Environmental Engineering

Department of Civil Engineering
University of Massachusetts at Amherst

Technical Report

The Feasibility of Variable Flow Discharge Permits for Wastewater Treatment Plants

Ileen Gladstone
Graduate Research Assistant

Richard R. Noss
Assistant Professor

October 1983 3

October, 1983
Env. Eng. Report No. 79-83-10

Technical Report

The Feasibility of Variable Flow Discharge Permits for Wastewater Treatment Plants

by

Ileen Gladstone
Graduate Research Assistant
and
Richard R. Noss
Assistant Professor

Department of Civil Engineering
Environmental Engineering Program
University of Massachusetts
Amherst, Massachusetts 01003

Submitted to the

Massachusetts Department of Environmental Quality Engineering
Division of Water Pollution Control
Anthony D. Cortese, Commissioner
Thomas C. McMahon, Director

October 1983

The Feasibility of Variable Flow Discharge Permits for Wastewater Treatment Plants

ACKNOWLEDGEMENTS

This material is based upon work supported in part by the Massachusetts division of Water Pollution Control. This report is the Master of Science thesis of the senior author.

Special thanks is extended to the staff of the Engineering Computer Station: Charlie Wilson, Dave Rosenberg and Kathy Rubin. Their advice, instruction, and support were instrumental in the execution and production of this work.

ABSTRACT

The objective of this work was to assess water quality standards, to propose alternative methods of establishing water quality standards and to demonstrate their impact on effluent discharge standards. Included is an extensive discussion of the development and use of water quality standards, and the distinction between standards and criteria. The discussion continues with a reaffirmation of the capacity of a stream to assimilate wastes. In addition, the practice of low flow protection and the subsequent selection of critical low flows are explored. Two interpretations of the "intent of standards" are presented. Graphical and regression analysis was performed on streamflow and quality data from the Quinebaug River in Massachusetts to demonstrate the feasibility of flow variable discharge permits. The discussion concludes with the proposal of seasonally based flow variable discharge permits for wastewater treatment plants.

TABLE OF CONTENTS

Chapter

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The management of stream quality has relied on the establishment of instream water quality standards coupled with wastewater discharge standards. An effluent discharge standard is a limitation applied to individual point sources of pollutants. They specify the allowable quality and quantity of a discharge. Water quality standards are legal, regulatory statements which must consider technological and political feasibility, the cost of achievement and administrative practicality. A water quality standard is composed of two parts. The first element is the definition of the designated uses of a water body; the second is the stipulation of appropriate criteria to assure that these intended uses are obtained.

Although a water quality standard is defined as a combination of these two elements, it actually has a much more far reaching affect as summarized by Feliciano (23).

> Water quality standards publicly define a state's water quality objectives and form the basis for its planning; They provide a basis for effluent limitations for pollutants not specifically addressed in the effluent guidelines or for pollutants for which the

> effluent guidelines are not stringent enough to protect desired uses; they serve as a basis for evaluating and modifying best management practices for the control of non-point source wastes; and they serve as a basis for judgement in other water quality related programs.

The attainment of water quality standards was integrated into the philosophy of water pollution control established by the Federal Water Pollution Control Act (FWPCA) Amendments of 1972 (66). O'Neil (47) asserts that social attitudes towards water quality has undergone two transformations. The first phase occurred during the 1960's when society recognized the extent of environmental pollution and culminated in the passage of the 1972 Amendments. The Amendments set forth a coherent, far-reaching and longterm national policy for correcting and controlling water pollution. The idealistic and herculean ambitions of the legislation is reflected by its ultimate goal--the elimination of all discharge of pollutants into the nation's waterways. The second transformation, which is still in progress, is the realization that the accomplishment of the original goal is prohibitively expensive. The original goals are being reevaluated and redefined. The beginning of this second transformation was marked by the passage of the Clean Water Act of 1977 (60). It included provisions for the Environmental Protection Agency (EPA) to review, and if necessary revise, effluent limitations and standards. The recognition that the control of water pollution is still a basic element of this second phase, but accompanying the desire for clean water is the realization that the solution must be economically efficient as well as environmentally effective.

