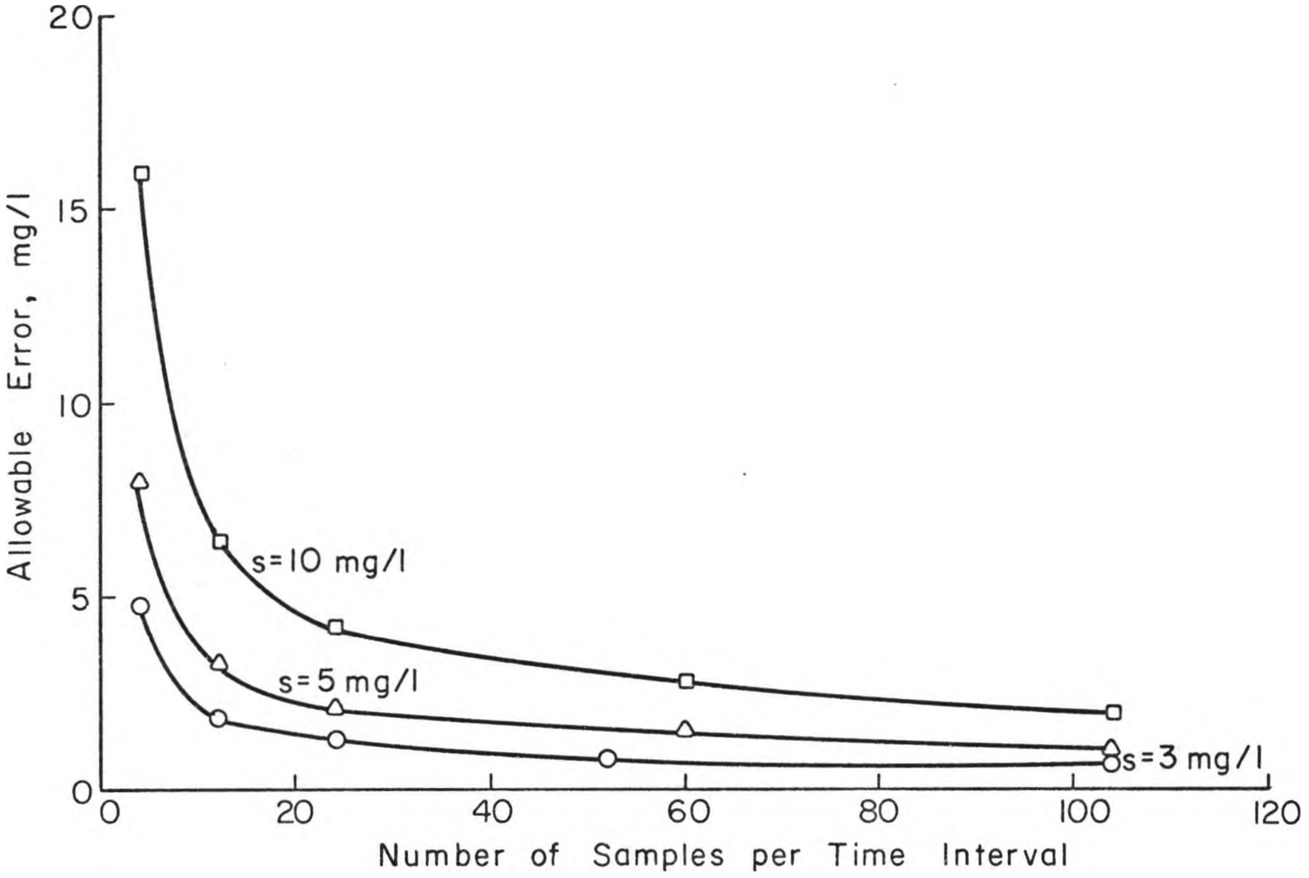

Figure 17. Allowable error in relation to number of samples for populations with standard deviations of 3, 5, and 10.

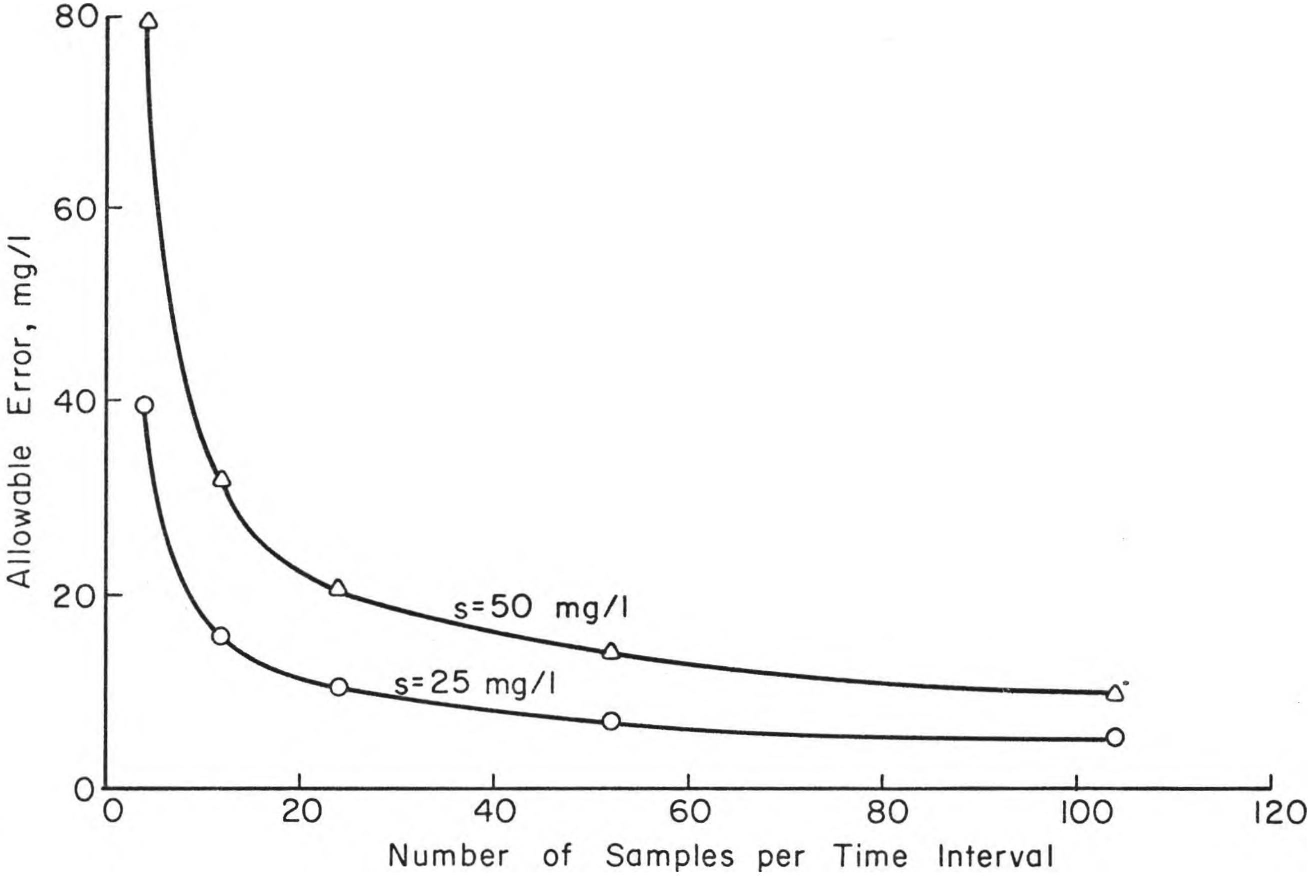

Figure 18. Allowable error in relation to number of samples for populations with standard deviations of 25 and 50.

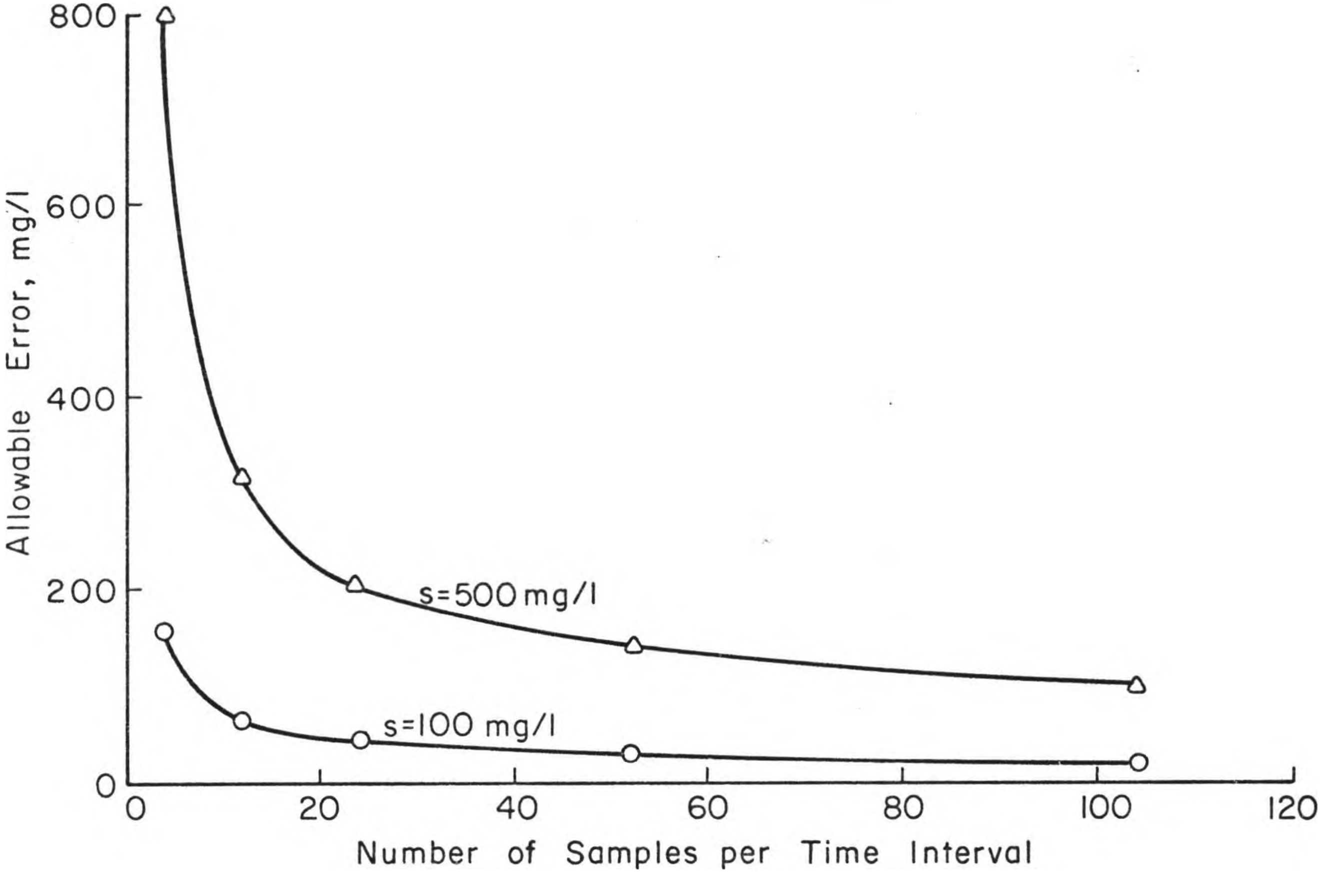

Figure 19. Allowable error in relation to number of samples for populations with standard deviations of 100 and 500.

water quality data are stored in the STORET system, the standard deviation for any parameter is easily obtainable.

The STORET system normally outputs a value for standard deviation with all historical data lumped together. However, if time dependent variation (such as long term trends) is present, the standard deviation obtained may be excessively large, since it contains the time dependent variation. This could result in significant over-prediction of necessary sampling frequencies using the methods presented here. For this reason, if the objective is to estimate sampling frequencies to obtain annual means within desired accuracy limits, the same time interval (i.e., one year) should be used to evaluate the sample standard deviation, S.

Actually, three situations can arise which must be considered when calculating a value for S to use in Figs. 16 through 19. First, if it can be shown that no significant time dependent variation exists, the calculated value for S with all data included can be used. Standard analysis of variance techniques can be used to test differences in observed means to check if time dependent variation is present.

If a time dependent variation does exist, the standard variation may remain the same from year to year, or it may change. This can be checked using Bartlett's test for homogeneity of variance, with a null hypothesis of H_0: $\sigma_1^2 = \sigma_2^2 = \sigma_3^2$. If no significant difference between variances is found, an individual value or direct average can be used to obtain a value for S.

When Bartlett's test indicates significant difference between the annual variances, a pooled variance can be obtained simply by calculating a weighted average with individual variances weighted by their respective degrees of freedom. The pooled variance is then used to estimate an S value for use with the figures.

The procedures just described are all presented by Snedecor and Cochran (36) and in most other texts on statistical methods. They were not used in the hypothetical example to follow in this chapter, but were used in the actual application example presented in Chapter 5.

Knowing the variance or standard deviation for a parameter of concern, the proper curve can be selected from the graphs (Figs. 16, 17, 18, and 19). For a given number of samples, then, a value can be read from the ordinate for the allowable error at a 95 percent confidence level. For that number of samples, an observed mean can be expected to be within the allowable error of the true mean 95 percent of the time. The term "allowable error," as used here, refers to deviation from the true mean in a + or - direction.

At this point, a hypothetical example might aid in use of the figures. Assume a parameter for which the available data shows an annual mean of 50 mg/l and a sample standard deviation, S, of 25 mg/l. The objective is to decide how many observations yearly are necessary to estimate the annual mean within ± 10 mg/l with a 5 percent risk that the error will exceed 10 mg/l. Selecting the appropriate curve (Fig. 18), it is found that 24 observations yearly, or a frequency of 2 samples monthly, is necessary. If the allowable error was raised to 15 mg/l, sampling once monthly would be adequate. Note that it was not necessary to use the value for the mean. The standard deviation is the only data characteristic necessary and the values obtained from the curve are valid if the mean is 50 mg/l 0r 50,000 mg/l. The mean is really only of concern in deciding upon a reasonable value for the allowable error. Here, it should be emphasized that individual observations will commonly exceed the allowable error and that the curves are applicable to the mean of these observations only.

These curves can also be used to evaluate a monitoring system or to evaluate data obtained from a system. Considering the latter, the statement can be made that if an observed mean greatly exceeds the allowable error for the given data and system characteristics, additional observation is desirable. The large deviation may be due to an actual significant change in water quality. Since the annual means are obtained from historical data, deviation for a given year from previous annual means may be due to long term trends. Judgment and additional study, including statistical analyses, would be necessary to determine the cause of the deviation.

To estimate the performance of an established surveillance system or schedule, the figures are entered with the known sampling frequency and standard deviation for the parameter of concern. The allowable error can then be read directly. This allowable error value is an estimate of the accuracy of the system in obtaining mean values for the parameter for the time period.

Model Approach

Using the simulation model for base level surveillance as described in the procedures chapter, data was obtained to further illustrate the statistical approach results. A time period of 1 year was selected and the mean for that period, or the annual mean, was used as a basis of comparison. For each run, a data set was generated consisting of daily values for a total of 10 years. The generated data was random, normally distributed about a specified mean, and had a specified standard deviation. The specified mean of the generated data was shifted each year to simulate a long term trend.

Various sampling schedules were tested to determine their ability to predict the annual mean within the allowable error for the given conditions. Sampling intervals tested were 5, 10, 15, 30, 60, and 90 days. The observed data values were those values of the generated data occurring on a day when sampling was scheduled. For each year an annual mean was calculated from the observed values and compared to the mean of the generated data. For the results shown, the specified mean and standard deviation of the generated data for the first year were 35 mg/l and 3 mg/l respectively. The specified mean was increased by 1 mg/l each year and the standard deviation held constant.

A summary of the results of these tests is listed in Table 6. The specified standard deviation of the population was used to compute the allowable error. The allowable error could also have been read directly from Fig. 17. The deviation of the observed annual means from the true mean of the generated data is compared to the allowable error. The statistical approach stated that we should not exceed the allowable error over 5 percent of the time. As shown in the table, the allowable error was exceeded 3 times in 60 trials, which is exactly 5 percent.

The deviation of the observed from the true mean decreases with increased sampling frequency, as shown in Fig. 20. Although the data shown in this figure is only applicable to the particular situation specified in the model, it does point out the type of relationship to be expected between sampling frequency and accuracy.

Multiple Sampling Stations

For base level surveillance, the results deal only with a single point in space. When considering a system on a stream, each station must still be handled separately when using the figures. The actual number of stations has no overall effect in this situation as it did previously when event detection was the objective. The objective here is to estimate a sampling frequency at each location which will result in data within desired accuracy limits. After this procedure is followed for each station location, the

Table 6. Base level surveillance from model simulation.

Sampling Interval, days	Number of Samples, per year	Standard Deviation of Population	Allowable Error, mg/l	Number of Trials	Number of Times Allowable Error Exceeded
5	73	3.0	0.70	10	0
10	37	3.0	0.99	10	0
15	25	3.0	1.20	10	1
30	13	3.0	1.66	10	1
60	7	3.0	2.27	10	0
90	5	3.0	2.68	10	1
			Total	60	3

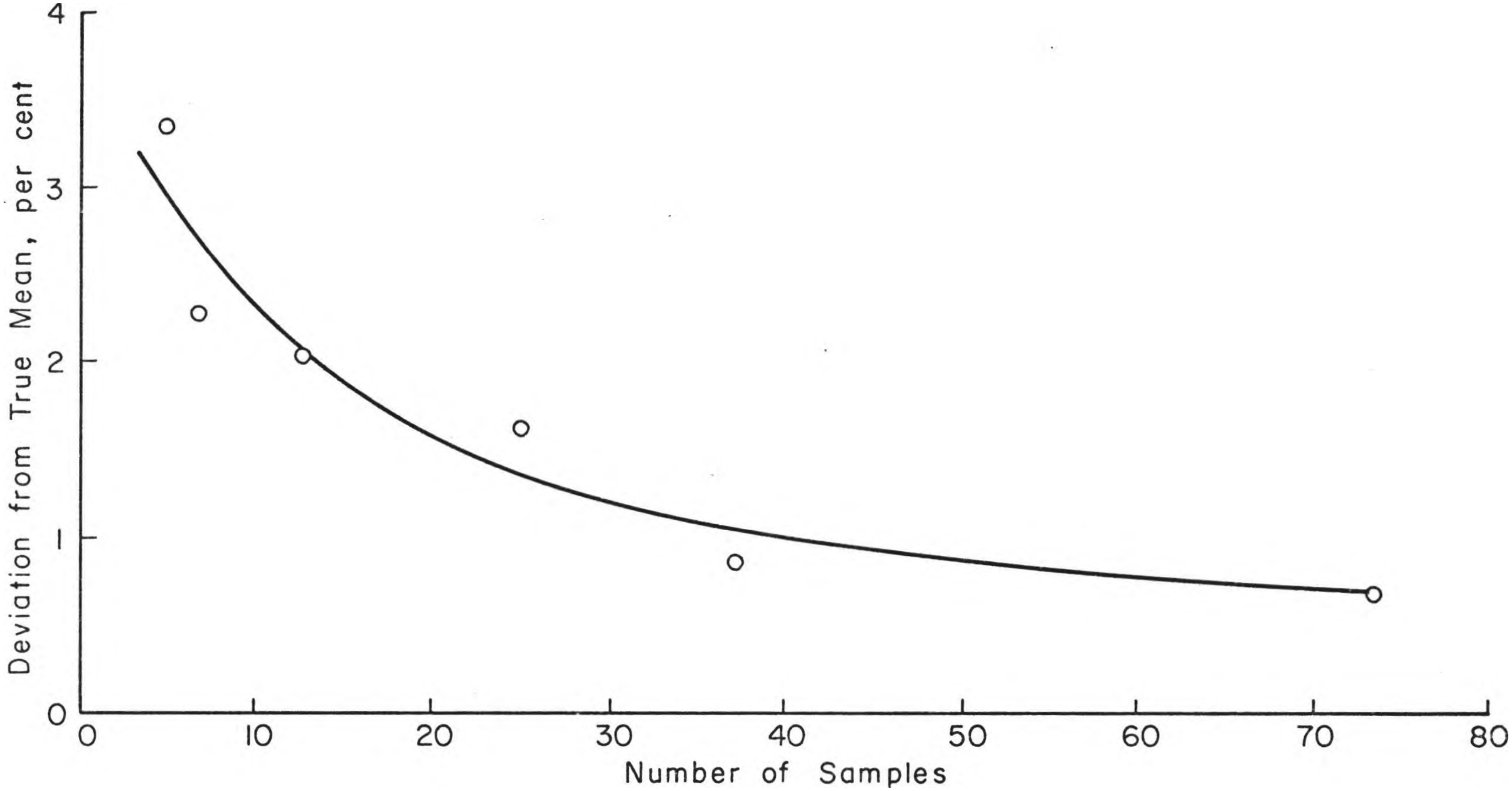

Figure 20. Observed deviations from true mean by base level surveillance model.

results must be combined to estimate an average sampling frequency for an entire stream. For a statewide surveillance system, the results for each river must be summed. Average sampling frequency can then be combined with the total number of stations to arrive at an estimate of the total number of samples necessary and, ultimately, the total sampling cost. By repeating this process for various accuracy limits, a cost-effectiveness curve can be derived. This process has been accomplished for a specific situation in the following chapter.

This approach for arriving at sampling frequency requires some arbitrary selection of the most significant quality parameters, since only one parameter can be considered at a time. To consider all parameters to be measured at a station would be a rather lengthy process. Instead, the method proposed is to select a few, say 3 or 4, important parameters and use these as a basis for sampling frequency selection, even though many parameters may be measured at each station.

To summarize the proposed method, then, the first step is to select the important parameters for a given station or stream. Knowing the variability of each parameter, a value for the desired accuracy limit or allowable error is selected. With these arguments, the figures are entered and a value for the number of samples at a station for the time period under consideration is read. This value is converted to a sampling frequency. The average sampling frequency for the parameters considered is the end result. This process is repeated for each station on the stream and an average sampling frequency for the entire stream can be computed. If desirable, this can also be expanded to a statewide basis. Obviously, since several averages are involved, individual stations will be above or below the desired accuracy for various parameters, but overall performance of a network can be estimated in this manner.

In addition to evaluating overall system performance, the method just described can be valuable for other purposes. For example, overall system accuracy could be upgraded by simply selecting the stations with water quality parameters of the greatest variability. Sampling frequency can be then increased at these stations, accomplishing the desired accuracy increase without having to increase sampling frequency at all stations.

The following hypothetical example is presented to illustrate use of the proposed method. Assume a stream with 3 sampling stations selected to obtain base level data. Table 7 lists the parameters selected as most important and their known characteristics from historical data. For this example, the allowable error is selected as 50% of the mean rather than specified in absolute terms. An observation period of 1 year was selected. The necessary number of samples for each parameter was read from the figures and listed in Table 7. The total number of

Table 7. Hypothetical example of base level surveillance sampling frequency for a stream having 3 stations.

Station	Parameter	Mean mg/l	Sample Standard Deviation, S mg/l	Allowable Error mg/l	Number of Samples Necessary
1	DO	6.0	1.0	3.00	1
	pH	7.5	1.0	3.75	1
	TDS	300.0	50.0	150.00	1
2	DO	5.5	2.0	2.75	2
	pH	7.4	1.0	3.70	1
	TDS	400.0	200.0	200.0	4
3	DO	5.0	2.0	2.50	2
	pH	7.4	1.0	3.70	1
	TDS	800.0	400.0	400.0	4
				Total	17

samples divided by the number of values making up the total gives the average number of samples necessary. In this case, the total of 17 divided by 9 results in a value of 1.89, or approximately 2 samples per year. From this analysis, it is decided that for the situation under consideration, a sampling frequency of once every six months will provide the desired overall accuracy. Restated, it can be said that, for these parameters, sampling twice a year will result in observed annual mean values within 50% of the true mean with a 5% chance of exceeding this limit.

The same situation, but calculated using an allowable error of 25% of the mean, resulted in a necessary sampling frequency of 6 samples per year, or once every 2 months. Again, as observed in the section on event detection, the relation of effectiveness to sampling effort is not linear.

This section has presented only the use of base level results for network design concerning long term means. Individual samples may vary significantly from these means. If the purpose of sampling stations is also to check on quality standards compliance, the results from analysis of individual samples are important by themselves and not only as a part of the mean. This should be considered in frequency selection to insure adequate surveillance.

Discussion

The data and procedures presented in this chapter are intended for use as aids in planning and evaluating water quality monitoring systems. The results are highly generalized and should be applicable to a wide variety of situations. As with any generalized guidelines, however, use must be combined with a certain amount of judgment. Individual circumstances may dictate more or less stringent sampling requirements than those indicated by this data.

Certain arbitrary decisions are also necessary for use of these guidelines. For example, if one is trying to decide what sampling frequency is necessary for base level data, he must select the most important parameters and decide the magnitude of the allowable error. If using the data for event detection, some decision must be made as to the spill durations expected. Examples of these and other decision factors are included in the following chapter describing application of the results to a particular situation.

Chapter 5

SYSTEM PLANNING

This chapter is intended to illustrate the procedures involved in planning a stream quality surveillance network using the results of this research. Cost constraints will be considered only to a limited extent, although the objective is to obtain the most effective network for the least cost. The network will be designed to meet the data needs indicated by the surveillance philosophy of the state agency. Only grab sampling methods will be considered.