Under the mandate of the FWPCA Amendments of 1972, the EPA developed technology based effluent limitations for all point source discharges. Where these limitations were inadequate to meet the water quality standards, the regulations necessitated the implementation of more stringent limits on point sources. The EPA has completed the needed effluent guidelines and the application of technology based regulations; now the EPA has begun to re-evaluate water quality standards. The proposed changes are intended to "provide states and local governments with increased flexibility to operate their programs and to assure that the basic requirements of the Clean Water Act are satisfied (65)." The main thrust of the modifications is the implementation of an approach to pollution control based on water quality by developing site-specific criteria to reflect local conditions.

Aside from using site-specific criteria there are many alternative approaches to water quality standard specification. There is a great potential for flexibility in water quality standards which in turn creates flexibility in effluent standards. It is the objective of this thesis to reassess water quality standards and demonstrate their impact on effluent standards.

The assessment of water quality standards includes a discussion on the development of standards and the difference between standards and criteria. The discussion continues with a reaffirmation of the capacity of a stream to assimilate wastes. In addition, the practice of low flow protection and the subsequent selection of a critical low flow is presented.

The examination of water quality standards serves as the foundation to understanding the concept of the "intent" of a standard. Some of the alternative methods of defining water quality standards may be evaluated only if the intent of the standard is scrutinized and the policy developed is in accordance with these intentions. The existence of some of the characteristics necessary to allow for modified effluent discharge permits is demonstrated by graphical and regression analysis. The data set used contains daily values for discharge, dissolved oxygen and specific conductance. The discussion concludes with the proposal of variable discharge permits based on seasonal variations of streamflow.

CHAPTER II

DEVELOPMENT AND USE OF WATER QUALITY STANDARDS

Standards vs. Criteria

The quality of a stream is not absolute, it is dependent on the intended use of that waterbody. Velz (69) identifies seven basic uses of streams:

1. Community and industrial water supply,
2. Electric power generation (hydro, fossil fuel atomic fuel),
3. Recreation (bathing, fishing and sports),
4. Irrigation,
5. Navigation,
6. Fish, shellfish and wildlife,
7. Ultimate disposal of wastewater.

Potable water must be hygienically suitable, with limits on harmful or aesthetically objectionable substances. Some industrial uses are limited only by water quantity, regardless of the chemical or bacteriological content. Other industries may require chemical restrictions more stringent than those for potable water. Dissolved oxygen is critical for fish, whereas, shellfish are most sensitive to bacterial effects. Each use may require a different water quality.

When the federal government issued the current guidelines for the water quality to be achieved by state water pollution programs it acknowledged only two legitimate uses. The Environmental Protection Agency (EPA) (19) stated as its policy that "all waters should be protected for recreational uses in and/or on the water and for the preservation and propagation of desirable species of aquatic biota--fishable, swimmable." Exceptions would be made of some waters "because of naturally occurring poor quality, man-made pollution or technological limitations." There are only a few hundred streams designated for uses less stringent than for the protection and propagation of fish and recreation. In addition, eight states have streams designated as Outstanding Natural Resources (23).

Criteria are not synonymous with standards. Water quality criteria specify quantitative concentrations or qualitative assessments of water constituents or parameters which, if exceeded, interfere with the intended use of a water body. Criteria are derived from scientific experimentation. The experiments may be in a laboratory, often as a bioassay test, or as *in situ* observations. They incorporate not only the chemical and physical properties of the water but also the effects, persistence, accumulation and fate of toxic, chemical, microbiological and radiological constituents. Criteria are not legal entities.

The criteria used to establish water quality standards can be traced to the "Water Quality Criteria" published by the State of California in 1952 and revised in 1963 (6). The National Technical Advisory Committee published its "Water Quality Criteria," known as the Green Book, in 1968 (43). This was followed by the National Academy of Sciences publication in 1973 of "Water Quality Criteria 1972," the Blue Book (42). In 1976 the EPA published "Quality Criteria for Water," this is known as the Red Book (22). The Red Book contains the most recent criteria.