The network will be designed to handle surveillance needs on the South Platte River Basin in Colorado. A map of this basin is shown in Fig. 21. The South Platte River has its origin in the high front ranges of the Rocky Mountains in Colorado. The river flows for approximately 450 miles in a northerly and easterly direction to its confluence with the North Platte River at North Platte, Nebraska. The South Platte River has several major tributaries, including the Big Thompson River, Cache la Poudre River and St. Vrain Creek. The drainage area in Colorado is about 19,022 square miles of which approximately 5550 square miles lie in mountainous regions. The remainder of the drainage area lies in the plains or high plains

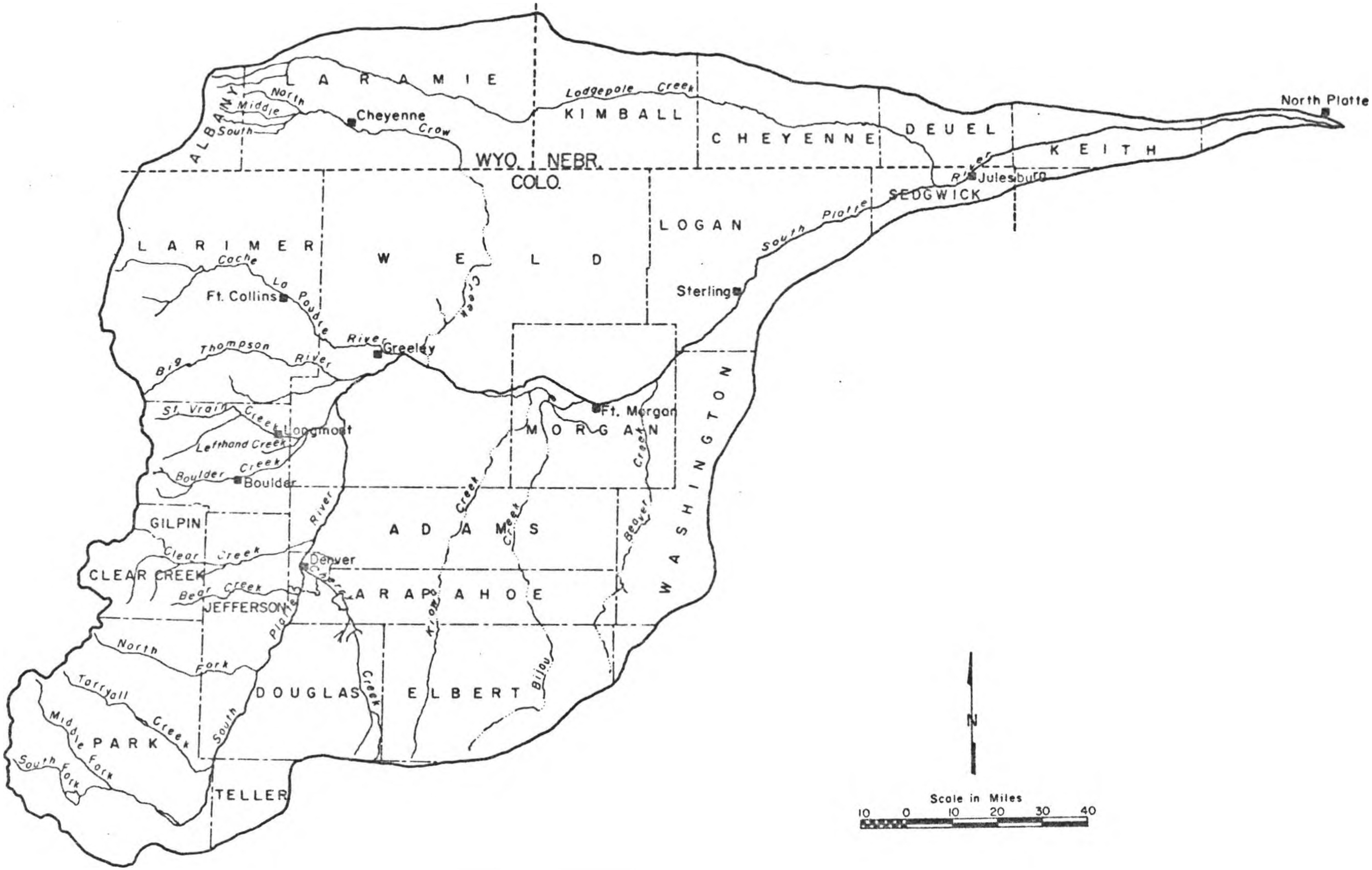

Figure 21. South Platte River Basin map.

regions with elevations of 3000 to 8000 feet. Precipitation in the plains regions is low, averaging about 11-13 inches annually. The precipitation is higher in the mountainous regions, up to a maximum of about 31 inches annually.

The greatest use of water within the basin is for irrigation. A large percentage of the basin is farm land, most of which is fertile, irrigated crop land, along with good grazing land. The mountainous areas of the basin provide the sources of many irrigation and community water supplies. These areas also serve as popular recreational spots.

Pollution Source Inventory

Although it is not intended to go into a detailed description of present and potential pollution sources for the basin, several of the major sources should be noted. These will play an important part in the selection of sampling station locations. Pollutants in the mountains originate primarily from recreation and mining. Mountain tourist towns have little wastes of a manufacturing or processing origin. Residential type human wastes are predominant with the quantity fluctuating seasonally in relation to the number of transients occupying the area. Mining wastes may be from active or abandoned mining and ore processing activities. Stream gradients are high in the mountain areas, resulting in much turbulence and aeration.

The eastern plains area waterborne wastes are mainly agriculturally derived. Basic agricultural wastes are exemplified by irrigation return waters, feed-lot drainage, and erosion from poorly managed lands. In the larger towns, industries process agricultural commodities such as sugar, meat, and canned produce. These processing wastes contain organic decomposable wastes and soils washed from the crops.

In the thirty-mile-wide densely populated area at the foot of the mountains, there are more significant waste sources. Also, these wastes are of a more diversified nature than in the mountains or plains areas. Agricultural related wastes are common. Mineral exploitation is primarily of non-metallic resources, especially those related to construction such as sand and gravel processing. In the larger urban areas, industrial wastes are varied; examples are wastes from machinery manufacturing, metal finishing, metal fabrication, petrochemical products, paper products, textiles, and leather products. Because of the unequal population distribution, this area has more domestic wastes than the entire remaining area of the basin. Several studies have been conducted describing pollution in the South Platte River Basin in detail (44,45,48).

Surveillance System Data Needs

In order to design a water quality surveillance system for a particular situation, one of the first items of information necessary is the strategy of the responsible agency. For example, it may concentrate on planning, or on enforcement, or a combination of these and others. The strategy of the Water Pollution Control Division (WPCD) of the Colorado Department of Public Health has been evaluated by Ward (~~52~~ 50). He has developed a simple method whereby a state agency determines where it is currently placing its main emphasis by evaluating its activities in each work area. This information can then be used to aid in design of a surveillance system which is consistent with the water pollution control strategy.

Ward's analysis concludes that the WPCD devotes a majority of its time to the specific objectives of aid programs, technical assistance, and regulation. As far as a data demand upon the surveillance network is concerned, the division primarily needs data to support its regulation and technical assistance activities. Ward indicates that planning will assume a larger role in the division's activities in the future and that data will have to be supplied for this purpose. The present strategy is to use routine surveillance to check compliance with stream standards and if a violation is found, a special stream survey is used to determine the cause.

The data needs dictated by the strategy just described fall into both categories covered in this study. The regulation function requires timely detection of significant short term quality variations, or what were termed pollution events earlier in this study. Planning requires data of the type termed base level data. The remainder of this chapter is presented to illustrate the possible alternatives in using grab sampling to meet these data needs.

Sampling Station Location

Assuming that all the data needs specified in the previous discussion are to be satisfied, the next question to be answered is how many sampling stations are necessary and where are they to be located. Some externalities come into the picture here, one of which is that Federal requirements may be interpreted to mean that a state must sample every stream reach where different quality standards apply. This automatically specifies a certain number and general area of sampling stations to check compliance with stream standards. Also, stations should be located to adequately monitor areas where significant pollution, or pollution potential, exists.

Ward (~~51~~ 50) describes a procedure whereby stream characterization data is used to locate sampling stations at indicated problem areas according to state strategy. He notes that stations will be established for the purposes of pollution prevention and abatement and explains these as follows:

> 1. Prevention - place sample station location at the critical quality point along the stream. The routine monitoring data will then give a general indication of the stream's overall quality. Parameters to be measured should be general data associated with the agencies' planning activities.
>
> 2. Abatement - place sample station location at the critical quality point below each major area of pollution sources. Measure those parameters denoted in the stream standards and any other parameters which are critical according to the waste outfall inventory.

The two situations mentioned above suggest that a possible approach could be a surveillance system consisting of different stations with different purposes. Due to the fact that this study has considered two basic data types, and since these data types fulfill the needs of most state agencies, it was decided that a system incorporating two different types of stations would be the best approach. The recommendations to follow incorporate this concept.

The system proposed will consist of two types of stations termed primary and secondary. Primary stations will be those designed to obtain regulatory and enforcement type data. They will be located at critical points as indicated by historical data and significant pollution sources. Primary stations will be sampled as frequently as possible to obtain a high chance of detecting stream standard violations and extreme values resulting from pollution events.

Normally, samples from primary stations will be analyzed for only a few index parameters, rather than making a complete water quality analysis. The selection of these parameters can be adapted to a particular situation, but for this analysis, the parameters selected were dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS), flow, and pH. In certain situations, microbiological and radiological measurements may also be desirable. These index parameters are intended to serve as indicators of quality problems. Their use will allow a higher sampling frequency without increasing analysis requirements, since more samples will be collected, but fewer analyses made on each sample.

Base level data for planning and other related purposes will be obtained at the secondary stations. These stations will be sampled much less frequently than primary stations, but a full range of analyses will be made on each sample. Most stations established to meet the requirement for a station in every different quality standard reach can probably be of the secondary type.

The proposed station network for Colorado's South Platte River Basin is listed in Tables 8 and 9. The station locations are shown on the map in Fig. 22. The primary stations were located considering the major pollution sources and critical water quality areas as indicated by historical quality data. Locations may be dictated by non-conservative pollutants as well as conservative pollutants. For example, station locations for detecting minimum DO levels will be determined from dissolved oxygen sag curves, taking into acocunt major sources of oxygen demanding pollutants as well as stream characteristics. The historical data was furnished by the Colorado Water Pollution Control Division and in most instances consisted of about four years of monthly observations. The locations of proposed stations for both types of data requirements coincide with existing stations, but the sampling frequency and sample analysis procedure will be changed. These stations also coincide with or are near flow gaging stations. Secondary stations were located at those points where base level data is necessary for planning purposes and for checking compliance with stream standards. At these points, however, pollution problems were considered minor.

For purposes of comparison, an alternate primary sampling network was selected and is listed in Table 10. Fewer stations are incorporated in the alternate system. The comparisons made are intended to illustrate the differences in cost and performance if it could be decided that

Table 8. Proposed primary sampling stations in the South Platte River Basin.

Stream	Station Location
1. Main Stem	Julesburg
2. Main Stem	Kersey
3. Main Stem	Henderson
4. Main Stem	Littleton
5. Cache La Poudre	below Greeley
6. Big Thompson	near mouth
7. St. Vrain	below Longmont
8. Boulder Creek	at Boulder-Weld County Line
9. Clear Creek	near mouth
10. Clear Creek	at Wheat Ridge
11. Clear Creek	above Golden
12. Bear Creek	at Jefferson-Arapaho County Line

Table 9. Proposed secondary sampling stations in the South Platte River Basin.

Stream	Station Location
1. Main Stem	Balzac
2. Main Stem	South Platte
3. St. Vrain	near mouth
4. St. Vrain	at Boulder-Weld County Line
5. Cache La Poudre	above Fort Collins
6. Left Hand Creek	near Niwot

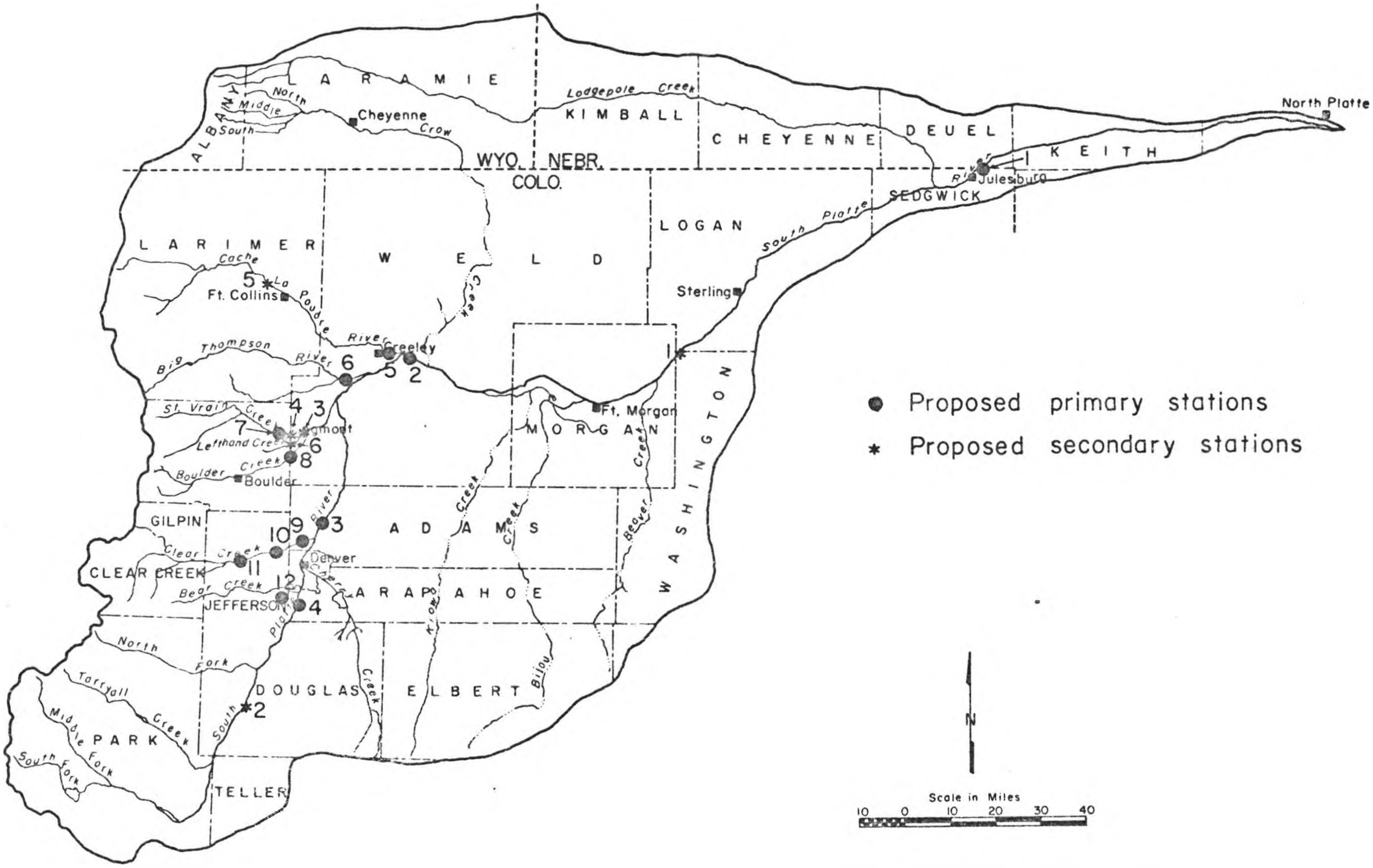

Figure 22. Location of proposed primary and secondary sampling stations in South Platte River Basin.

Table 10. Proposed primary sampling stations in the South Platte River Basin - alternate network.

Stream	Station Location
Main Stem	Julesburg
Main Stem	Henderson
Cache La Poudre	below Greeley
St. Vrain	near mouth
Clear Creek	near mouth
Big Thompson	near mouth

adequate surveillance could still be obtained by a reduced number of stations. An alternate secondary sampling network was not included, since the results of this study indicate that effectiveness is not a function of station numbers for base level data acquisition.

Ward (51) gives a detailed explanation of the methodology used in selecting these stations. Due to extensive potential pollution sources in the South Platte Basin, the majority of the stations selected for this sytem are designated as primary. This is probably an exceptional case and in most instances, secondary stations would outnumber primary stations. At least, this would be the case for the other river basins in Colorado.

The results cited earlier indicated that the peak effectiveness in detection was obtained by single station surveillance. This would imply that establishing a single sampling station at the downstream end of the basin with a very high sampling frequency would detect the most events with the least cost. Although this is probably true, it would be nearly impossible to establish the origin of the pollution events using a single station. This is probably the single most important reason for establishing several primary stations.

System Performance Analysis

After selecting sampling station types, numbers, and locations, the next step is to use the results from the previous chapter to analyze overall system performance. Rather than specify a certain performance level and corresponding sampling frequency, an effectiveness-sampling frequency curve for the system will be developed. Ultimately, a cost-effectiveness curve will be prepared. Curves of this type will permit an agency to choose the level of cost and effectiveness most consistent with needs and constraints.

For this analysis, it will be assumed that only primary stations will be used to obtain regulation and enforcement type data and only secondary stations will be used to obtain base level type data. Since secondary stations will not be sampled frequently, their contribution to pollution event detection will be negligible. The surveillance system will be analyzed with respect to acquisition of each type of data separately.

Pollution event detection. Twelve primary sampling stations have been selected for the main purpose of pollution event detection. The alternate network contains six primary stations. In addition to pollution event detection, the primary stations will also supply a significant amount of base level data for the parameters measured. To analyze the effectiveness of these stations in detection of pollution events, the same procedure as described in the "Multiple Sampling Stations" section in Chapter 4 was used. A 0-3 day random spill duration was assumed to be representative of the common spills that can be expected in the basin, so values obtained from Fig. 5 can be used directly. The main stem and each tributary were analyzed as individual streams and the results averaged to estimate overall performance. Relative effectiveness factor (REF) values were obtained from Fig. 12 corresponding to the number of stations used on each stream. Tables 11 and 12 summarize the stations and respective REF values for each stream. Since the procedure and sample calculations were described in Chapter 4, these will not be repeated in this section. For this example, direct use of the proposed calculation methods will result in a situation at high detection levels where streams with multiple stations require a higher sampling frequency per station than streams with single stations. When this occurs, use of REF values is discontinued and each station handled individually. Necessary sampling frequencies for a range of system detection values from 0 to about 80% were calculated and these have been plotted in Fig. 23. Detection values above 80% were not considered since the curve in Fig. 23 indicates the sampling frequencies necessary above this level would be impractical using routine grab sampling surveillance.

Assuming a linear relation between number of samples and sampling cost, cost-effectiveness curves for the systems were then developed. An estimated cost of $75.00 per sample was used in computing total sampling costs. The Colorado estimate of $66.38 per sample (24) was increased slightly to arrive at the $75.00 estimate. The

Table 11. Summary of proposed primary sampling stations and respective stream relative effectiveness factor (REF) values.

Stream	Number of Primary Stations	REF Value (from Fig. 12)
Main Stem	4	0.62
Cache La Poudre	1	1.0
Big Thompson	1	1.0
St. Vrain	1	1.0
Boulder Creek	1	1.0
Clear Creek	3	0.66
Bear Creek	1	1.0

Table 12. Summary of primary sampling stations and respective stream relative effectiveness factor (REF) values - alternate network.

Stream	Number of Primary Stations	REF Value (from Fig. 12)
Main Stem	2	0.75
Cache La Poudre	1	1.0
St. Vrain	1	1.0
Clear Creek	1	1.0
Big Thompson	1	1.0

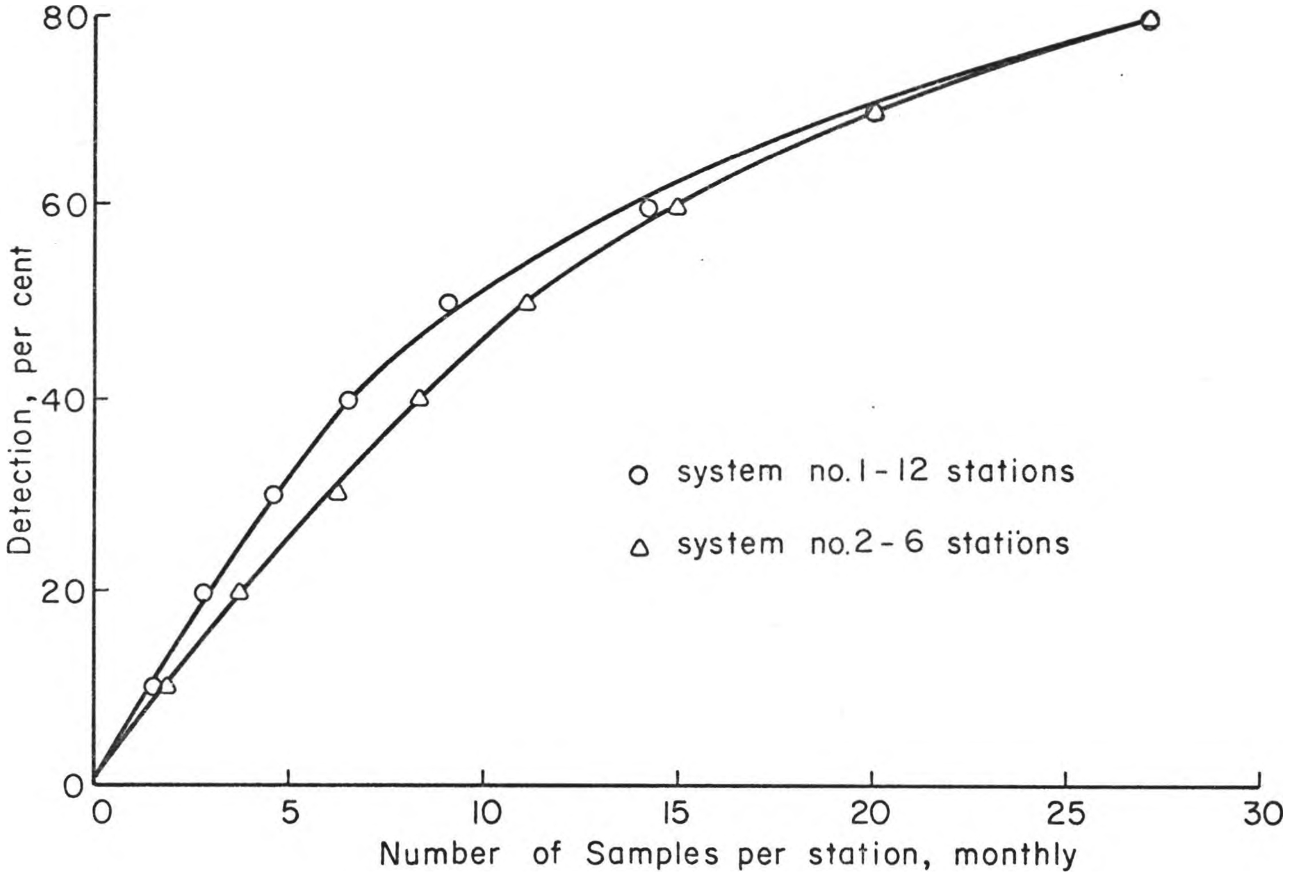

Figure 23. Relation between detection and sampling frequency for proposed and alternate South Platte River Basin surveillance networks.

results showing total annual sampling cost as a function of detection level have been plotted in Fig. 24.

Use of Figs. 23 and 24 is simple and straightforward. For example, if it was desired to sample the proposed network of 12 stations on a schedule to obtain a detection level of approximately 50%, about 9 samples per station would be necessary each month. The annual cost for this level would be about $105,000. To reach a 70% detection level, about 28 samples per station would be necessary and the cost would increase to about $300,000 annually.

A comparison of the proposed network of 12 stations and the alternate network of 6 stations can be made using the curves in Fig. 23. The alternate network requires a higher sampling frequency than the proposed network for the same detection levels up to about 65% detection. Above 65%, both networks require essentially the same sampling frequency. This is due to the fact that at about the 65% level, use of REF values in the calculation was discontinued and each station is considered separately.

Since the two curves in Fig. 33 are not far apart, the alternate system requires a lower total number of samples than the proposed system for the same detection level. The curves in Fig. 24 reflect the total number of samples, since cost is linearly proportional to this value. Obviously, the alternate system attains the same detection levels at less cost.