The validity of these criteria, and the methods by which they were developed have been questioned. Criteria have often been developed using laboratory toxicity or bioassay tests, they are an integral part of standards. The experimental data often collected is that constituent concentration that would be lethal to 50% of the organisms during the duration of the test--LC50. Typically, the duration of the test is 96 hours. This produces a single piece of information to be included in a standard. It does not address the range of contaminant exposure from acute instantaneous exposures to long term chronic exposures. In addition, it assumes that the protection of fish is synonymous with controlling mortality. It does not provide the information to allow for protection such as the safeguarding of spawning ability, growth rate or morbidity (45).

The use of single species tests may also be questionable. Ecological systems are highly complex, and the interactions of different organisms are crucial in establishing the tolerances of a community. The assumption implicit in the use of single species test is that the test organism is the most sensitive species, and that by protecting it all other species are protected. However, only a relatively small number of species are used for laboratory testing; it cannot be concluded that one of these available species is actually the most sensitive in a system. Conversely, the single species test does not account for the complexity of natural systems and their various types of redundancies; the criteria may just as likely be overprotective (5).

In many cases criteria were not developed from laboratory tests whose sole intent was to provide the needed scientific data for criteria. Much of the literature used studied organism behavior; the intent of the research was not criteria development. The experimental methods were not standardized for the purpose of criteria development, nor was the information gathered in a systematic way. Synthesizing this diverse data into criteria requires professional judgment and integrity; but the authors of the criteria are unknown. This anonymity conceals the credentials of those making scientific decisions (5).

Krenkel (32) points out that some water quality standards are below *minimum* detectable limits. Table 1 shows several parameters, their minimum detectable concentrations (as reported by well experienced, reputable laboratories using the latest instrumentation and techniques) and their associated criteria.

The EPA recommends that criteria be expressed as numerical values where ever possible (22). If that is not practical biological or bioassay parameters should be used. Narrative descriptions are appropriate when other values can not be established.

Numerical limitations of water quality standards may be expressed in several forms. The most common is by establishing a threshold value which is either a maximum or minimum concentration, e.g. "the concentration of cyanide may not exceed 5.0 ug/l." In place of a threshold value the limits may be stated as a statistical occurrence, "the total dissolved solids shall not exceed 250 mg/l for a 90 day arithmetic mean." "Temperature not to exceed 2 F above that due to natural causes" is an example of a limitation that incorporates natural conditions. The simple threshold limit may be modified by stipulating a duration along with a

Table 1

Comparision of Minimum Detectable Concentrations (MDC) in Many Laboratories with Water Quality Criteria (32)

Parameter	MDC (ug/l)	Standard Deviation (ug/l)	Accuracy (% Bias)	Water Quality Criteria (ug/l)
Hg	0.2	0.28 @0.21	66. @0.21	0.05
Se	2.0	0.6 @5.0	100.0 @5.0	0.01
Cd	2.0	5.0 @1.4 2.8 @2.8	135.0 @1.4 4.7 @2.8	0.04
CN^-	20.0	5.0 @60.0	85.0 @280.0	5.0
Cl (DPD)	100.0	46.0 @100.0	8.1 @280.0	5.0
Phenol	5.0	1.0 @9.6	--	1.0
	2.0	9.5 @3.8	78.0 @5.3	-- --

concentration, "dissolved oxygen may not be less than 7 mg/l 16 hours/day and not less the 5 mg/l at anytime." Likewise, the statistical threshold may be made more complex, "coliform bacteria may not exceed a median of 1000 per 100 ml and may not exceed 2400 in more than 20% of the samples collected (3)."

The responsibility for establishing water quality standards was delegated to the states by the Federal Water Pollution Control Act (FWPCA) Amendments of 1972 (66). The Amendments require for the EPA to develop and publish water quality criteria that could be used by the states to establish water quality standards. These standards were subject to EPA approval. Every three years the states are required to review, and if necessary, update the standards, again subject to EPA approval.

The introductory pages of the Red Book acknowledge that nationwide standards are inappropriate, and that the natural variability of the nation's ecosystems preclude the federal government from creating standards. However, in 1978 the EPA asserted a policy of "presumptive applicability" which essentially forced the states to adopt the criteria presented in the Red Book as their standards. Presumptive applicability assumed that the data base used to establish the Red Book criteria was broad enough to account for the local variability (63). The EPA would approve of state standards less stringent than the of the Red Book criteria only if a state could provide adequate technical justification for the deviation. It became the burden of the state to provide the documentation necessary to allow for the flexibility of criteria applicable to local conditions, but the EPA provided no guidance of how this was to be accomplished.