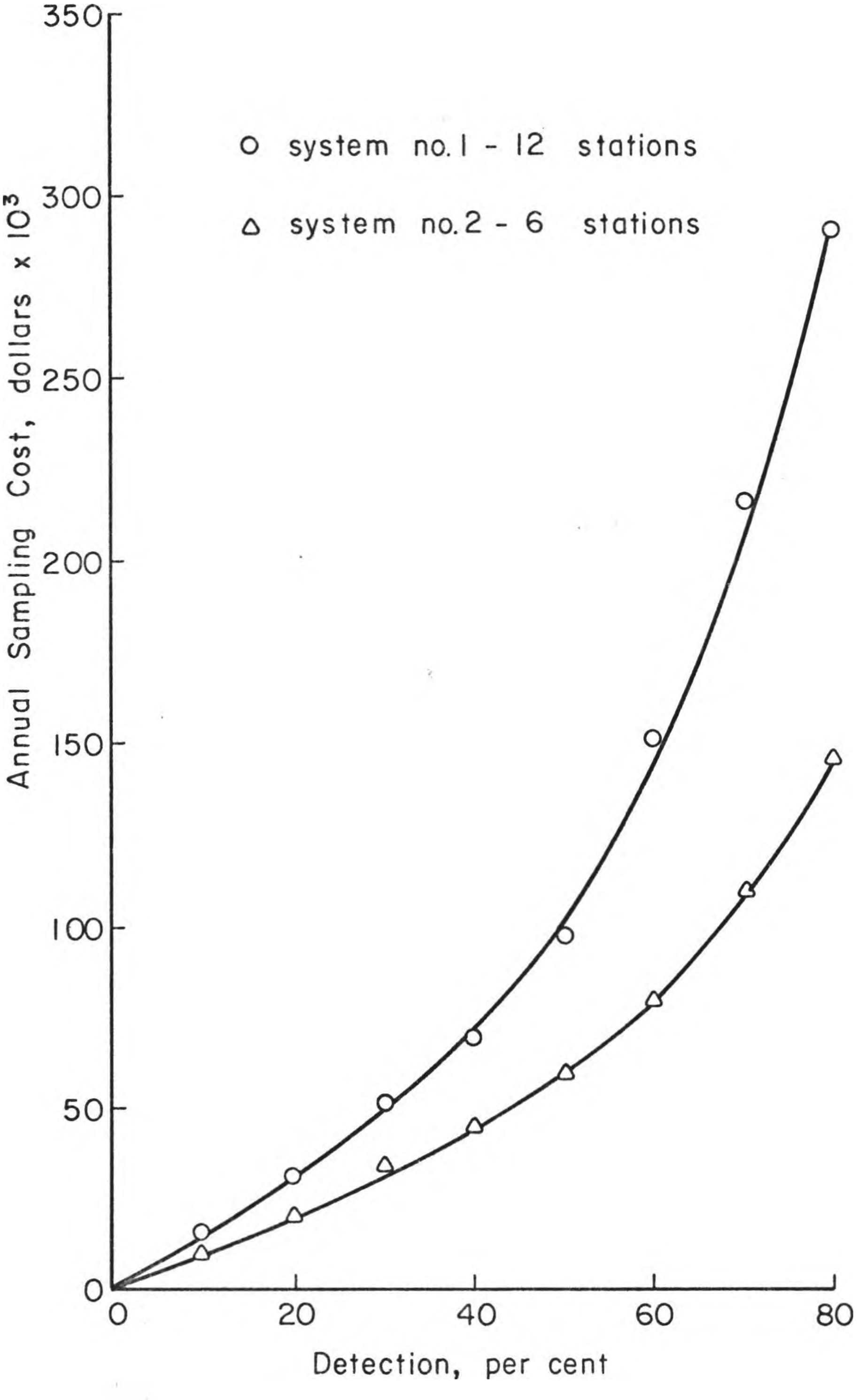

Figure 24. Annual sampling cost at various detection levels for proposed and alternate South Platte River Basin surveillance networks.

The comparisons just made can be misleading if not correctly interpreted. The alternate network with fewer stations is more effective since each individual station must monitor a larger area. When an area becomes too large to be adequately monitored by an individual station, effectiveness at that station will drop. The objective, then, is not just to reduce the number of sampling stations to a minimum. Rather, the objective is to establish the minimum number of stations to adequately monitor the total area. The proposed network was felt to contain the minimum number of stations to adequately monitor the South Platte River Basin. The alternate network was presented to illustrate the desirability of fewer stations when practical.

From Fig. 24, it is obvious that costs increase tremendously when trying to obtain high detection levels. This indicates that grab sampling methods are probably not practical due to prohibitive costs when high detection levels are needed.

<u>Base level data acquisition</u>. As previously noted, all stations, both primary and secondary, can be considered as contributing to base level data collection. However, since the primary purpose of secondary stations is base level data collection, the secondary network will be analyzed separately from the primary network. Data from primary stations, when combined with that from secondary stations, will tend to improve the data accuracy for the parameters measured at both types of stations. Also, a

portion of the samples (say 1 of 4, or some other frequency) collected at the primary stations could be analyzed for the wider range of parameters employed at secondary stations, thereby providing additional base level data.

The proposed secondary sampling network consists of 6 stations, 2 on the main stem of the South Platte River and 4 on major tributaries. For this analysis, the annual mean is considered the important parameter for evaluating trends and for planning purposes. Although individual values are still important in checking compliance with stream standards, this analysis will be based upon the ability of the system to estimate annual means within certain accuracy limits. Four parameters will be used in the evaluation, DO, BOD, pH, and TDS, although it is anticipated that a wide range of parameters will be measured at secondary station locations.

Historical data for the selected parameters is listed in Table 13. This data is a summary of the parameter values computed from the raw data. The statistical procedures outlined in Chapter 4 for estimating the values of the sample standard deviation, S, were used for arriving at the values in Table 13. A 0.05 level of significance was used in all tests. In the case of pH data, no significant time dependent variation was found at any station and the calculated S value is for all historical data combined. When DO, BOD, and TDS were considered, some stations had significant time dependent variation, and

Table 13. Stream characterization data for proposed secondary station locations in the South Platte River Basin.

Station	Parameter	Mean mg/l	Sample Standard Deviation,S mg/l
Main Stem (Balzac)	DO	8.2	2.0
	pH	8.1	0.5
	BOD	3.5	2.1
	TDS	1287	191
Main Stem (South Platte)	DO	9.8	1.7
	pH	7.6	0.2
	BOD	1.9	0.2
	TDS	126	43
St. Vrain (mouth)	DO	6.4	1.3
	pH	7.9	0.4
	BOD	5.9	3.8
	TDS	936	207
St. Vrain (Boulder-Weld County Line)	DO	4.0	0.9
	pH	8.1	0.3
	BOD	14.3	5.8
	TDS	864	135
Cache La Poudre (above Ft. Collins)	DO	7.7	1.8
	pH	8.3	0.5
	BOD	1.8	1.0
	TDS	69	32
Left Hand Creek (near Niwot)	DO	7.8	
	pH	7.9	
	BOD	1.6	0.4
	TDS	632	

some did not. The data that did exhibit this variation was tested for homogeneity of variance by Bartlett's test. If no significant difference in variation was found, a direct average was used to calculate S. If a difference was significant, a weighted average of the annual variances, using degrees of freedom as weighting factors, was used to calculate S.

The procedure used in this section corresponds with the multiple base level station analysis described in Chapter 4, with the exception that in this case parameter values for the 6 stations were averaged prior to analysis. Necessary sampling frequencies over a range of allowable error levels were calculated and the results plotted in Fig. 25. Using an estimated cost of $75.00 per sample, cost-effectiveness data was computed and plotted in Fig. 26.

For the proposed secondary sampling station network, Figs. 25 and 26 can be used to estimate performance and costs for various levels of surveillance. As was the case in pollution event detection, costs and sampling requirements increase rapidly at high data accuracy levels.

Discussion

This chapter has illustrated how the results of this study might be applied to an actual physical situation. No recommendations were made concerning specific surveillance levels. These are decisions which must be made considering agency strategy, data needs, and constraints.

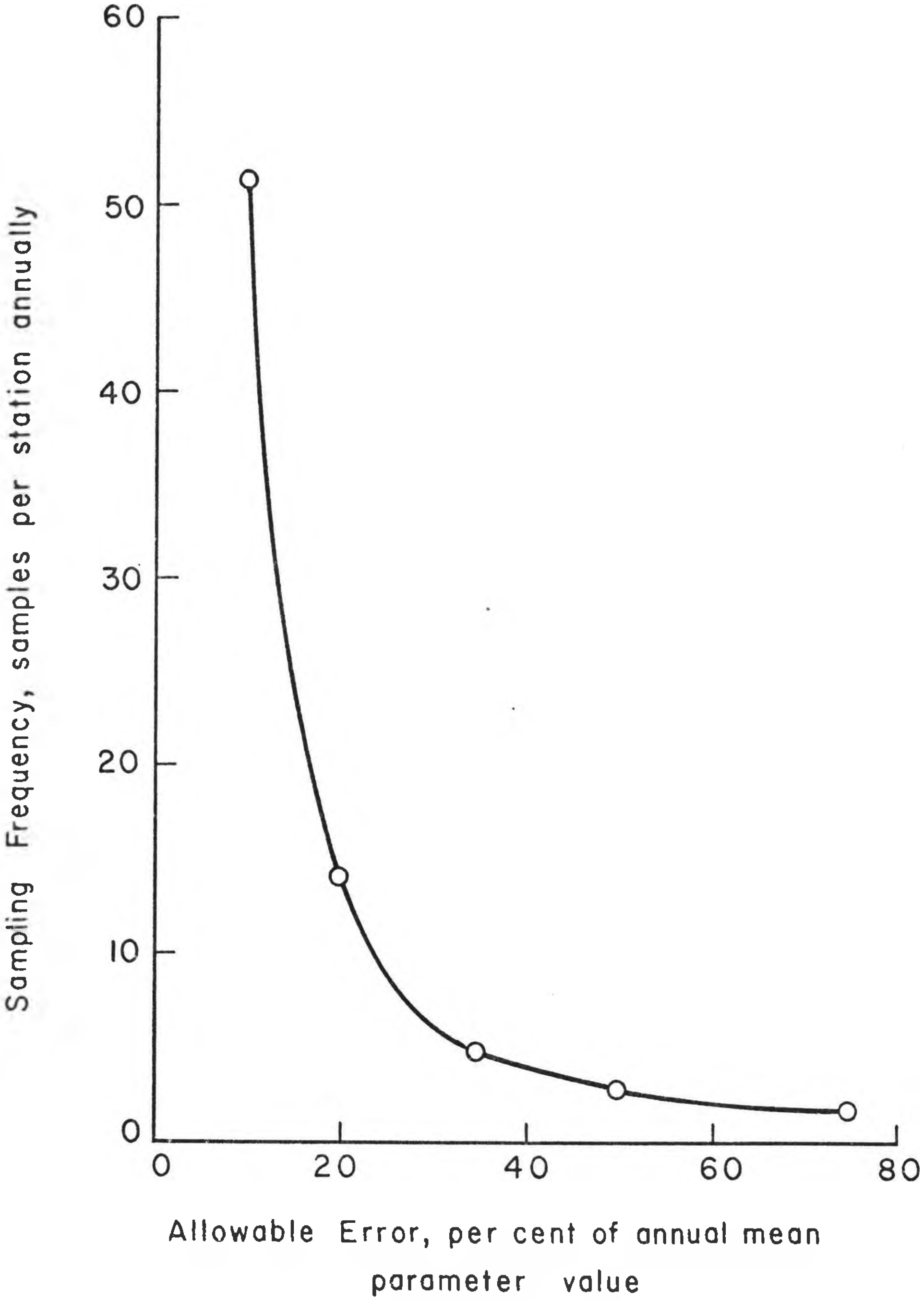

Figure 25. Relation between allowable error and sampling frequency for proposed South Platte River Basin surveillance network.

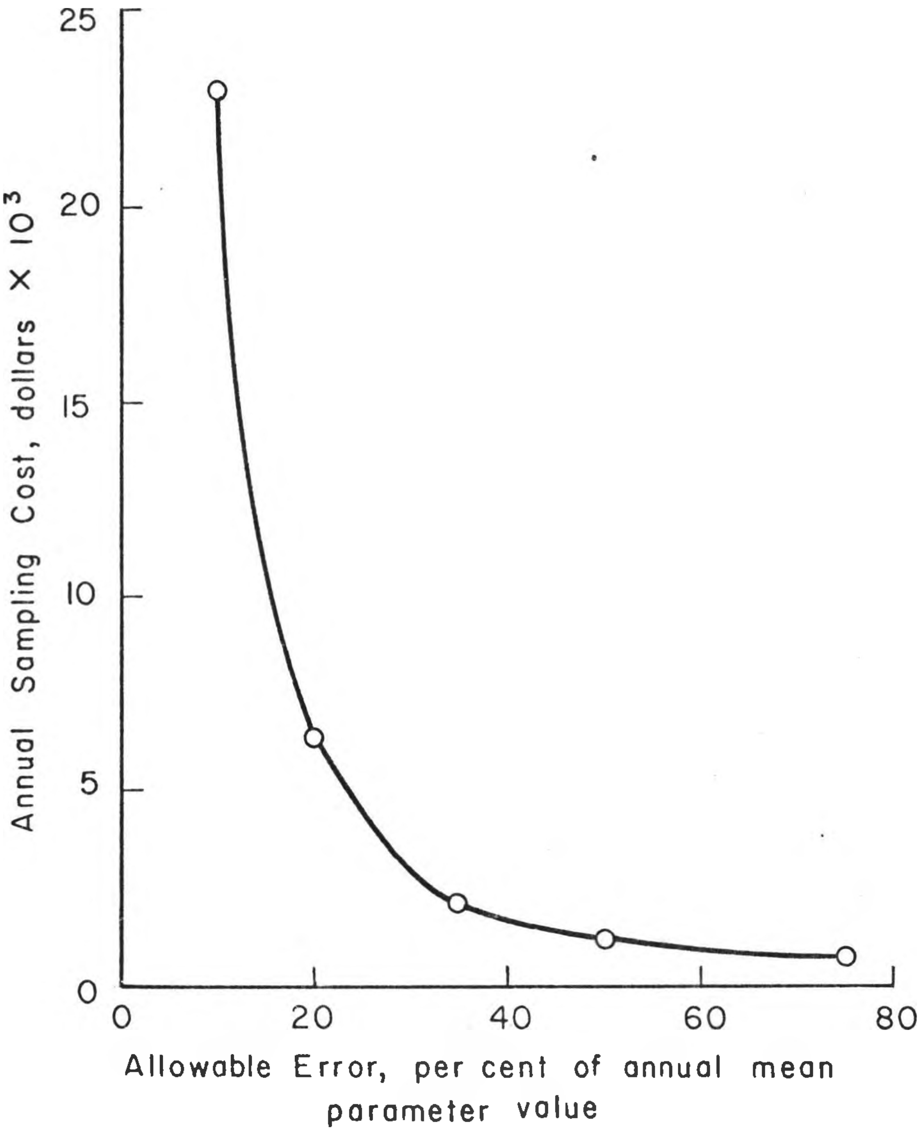

Figure 26. Annual sampling cost in relation to allowable error for proposed South Platte River Basin surveillance network.

However, the methods and results presented should prove valuable tools in making decisions of this type. Refinement and adaptation to specific situations are left to the users.

Chapter 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Two models were developed to evaluate the effectiveness of grab sampling methods in water quality data acquisition. One model was used to predict the detection of significant short term pollution events or quality variations. Several combinations of sampling frequency and location were tested with events of varying magnitude and duration. The second model was primarily used for illustrative purposes, along with a simple statistical prediction method. The statistical approach was used to predict the effectiveness of grab sampling to obtain what can be termed base level type data. For this type of data, the primary concern is the accuracy of observed means, trends, etc., with regard to the true values.

The basic variable evaluated was system effectiveness, as a function of sampling frequency. In the first case, system effectiveness was represented by the ability of the sampling combination to detect pollution events generated along a hypothetical stream depicted in a mathematical model. In the latter case, effectiveness was measured by the accuracy of observed mean parameter values using various sampling configurations. Each data type was handled separately throughout the study.

As an example for use of the study results, a surveillance system for the South Platte River Basin in Colorado was planned. Networks of primary and secondary sampling stations for obtaining regulation and base level data, respectively, were proposed. Cost-effectiveness curves for both types of stations were developed for use in planning surveillance levels.

The nature of the problem prevented verification of the models by field studies or similar methods. The sensitivity of the detection model solutions to certain variable changes was tested with the results indicating negligible effects. However, the results presented are not intended to be taken as absolute values for any stream situation. The extreme variability of natural streams and of pollution sources prevents general solutions from accurately predicting values under individual circumstances.

Conclusions

The conclusions drawn from the results of this study were:

1. Water quality surveillance system effectiveness can be estimated using the models and procedures developed in the study. Prediction may be in error if individual circumstances are not fully considered.

2. Surveillance system effectiveness is dependent upon both sampling location and sampling frequency. Selection of each of these is based on different variables.
3. There is a decreasing return in system effectiveness and a corresponding cost increase as surveillance efforts are increased to obtain high effectiveness levels.
4. Adequate knowledge of stream and pollution conditions is a necessary prerequisite to successful surveillance planning and design. This can be obtained from historical data, intensive stream surveys, or other sources. Use of the methods developed in this study requires this information.
5. Periodic review and evaluation of established surveillance systems is desirable to maintain and increase system effectiveness. Additional data and physical changes may indicate desirable modifications to existing systems.

Recommendations for Further Research

Necessary oversimplification of physical conditions in the models limits the accuracy of the solutions obtained. Refinement of the detection model to more adequately describe actual stream conditions and pollution events should permit better surveillance system evaluation in specific situations. Sophisticated mathematical water quality models exist, but no indication was found in the literature to show that they had been combined with surveillance models. This concept should be developed to provide tools to fill the gap that presently exists in surveillance system design information.

Model verification may also be possible through the use of tracers and similar techniques. This has previously been accomplished to study the movement of pollutants in streams. Simulation of actual pollution events with tracers could produce much information useful in surveillance system design.

The concept of having two types of sampling stations, primary and secondary, as proposed in the study, should be further pursued. A system of this type may adapt well to many situations, resulting in more effective surveillance and reduced costs. This concept should prove exceptionally useful when a combination of continuous automatic monitoring and grab sampling methods is used. This has already been done to a limited extent in some areas, but this concept merits more widespread consideration.

Finally, the relation of agency strategy to data needs and of data needs to surveillance efforts should be studied further. In most situations, this can be accomplished with an in-house study by the concerned agency.

BIBLIOGRAPHY

1. Anderson, P. W., Faust, S. D., and Zogorski, J. S., "Analyses of Long Term Trends in Water Quality Parameters," Proc. Fourth American Water Resources Conf., New York, N.Y. (1968).

2. Ball, M. D., "Errors to Avoid in Water Quality Collection and Sampling," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin (July 1970).

3. Ballinger, D. G., "Effective Water Pollution Control Requires Accurate Data," Environmental Sci. and Tech., 1:612-616 (1967).

4. Bramer, H. C., "Data Needs in Engineering Design," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management," Madison, Wisconsin (July 1970).

5. De Falco, P., Jr., "Data Acquisition Systems in Water Quality Control," in Symposium, Environmental Measurements, Valid Data and Logical Interpretation, U.S. Public Health Service Pub. No. 999-AP-15 (1964).

6. Durum, W. H., "Relationship of the Mineral Constituents in Solution to Stream Flow, Saline River near Russell, Kansas," Trans. American Geophysical Union, 34:435-442 (1953).

7. Environmental Protection Agency, Water Quality Office, State Program Grant Application, Final Draft, Washington, D.C.: Government Printing Office (1971).

8. Environmental Protection Agency, Water Quality Office, "Guidelines for Water Quality Management Planning," Washington, D.C.: Government Printing Office (1971).

9. Fair, G. M., Geyer, J. C., and Okun, D. A., Water and Wastewater Engineering, Vol. 2, Water Purification and Wastewater Treatment and Disposal, New York, N.Y., John Wiley and Sons, Inc. (1968).

10. Gannon, J. J., and Wezernak, C. T., "Collection and Interpretation of Stream Water Quality Data," Proc. Third American Water Resources Conf., San Francisco, Calif. (1967).

11. Gibbs, C. V., and Isaac, G. W., "Seattle Metro's Duwamish Estuary Water Quality Program," J. Water Pollution Control Fed., 40:385-394 (1968).

12. Glover, R. F., "Dispersion of Dissolved or Suspended Materials in Flowing Streams," U.S. Geological Survey Professional Paper 433 B (1964).

13. Gunnerson, C. G., "Optimizing Sampling Intervals in Tidal Estuaries," J. San. Engr. Div. ASCE, 92:103-125 (1966).

14. Gunnerson, C. G., "Sacramento River Water Pollution Survey," Sacramento, Calif., Calif. Dept. of Water Resources Bull. No. 111 (1962).

15. Gunnerson, C. G., "Streamflow and Quality in the Columbia River Basin," J. San. Engr. Div. ASCE, 93:1-16 (1967).

16. Haney, P. D., and Schmidt, R., "Representative Sampling and Analytical Methods in Stream Studies," Sewage and Ind. Wastes, 30:812-820 (1958).

17. Kittrell, F. W., "A Practical Guide to Water Quality Studies of Streams," U.S. Dept. of the Int., FWPCA Pub. CWR-5 (1969).

18. Kittrell, F. W., and West, A. W., "Stream Survey Procedures," J. Water Pollution Control Fed., 39:627-641 (1967).

19. Klein, W. L., Dunsmore, D. A., and Horton, R. K., "An Integrated Monitoring System for Water Quality Management in the Ohio Valley," Environmental Sci. and Tech., 2:764-771 (1968).

20. Maylath, R. E., "Water Quality Surveillance in New York State," Albany, N.Y., New York State Dept. of Environmental Conservation (1970).

21. McDermott, J. H., "Water Quality Surveillance in Water Resource Development and Control," Paper presented at the Pan American Health Organization Water Quality Control Laboratory Symposium, Rio De Janeiro, Brazil, September (1968).

22. Mentink, A. F., "An Opinion on the Water Quality Instrumentation Systems Installed at the United Gas Industries and Merc Chemical Plants," Paper prepared for the Water Quality Section, Dept. of Health, Commonwealth of Pennsylvania (1970).

23. Misbach, G., Private Communication, Data on Colorado Sampling Station Locations, Denver, Colorado (1971).

24. Misbach, G., Private Communication, Sampling Cost Data for Colorado, Denver, Colorado (1971).

25. Moody, D. W., "Organizing a Data Collection Program for Water Resources Planning, Development and Management," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin (July 1970).

26. Morgan, P. V., "Basic Data Requirements to Evaluate Water Pollution in Quality Control Programs," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin, (July 1970).

27. O'Connor, D. J., St. John, J. P., and DiTor, D. M., "Water Quality Analysis of the Delaware River Estuary," J. Sanitary Engr. Div. ASCE, 94:1225-1252 (1968).

28. Palmer, M. D., and Sato, G. K., "Review of Water Quality Station Density Statistical Procedures," Toronto, Ontario, Ontario Water Resources Commission (1968).

29. Petri, L. R., "Need for Water Quality Data in Planning Water Resource Developments," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin (July 1970).

30. Pomeroy, R. D., and Orlob, G. T., "Problems of Setting Standards and of Surveillance for Water Quality Control," Sacramento, Calif., California State Water Quality Control Commission Pub. No. 36 (1967).

31. Richardson, W. F., Private Communication, Data on Pennsylvania Monitoring System (1971).

32. Rizvi, S. S. A., "Statistical Approach to Water Quality Monitoring Programs," Toronto, Ontario, Ontario Water Resources Commission (1969).

33. Roche, W. M., "Organizing a Data Collection Program," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin (July 1970).

34. Roskopf, R. F., "A Composite-Grab of Water Pollution Control Sampling," J. Water Pollution Control Fed., 40:492-498 (1968).

35. Snedecor, G. W., and Cochran, W. G., Statistical Methods, Iowa State University Press, Ames, Iowa (1967).

36. Standard Methods for the Examination of Water and Wastewater, 12th Ed., New York, N.Y. American Public Health Assoc., Inc. (1965).

37. Steele, T. D., "A Technique for Improving Estimates of Long-Term Chemical Quality Characteristics of Streams," Paper presented at the National Fall Meeting, American Geophysical Union, San Francisco, Calif., December (1969).

38. Steele, T. D., "Beneficial Uses and Pitfalls of Historical Water Quality Data," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin (July 1970).

39. Sylvester, M. A., "Application of Automatic Monitoring to State Water Quality Surveillance Programs," Unpublished M.S. Thesis, Dept. of Zoology, Colorado State University, Fort Collins (1972).

40. Taylor, P. L., "Experiences with a Water Pollution Control Storage and Retrieval System (STORET)," Paper presented at the National Symposium on Data and Instrumentation for Water Quality Management, Madison, Wisconsin (July 1970).

41. Thomann, R. V., "Time Series Analysis of Water Quality Data," J. San. Engr. Div. ASCE, 93:1-23 (1967).

42. U.S. Dept. of the Interior, F.W.P.C.A., "STORET II, Storage and Retrieval of Data for Open Water and Land Areas," Washington, D.C.: Government Printing Office (1966).

43. U.S. Dept. of the Interior, F.W.P.C.A., "Effects of Pollution on Aquatic Life Resources of the South Platte River Basin in Colorado," Denver, Colo.: South Platte River Basin Project (1967).

44. U.S. Dept. of the Interior, F.W.P.C.A., "Water Quality, Middle Basin Tributary Streams, Summer 1965," Denver, Colo.: South Platte River Basin Project (1967).

45. U.S. Dept. of the Interior, F.W.Q.A., "Design of Water Quality Surveillance Systems," Washington, D.C.: Government Printing Office (1970).

46. U.S. Geological Survey, "Methods for Collection and Analysis of Water Samples," U.S.G.S. Water Supply Paper 1454, Washington, D.C.: Government Printing Office (1960).

47. U.S. Public Health Service, Federal Security Agency, "Report, South Platte River Basin Water Pollution Investigation," Cincinnati, Ohio: Environmental Health Center (1950).

48. Velz, C. J., "Sampling for Effective Evaluation of Stream Pollution," Sewage and Ind. Wastes, 22:666-682 (1950).

49. Wang, W., and Evans, R. L., "Dynamics of Nutrient Concentrations in the Illinois River," J. Water Pollution Control Fed., 42:2117-2123 (1970).

50. Ward, R. C., "Data Acquisition Systems in Water Quality Management," Project Report No. 16090 FUO12/71, Environmental Protection Agency, Water Quality Office, December (1971).

51. Wastler, T. A., "Application of Spectral Analysis to Stream and Estuary Field Surveys - I. Individual Power Spectra," U.S. Public Health Service Pub. No. 999-WP-7, Washington, D.C.: Government Printing Office (1963).