Types of Standards

The most common method of establishing a water quality standard is to prescribe a limiting threshold value. This value is often that of the Red Book criterion. However, many states have deviated from the Red Book values, usually proposing standards which are more stringent.

Dissolved oxygen is a parameter commonly used to indicate the quality of a stream. All states have a dissolved oxygen standard. The Red Book (22) criterion for fresh water aquatic life is that the "minimum concentration of dissolved oxygen to maintain good fish population is 5.0 mg/l." This criterion also stipulates an aesthetic requirement that the "water should contain sufficient oxygen to maintain aerobic conditions in the water column..."

The dissolved oxygen standards in Massachusetts (10) is simply a slight variation of the Red Book criteria. The standard uses two categories, warm water and cold water fisheries, stipulating that the dissolved oxygen concentration should not fall below 5 mg/l and 6 mg/l, respectively.

The dissolved oxygen standard in Maine (18) is more flexible than a single threshold value. It accounts for designated uses and local conditions. In its antidegradation policy, Maine recognizes that it is "...sufficiently large and diverse that natural water quality varies considerably throughout its limits (15)." Maine has five classifications of fresh waters and five classsifications of tidal or marine waters; each class has been assigned a dissolved oxygen level in accordance to its use (Table 2). Class B waters are suitable for recreation, potable water supply and for fish and wildlife habitat. The standard insists that dissolved oxygen concentrations must be at least 75% of saturation and can never fall below 5 mg/l. This standard is more stringent than the Red Book criterion; the 75% dissolved oxygen saturation of 25 C water is 6.30 mg/l and that of 10 C water is 8.48 mg/l. The Maine standard demands high water quality, but it is flexible, allowing for the effects of locality and seasonal temperature variations.

Table 2

Designated Use and Dissolved Oxygen Standard
State of Maine (17, 18)

Classification	Designated Use	DO Standard
Class A	Highest classification and shall be of such quality that it can be used for recreational purposes, including bathing, and for public water supplies after disenfection.	Not less than 75% saturation.
Class B-1	Acceptable for recreational purposes, including water contact recreation, for use as potable water supply after adequate treatment and for fish and wildlife.	Not less than 75% saturation, and not less than 5 ppm anytime.
Class B-2	Acceptable for recreational purposes, including water contact recreation, for industrial and water supplies after adequate treatment, and for a fish and wildlife habitat.	Not less than 60% saturation and not less than 5 ppm anytime.
Class C	Satisfactory for recreational boating and fishing, for a fish and wildlife habitat and for other uses except potable water supplies and water contact recreation, unless such waters are adequately treated.	Not less than 5 ppm at anytime.
Class D	Only where a higher classification can not be attained after utilizing the best practicable treatment or control of sewage or other wastes. Water of this class may be used for power generation, navigation and industrial process waters after adequate treatment.	Not less than 2 ppm at anytime.

In 1980 the EPA modified its policy, conceding that presumptive applicability was too rigid and limiting. The agency acknowledged that the Red Book criteria were based on laboratory conditions, which might impose overly stringent criteria, not ambient surface water conditions.

> In certain circumstances, the criteria may not accurately reflect the toxicity of a pollutant because of the effect of local water quality characteristics or varying sensitivities of local populations. For example, in some cases, ecosystem adaptation may enable a viable balanced aquatic population to exist in waters with high natural background levels of certain pollutants. Similarly, certain compounds may be more or less toxic in some waters because of differences in alkalinity, temperature, hardness and other factors (64).

Presumptive applicability caused criteria to become standards. It disregarded that standards are legal entities incorporating not only uses and their associated criteria, but economic, technological and administrative practicality.