52. Weisbecker, L. W., Mackin, J. L., Knight, A. W., and Brocksen, R. W., "An Environmental Monitoring Program for the Sacramento-San Joaquin Delta and Suisun Bay," Menlo Park, Calif., Stanford Research Institute (1970).

53. Wisconsin, Statutes, Chap. 144, Sec. 144.025.

54. Draper, N., and Smith, H., Applied Regression Analysis, New York, N.Y., John Wiley and Sons, Inc. (1966).

APPENDIX A

THE COMPUTER PROGRAM FOR POLLUTION EVENT DETECTION

APPENDIX A

The Computer Program for Pollution Event Detection

Brief Description

The program is written in Fortran IV language, with necessary additional instructions to run on a CDC 6400 computer. The main program is called DEPROB, containing part of the logical network and data input and output instructions. The dispersion curve calculations are performed in a subroutine named DISPER. The logical network for determining event detection is also contained in subroutine DISPER. Another subroutine, SOURCE, is used to generate random times and locations for origin of pollution events.

Table A1. Dictionary of Fortran Symbols Program DEPROB.

Fortran Symbol	Representation
A	Cross sectional stream area, $ft.^2$
B	Width of stream, ft.
CS	Background concentration of pollutant in stream, PPM.
CSD	Specified minimum concentration for event detection, PPM.
CST	Total concentration of pollutant in stream, PPM.
C_1	Chezy Coefficient.
D	Depth of stream, ft.
DP	Distance from sampling point to origin of pollution event, ft.
G	Acceleration of gravity, $ft./sec.^2$
HR	Hydraulic radius of stream, ft.
I	Time subscript for pollutant concentration at a point.
J	Counter for number of events in a set.
K	Location subscript for sampling point.
L	Time subscript for sampling at a point.
M	Counter for event detection.
NM	Counter for number of 1000 event sets.
NN	Counter for number of 50 event sets.
PEL	Location of pollution event origin measured from upper end of reach, ft.
Q	Streamflow, cfs.
QS	Pollutant quantity, lb.
RC	Manning "n" value.

RX	Generated uniformly distributed random number in range 0 to 1.0.
SPL	Location of sampling point measured from upper end of reach, ft.
T	Time, with beginning of 30 day period as time zero, min. or sec.
TA	Time added to pollution event detection interval due to continuous discharge, random or specified, min.
TF	Time of final detectable concentration point on dispersion curve.
TI	Time of initial detectable concentration point on dispersion curve.
TPE	Time of pollution event origin with beginning of 30 day period as time zero.
TSA	Time of sampling with beginning of 30 day period as time zero.
V	Stream velocity, fps.
VS	Shear velocity, fps.
XK	Longitudinal diffusion coefficient, $ft.^2$/sec.

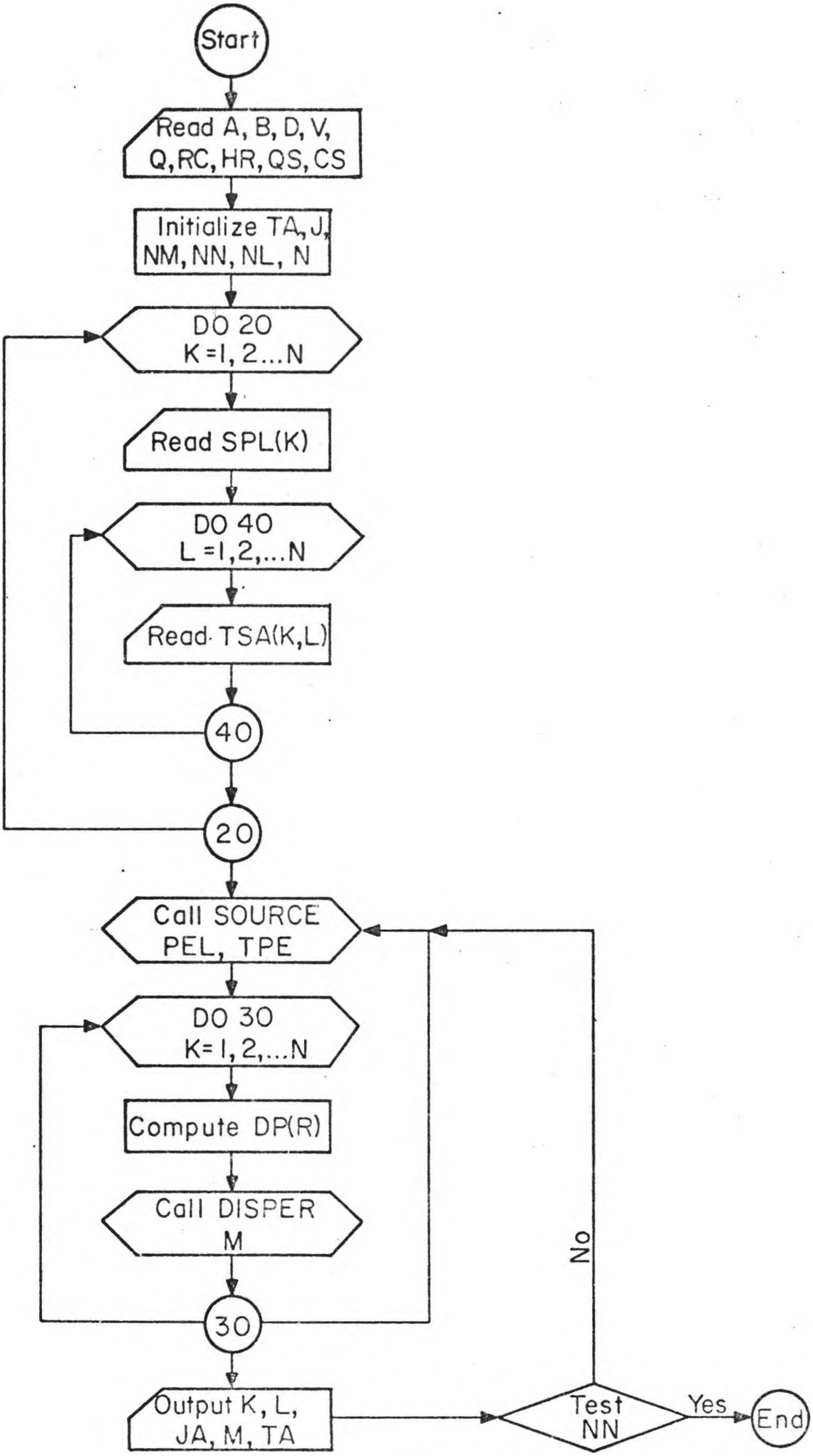

Figure A.1 Flow diagram for program DEPROB.

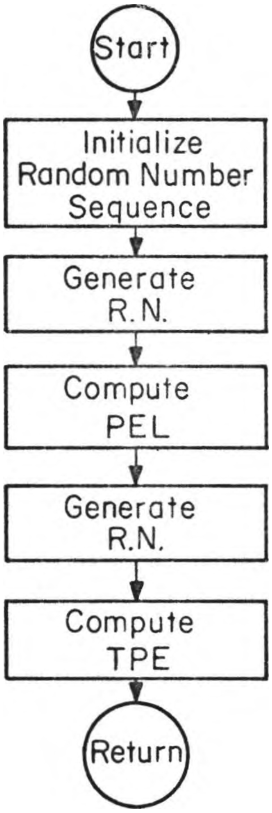

Figure A.2 Flow diagram for subroutine SOURCE.