Assimilative Capacity

The practice of using rivers and streams as the receiving waters for sewage did not begin until the late 19th century. Previously, wastewater was deposited in dry wells, leaching cesspools (holes lined with broken stones), or by simply throwing it on the ground (57). The development of piped-in water and the flush toilet produced the problem of large volumes of wastewater, making the commonly used methods of disposal inadequate. The increased water flows led to the overflowing of cesspools. Public health officials, city planners and engineers recognized the health hazards and the necessity to develope a new wastewater disposal system.

The practice that developed was a "water carriage system" which used the wastewater itself as the transmission medium (57). Most cities built combined sewers in which both storm runoff and sewage were collected in the same pipe; this wastewater was then disposed of in the river. This procedure was based on the belief that a legitimate use of a stream is the receiving and transporting of wastes, and that running water purifies itself, concepts that are generally incorporated by the term "assimilative capacity."

Chow (8) defines the waste assimilative capacity of a stream as the "amount of waste which will not cause water quality deterioration beyond the limits required for other beneficial uses." Any wastewater disposal scheme apart from "zero-discharge" uses the self-purification potential of a stream. Four principle wastes that a stream must assimilate are organic, microbial, inorganic and thermal (69). Traditionally, the greatest stress placed on a waterway has been the depletion of oxygen due to the decay of organic matter. Self-purification proceeds as a combination of physical, chemical and biological processes. Biochemical stabilization and dilution are crucial along with forces such as settling, photosynthesis, reaeration and oxidation-reduction. Suspended solids will settle if the stream velocity is less than the scour velocity of the particles (56). Currents assist in the dispersion of organics and the prevention of sludge deposits (44). Sunlight acts as a bleaching agent in the removal of color, and as a disinfectant (26). The potential for self-purification in each stream is unique and dynamic.

Dissolved oxygen is essential to a healthy stream. Several mechanisms of self-purification aid in reaeration. Sunlight is the driving force of photosynthesis. During the day photosynthesis by green aquatic plants reduces the concentration of carbon dioxide and increases that of dissolved oxygen. Turbulence continually creates new water air interfaces for the exchange of gases, in this way oxygen is added to the water and carbon dioxide is removed. Temperature affects the solubility of oxygen in water and the role of reaeration.

Dilution is a critical component of stream self-purification. It is a physical phenomenon which reduces the concentration of constituents to a level where they may be effectively assimilated by such processes as biochemical stabilization without adversely affecting overall water quality in a stream.

Waterways are multiple use resources, and as such they must not be the victims of single minded objectives. Although the use of streams to receive, transport and assimilate wastes are legitimate, the indiscriminate dumping of raw industrial and municipal wastes is not. The capacity of a stream to assimilate the waste disposed in it is an essential resource which must be used prudently. The challenge in waste disposal is to use the stream efficiently, while maintaining it as a multipurpose resource. The assimilative capacity of a stream may be integrated into water quality standards as long as it is not abused.

The FWPCA Amendments of 1972 (66) require states to limit point source discharges. In addition, water quality standards must be achieved. These two approaches are to be used concurrently to achieve the goal of "fishable, swimmable waters." Discharge limitations are assigned to individual point sources of pollutants; they specify the allowable quality and quantity of the discharge. The minimum treatment levels are based on practical, possible or achievable technology, and are applied independent of existing water quality.

The effluent standard for secondary wastewater treatment plants is:

> The arithmetic means of the secondary effluent five day, biochemical oxygen demand (BOD) and suspended solids (SS) concentrations shall not exceed 30 mg/l in a period of 30 consecutive days, nor shall exceed 45 mg/l in a period of 7 consecutive days. In addition, the arithmetic mean of the concentration of BOD and SS remaining in the effluent over any thirty day period shall not exceed 15 percent of the arithmetic mean of the values in the influent (85 percent) (61).

This standard is based on what can be achieved technologically without considering water quality standards. It is rigid and does not consider the possibility of either the underprotection or overprotection of stream quality.

A stream segment must be defined as being water quality limited or effluent limited. An effluent limited stream exists when the water quality standards are met by attaining the effluent standards. A reach is water quality limited if the effluent standards are not sufficient to meet the water quality standards.