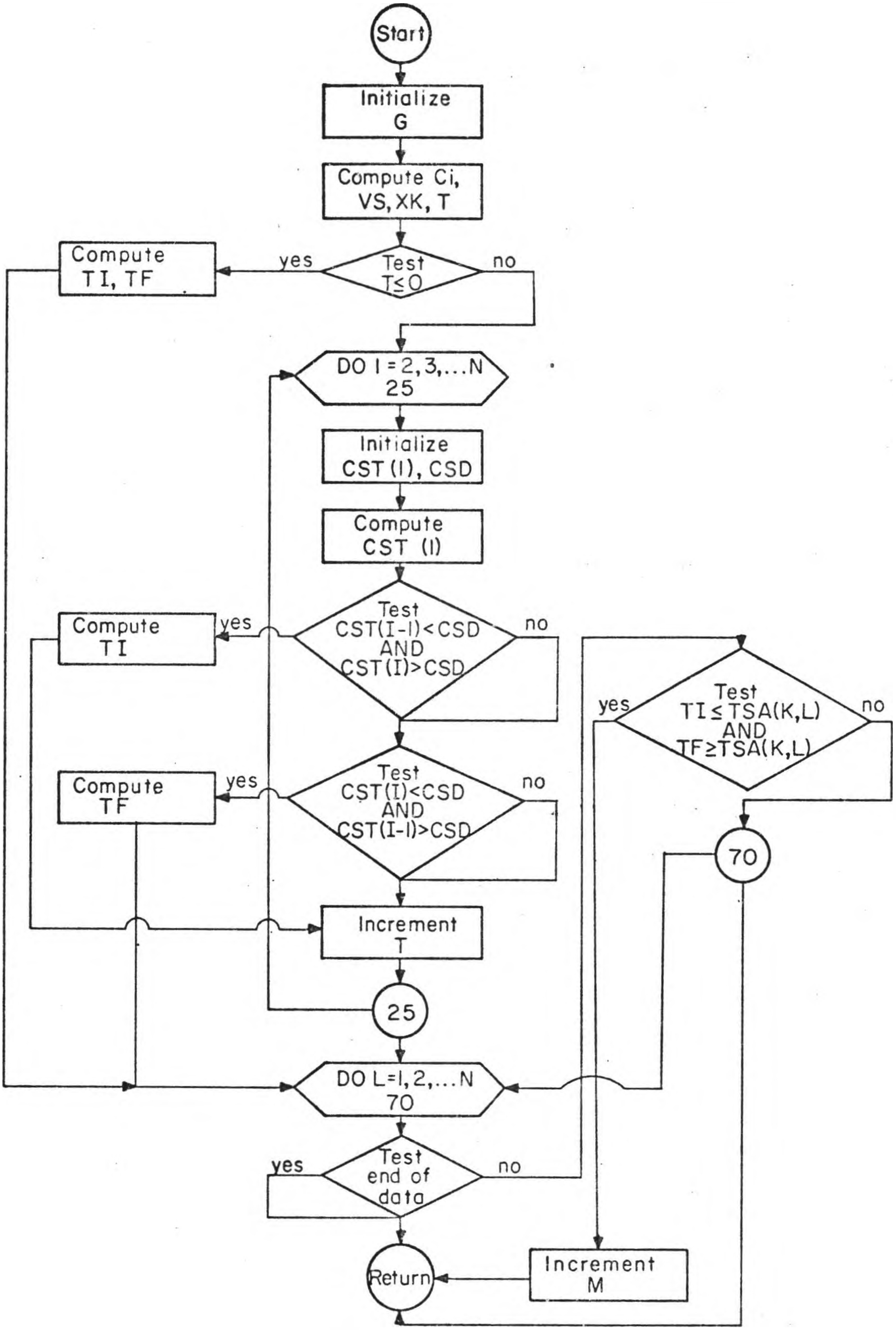

Figure A.3 Flow diagram for subroutine DISPER.

```
FTN.
LGO.
0000000000000000000000
      PROGRAM DEPROB
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON Q,V,B,D,A,RC,HR,QS,DP(50),CS,TSA(102,102),CST(99),K,TPE,PEL
     1,J,SPL(50),L,M,TA,MJ
C     THIS PROGRAM ESTIMATES DETECTION PROBABILITY OF AN INSTANTANEOUS
C     RANDOM POLLUTION EVENT WITH A CONSERVATIVE POLLUTANT
C     Q=FLOW,V=VEL,B=BOTTOM,D=DEPTH,A=AREA,RC=MANNING N,HR=HYD RAD,DP=
C     DIST TO SAMPLE  POINT, QS=LB POLLUTANT DUMPED
C     CS=BACKGROUND CONC IN STREAM IN PPM
      CALL RANSET(37.)
C     RANSET SPECIFIES START OF RANDOM NUMBER SEQUENCE
      NM=0
C     NM IS COUNTER FOR NUMBER OF 1000 EVENT SETS
C     TA IS TIME ADDED FOR CONTINUOUS DISCHARGE, RANDOM OR SPECIFIED
      NN=1
C     NN IS COUNTER FOR NUMBER OF 50 EVENT SETS
    1 READ(5,2)Q,V,B,D,A,RC,HR
    2 FORMAT(7F10.3)
    3 READ(5,4)QS,CS
    4 FORMAT(2F10.2)
      M=0
C     M IS COUNTER FOR EVENT DETECTION
      J=0
C     J IS COUNTER FOR NUMBER OF EVENTS IN A SET
      N=105
      DO 20 K=1,N
      READ(5,6)SPL(K)
    6 FORMAT(1F15.1)
C     SPL=SAMPLING LOCATION WITH UPSTREAM END OF REACH = 0
C     K IS SUBSCRIPT DESIGNATING SAMPLE POINT
      IF(SPL(K).EQ.5.)GO TO 60
      DO 40 L=1,N
      READ(5,8)TSA(K,L)
    8 FORMAT(1F15.1)
C     L SUBSCRIPT REFERS TO TIME OF SAMPLING AT A GIVEN STATION
C     TSA=TIME OF SAMPLING, MINUTES
C     MIDNIGHT ON FIRST DAY OF MONTH IS TAKEN AS TIME ZERO
      JB=L-1
      IF(TSA(K,L).EQ.3.)GO TO 20
   40 CONTINUE
   20 CONTINUE
   60 WRITE(6,51)
   51 FORMAT(1H1)
      WRITE(6,52)
   52 FORMAT(*  NUMBER     NUMBER     NUMBER     NUMBER    DISCHARGE*,/,* SA
     1MPLING    TIMES   POLLUTION    TIMES       TIME   *,/,* STATIONS   SAM
     1PLED    EVENTS   DETECTED    ADDED    *)
    7 CALL SOURCE
      MJ=1
      J=J+1
      JA=J-1
      IF(J.EQ.51)GO TO 50
      DO 30 K=1,N
      IF(SPL(K).EQ.5.)GO TO 7
      IF(MJ.EQ.2)GO TO 7
      DP(K)=SPL(K)-PEL
      IF(DP(K).LE.0.)GO TO 30
      CALL DISPER
   30 CONTINUE
      GO TO 7
```

```
   50 K=K-1
      L=L-1
      WRITE(6,54)K,JB,JA,M,TA
   54 FORMAT(1I5,3I10,1F10.1)
      NN=NN+1
      M=0
      J=0
      IF(NN.EQ.21)GO TO 70
      GO TO 7
   70 NM=NM+1
C     TA CAN BE VARIED HERE IF NOT ASSIGNED A RANDOM VALUE
      IF(NM.EQ.1)CALL EXIT
      NN=1
      GO TO 60
      END
      SUBROUTINE DISPER
      COMMON Q,V,B,D,A,RC,HR,QS,DP(50),CS,TSA(102,102),CST(99),K,TPE,PEL
     1,J,SPL(50),L,M,TA,MJ
C     THIS COMPUTES DISPERSION OF A POLLUTANT BY GLOVER METHOD
C     REFERENCE USGS PROF  PAPER 433-B
      G=32.2
      C1=(1.486/RC)*HR**0.167
C     C1=CHEZY COEFFICIENT
      Y=C1/G**0.5
      VS=V/Y
C     VS=SHEAR VELOCITY
      XK=500.*HR*VS
C     XK=LONGITUDINAL DIFFUSION COEFFICIENT
      T=(DP(K)/V)-6000.
      IF(T.LE.0.)GO TO 60
C     T=TIME, SEC
      N=105
      DO 25 I=2,N
      CST(1)=1.
      XA=(DP(K)-V*T)**2/(4.*XK*T)
      IF(XA.LT.0.001)XA=0.0
      XB=2.718**(-XA)
      XC=(4.*3.1416*XK*T)**0.5
      S=(QS/A)*(XB/XC)
      XM=S*1000.*(453.6/28.32)
      CST(I)=CS+XM
C     CST=TOTAL  CONC IN STREAM
      CSD=2*CS
C     CSD=DETECTABLE CONCENTRATION
      T=T/60.
      IF(CST(I-1).LT.CSD.AND.CST(I).GT.CSD)GO TO 30
      IF(CST(I).LT.CSD.AND.CST(I-1).GT.CSD)GO TO 40
      GO TO 22
   30 TI=T+TPE
C     TI IS INITIAL TIME OF DETECTABLE CONCENTRATION
      GO TO 22
   40 TF=T+TPE
C     TF IS FINAL TIME OF DETECTABLE CONCENTRATION
      RX=RANF(0.)
      TA=RX*4320.
C     TA MAY BE VARIED AT THIS POINT IF BEING ASSIGNED RANDOM VALUES
      TF=TF+TA
      GO TO 45
   22 T=T*60.
      T=T+300.
   25 CONTINUE
      RETURN
   45 DO 70 L=1,N
      IF(TSA(K,L).EQ.3.)GO TO 71
      IF(TI.LE.TSA(K,L).AND.TF.GE.TSA(K,L))GO TO 46
   70 CONTINUE
```

```
      GO TO 71
   46 M=M+1
C     THIS ASSUMES DETECTION IF TSA IS BETWEEN TI AND TF
C     M INDICATES NUMBER OF TIMES EVENT DETECTED
      MJ=2
   71 RETURN
   60 TI=TPE+(DP(K)/V)/60.
      TF=TI+TA
C     THIS ALLOWS DETECTION OF  A CONTINUOUS DISCHARGE WHEN SPILL IS TOO
C     CLOSE TO SAMPLING POINT FOR CALCULATION OF DISPERSION CURVE
      GO TO 45
      END
      SUBROUTINE SOURCE
      COMMON Q,V,B,D,A,RC,HR,QS,DP(50),CS,TSA(102,102),CST(99),K,TPE,PEL
     1,J,SPL(50),L,M,TA,MJ
C     THIS SUBROUTINE SELECTS RANDOM LOCATIONS AND TIMES FOR POLLUTION
C     EVENT OCCURRENCES, TPE=POLL EVENT TIME, PEL=POLL EVENT LOCATION
C     UPSTREAM END OF REACH=0
      RX=RANF(0.)
      PEL=RX*105600.
      RX=RANF(0.)
      TPE=RX*43200.
      IF(TPE.LE.1.)TPE=0.
      IF(PEL.LE.1.)PEL=0.
      RETURN
      END
```

APPENDIX B

THE COMPUTER PROGRAM FOR BASE LEVEL DATA ACQUISITION

APPENDIX B

The Computer Program for Base Level Data Acquisition

Brief Description

The program is written in Fortran IV language, with necessary additional instructions to run on a CDC 6400 computer. The main program is called HISDAT, containing the main logical network and data input and output instructions. Random number generation and the calculation of hypothetical data values are performed in subroutine NORDIS.

Table B1. Dictionary of Fortran Symbols Program HISDAT.

Fortran Symbol	Representation
AM	Specified mean of generated data.
AVE	Computed mean of observed data.
AVV	Computed mean of generated data.
I	Counter for number of observed data values.
J	Counter for number of trials.
K	Subscript for data day.
N	Number of generated data values.
S	Specified standard deviation of generated data.
SD	Computed standard deviation of observed data.
V	Generated random normally distributed data value.
VA(K)	Subscripted data value.

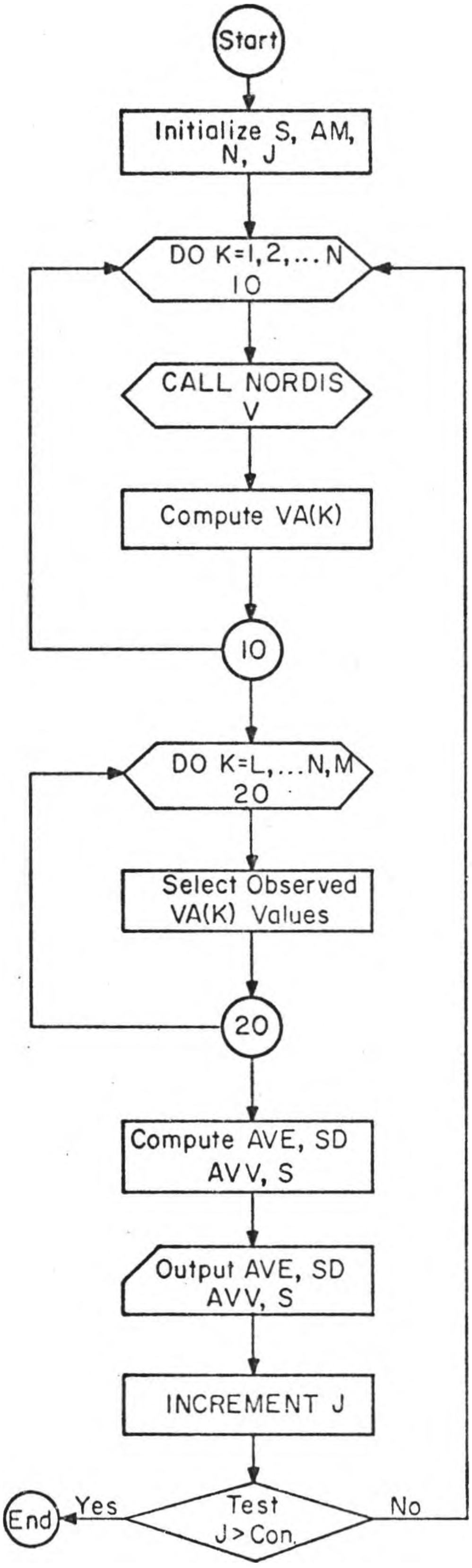

Figure B.1 Flow diagram for program HISDAT.

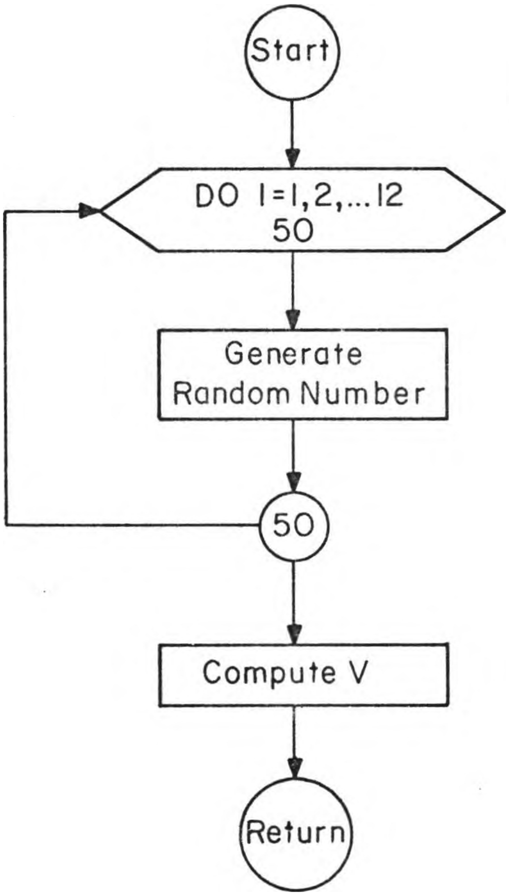

Figure B.2 Flow diagram for subroutine NORDIS.

```
FTN.
LGO.
0000000000000000000000
      PROGRAM HISDAT
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     THIS PROGRAM ESTABLISHES A SET OF DATA USING NORMALLY DISTRIBUTED
C     RANDOM NUMBERS WITH GIVEN MEAN AND STANDARD DEVIATI ON
      DIMENSION VA(1000)
      CALL RANSET(15.)
      N=365
      S=3.
C     S IS DESIRED STANDARD DEVIATION
      AM=35.
C     AM IS DESIRED MEAN
      J=1
    1 WRITE(6,3)
    3 FORMAT(1H1)
      TOTA=0.0
      TOA=0.0
      DO 10 K=1,N
      CALL NORDIS(S,AM,V)
      VA(K)=V
      LA=K
      TOTA=TOTA+VA(K)
   10 CONTINUE
      AVV=TOTA/365
      TOT=0.0
      I=0
      DO 20 K=5,365,90
C     SAMPLING INTERVAL IS SPECIFIED IN THIS STEP
      WRITE(6,16)VA(K),K
   16 FORMAT(*  OBSERVED CONC IS*,1F10.5,* ON DAY*,I5)
      TOT=TOT+VA(K)
      TOA=TOA+VA(K)**2
      I=I+1
   20 CONTINUE
      AVF=TOT/I
      WRITE(6,22)AVE
   22 FORMAT(1H0,* THE MEAN ANNUAL OBS CONC IS*,1F10.4)
      WRITE(6,12)AVV
   12 FORMAT(*   OVERALL MEAN IS*,1F10.5)
      TOB=TOT**2/I
      SS=(TOA-TOB)/(I-1)
      SD=SQRT(SS)
C     SD IS STANDARD DEVIATION OF OBSERVED DATA
      WRITE(6,24)SD
   24 FORMAT(*  STANDARD DEVIATION OF OBS DATA IS*,1F10.5)
      AM=AM+1.
      J=J+1
      IF(J.GE.11)CALL EXIT
      GO TO 1
      END
      SUBROUTINE NORDIS(S,AM,V)
C     THIS SUBROUTINE COMPUTES A NORMALLY DISTRIBUTED RANDOM NUMBER WITH
C     A GIVEN MEAN AND STANDARD DEVIATION REF- SCIENTIFIC SUBROUTINE
C     PACKAGE SUBROUTINE GAUSS
      A=0.0
      DO 50 I=1,12
      Y=RANF(0.)
   50 A=A+Y
      V=(A-6.0)*S+AM
      RETURN
      END
0000000000000000000000
```