Low Streamflow Analysis

The determination of whether a stream is either effluent limited or water quality limited is typically accomplished by examining the stream quality during low flow conditions. The frequency and magnitude of low flows are incorporated in water quality management decisions. The physical and chemical qualities of a stream differ between high and low flows, and the low flow conditions are usually worse. The aesthetic quality of a stream is often degraded during low flows and parts of the channel bed are exposed. The concentration of dissolved materials tends to increase during low flows, undesirable plants may prosper and the capacity to maintain aquatic life is reduced (50).

Statistical methods. Statistical methods of analyzing low flows have been developed. One method is a recurrence interval analysis using Gumbel's theory of extreme values. It enables a hydrologic data series to be presented as a straight line on extreme probability paper by assuming that the series follows a standard skewed distribution (9). The extreme probability grid which predicts the probability of the exceedence of flood flows has been transformed to accommodate drought flows by assuming that the cause of the low flow is a "hydrological event" in the same fashion that a high (flood) flow is presumed caused by a hydrological event. This method is adapted to low flows by ranking each event in its order of severity rather than in its order of magnitude (the lowest flow has a rank of one) and accounting for three time elements (69):

1. The season in which the selection is made,
2. The length of time over which a low flow is averaged,
3. The base unit of time from which a low flow is selected from the record

The season in which the choice of the year's extreme value is made is important. The characteristics associated with low flows due to winter freezing and ice cover are quite different from warm weather low flows (69). The warm weather low flows and their high temperatures are much more significant to water quality management because adverse and undesirable conditions are more likely during low flow conditions than at other times.

The duration of the low flow may be taken as any consecutive period, regardless of the calendar. For sophisticated analysis, Velz (70) recommends four separate low flows--the minimum daily average and the minimum consecutive seven day, fifteen day and thirty day averages. Practical problems may be resolved using the extreme values of the minimum daily and minimum monthly averages, and the minimum consecutive seven day average.

The base unit of time must contain a large set of observations from which to choose the extreme values. An annual series is often used in analyzing streamflow. Most records are reported as daily average flows, thus a base unit of one year contains 365 observations.

An annual series is used to construct a low flow frequency curve, and is composed of the lowest flow of each year of record. The number of extreme events considered equals the number of years of record.

An annual series may be summarized as a cumulative distribution function. A cumulative distribution function relates the probability of outcomes in the range of occurrences that are less than or equal to a stated limiting value. It provides a rapid means of determining the probability of the event equal to or less than some specified quantity (71). This attribute is used to obtain recurrence intervals for observed data.

There are several expressions relating rank of flow, years of record and recurrence interval. A simple and often used approximation of the recurrence interval is:

$$T = (n+1)/m$$

where: T = recurrence interval
m = rank of the low flow
n = years of record

The recurrence interval is the average number of years during which a flow of a specified magnitude or less will be expected to occur. A low flow frequency curve is constructed by plotting each low flow against its associated recurrence interval (or return period). The recurrence interval (T) can be related to the probability (P) that a low flow of a given magnitude or lower will occur in a given year by P=1/T.

The partial duration series is an alternative to the annual series. Extreme values are analyzed without regard to the period (that is, year) of occurrence. The partial duration series is constructed without a base unit of time. It accounts for the possibility that the second lowest flow in any year may be higher than the lowest flow of another year (55). All the events are ranked in their order of severity without regard to the year in which they occurred. The base flow is chosen such that the number of flows included in the partial duration series is equal to the number of years of record (8). Since the lowflows were ranked only by magnitude, a year may be represented by more than one flow, while another year may not be represented at all within the series. The partial duration series may be preferred when investigating short recurrence intervals (35) or long durations (ie., periods over which the flows are averaged (56).

A complete series consists of all observed data (13). A low flow duration curve is based on a complete series. The flow duration curve is a cumulative frequency curve which depicts the percent of time during which specified discharges were equaled or exceeded (13). The curve is prepared by ranking all the time-averaged low flows in ascending order and calculating the percent of time each flow is equalled or exceeded. The curve is drawn as a best fit curve of specified discharges verses the percent of time during which they were equaled or exceeded (13). Percent of time is used rather than return periods since the complete series was used. The flow duration curve represents the availability and variability of sustained flow but not the actual sequence of flows (71). Figures 1 and 2 represent a low flow frequency curve and a flow duration curve.

7Q10. A low flow characteristic refers to a low flow of specified duration and return period. A commonly used low flow characteristic is the 7Q10--the average seven day low flow which is expected to occur, on the average, once in ten years. The 7Q10 is determined from the low flow frequency curve fabricated from the annual series of seven day flows. The flow associated with the ten year recurrence interval is the 7Q10. In the situation of the 7Q10 the recurrence interval is ten years and thus there is a one in ten year chance (P=0.10) that a low flow less than the 7Q10 will

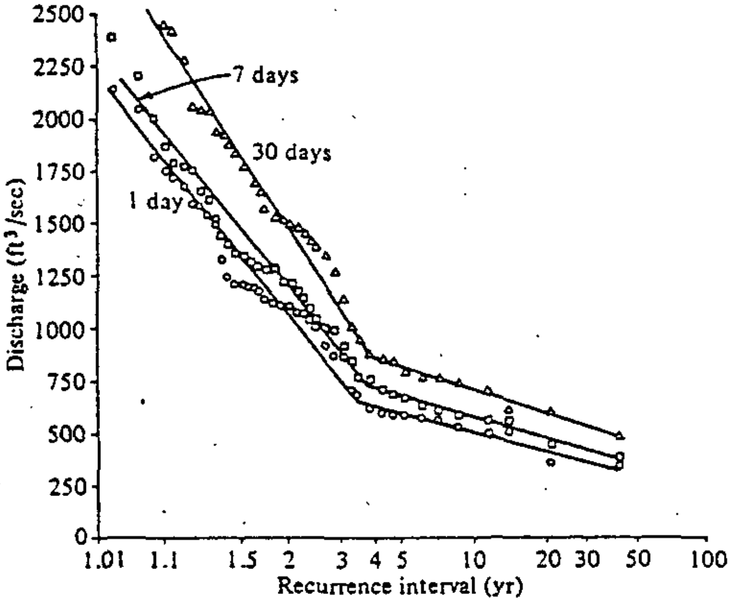

Figure 1. Sample low flow frequency curve (70).

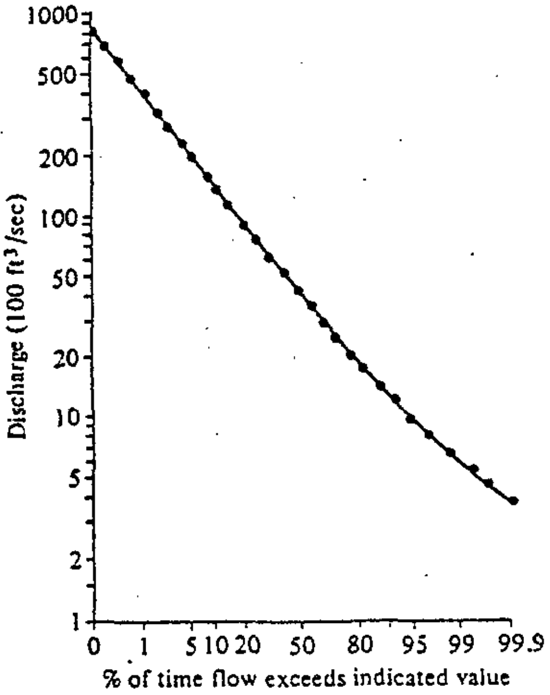

Figure 2. Sample low flow duration curve (70).

occur.

Ray and Walker (48) investigated the percentage of time the 7Q10 was equaled or its severity exceeded at thirty United Stated Geological Survey (USGS) gauging stations on Virginia rivers. They concluded that in all cases but one, the seven day ten year low flow standard provided a minimum design flow that was equal to or less than 99% of the daily flow. The one exception was exceeded by 98% of the daily flows. That is, although flows less than, or equal to, the 7Q10 are expected only once in ten years in actual fact they are exceeded by 99% of the daily flows.

This apparent discrepancy between the recurrence interval and probability of exceedence may be clarified by realizing that it is a 10% probability of the years as opposed to the less than 1% probability of all the seven day flows.

The example provided by Male and Ogawa (36) presents fifty years of record, the recurrence interval method would consider only fifty flows--the lowest seven day flow of each year. The fifth ranked low flow would have a ten year recurrence interval (m=5; t=n/m=50/5=10), and the associated probability would be 5/50 or 0.10. In the complete series this same low flow is part of 2600 events (ie. fifty-two seven day series per year for fifty years), and its probability of exceedence would be 5/2600 or 0.0019. Thus the 7Q10 is exceeded by more than 99 percent of the daily flows.

The routine way of protecting streams during low flow conditions is to stipulate a critical flow and to regulate that the water quality standards must be meet at that and all exceeding flows. The Environmental Protection Agency (EPA) does not specify how this is to be accomplished but it explicitly states:

> measure of time period and limiting values which will govern for purposes of the criteria must be defined, e.g. annual arithmetic mean concentration. Where appropriate, the specified recurrence and duration of the accepted design stream should be defined, e.g., 7-day 10-year frequency return flow. (19).

The majority of states have chosen the 7Q10 as this single critical flow. Several states have chosen critical flows other than the 7Q10 (20). Texas and Oklahoma use a 7Q2, South Dakota a 7Q25, Tennessee a 3Q20 and New Hampshire a 10Q20. Some states do not specify a critical low flow at all.

Use of the 7Q10 has a long historical precedent, but apart from habit the reasons for its choice are unclear. The seven day duration may have been selected to average out the manmade fluctuations in discharge and stream quality occurring over a week. And ten years is a nice round number.

The protection of water quality offered by one critical low flow over another is insignificant. Sherwani (52) compared the 7Q10 and 30Q10 of twenty seven North Carolina streams examining the percent of time the low flows were exceeded (Table 3). These comparisons illustrate the arbitrary nature of selecting a critical low flow. The percent of time the 7Q10 and the 30Q10 are exceeded are almost the same, and both are exceeded significantly greater than 90% of the time. However, the choice of the critical low flow has important implications. The choice includes not only a magnitude, but in addition, a duration and frequency. This in turn effects the severity of the water quality standard designed around it.

Table 3

Duration Percentages for Specific Flows from Sherwani's Results on 37 Streams in North Carolina (52)

	Average Flow	7-Day, 10-Year Flow		30-Day, 10-Year	
	(cfs/sq mile)	(cfs/sq mile)	% time >	(cfs/sq mile)	% time >
mean	1.74	0.206	99.08	0.251	97.91
max	3.74	0.766	99.4	0.884	98.55
min	0.81	0.000	98.6	0.0	97.0

CHAPTER III

THE INTENT OF STANDARDS

The promulgation of water quality standards has derived from the government's guardianship of the public health and welfare. Traditionally most water pollution control programs were sponsored by state public health departments (4). In general, water borne epidemic diseases have been arrested, yet the scope of these programs have been expanded to include more sophisticated concerns. Health efforts have broadened to incorporate the effects of small amounts of toxic chemicals on humans and other forms of life (4). The avoidance of nuisance once was the primary aesthetic concern (41); however, society's aesthetic aspirations have also increased to include aquatic and ecological protection. The growth of industries and cities has led to widespread, severe and observable water pollution. As society has become increasingly affluent and leisure oriented its demand for outdoor recreation has grown (11). Society has increasingly turned to government to control and improve water quality. As its perception of water quality has changed it has asked pollution control agencies to "express quality in numerical terms and then translate these numbers into other qualitative factors which in themselves are not conceived as continuous variables (41)."

In the Federal Water Pollution Control Act (FWPCA) Amendments of 1972 the federal government responded to these requests by completely altering the tactics used to control water pollution. Previous water pollution control legislation relied only on instream water quality standards; the FWPCA 1972 Amendments (66) established a new direction by imposing uniform effluent standards. The National Pollutant Discharge Elimination System (NPDES), a national permit program was created to control and monitor the discharge of pollutants into the nation's waterways (21). The FWPCA required publicly owned wastewater treatment plants to provide a minimum of "secondary treatment" by July, 1 1977 and to apply "best practicable technology" by July 1, 1983 (66). Secondary treatment was subsequently defined by the Environmental Protection Agency (EPA) as discharges of 30 mg/l BOD and 30 mg/l SS (61). However, where this discharge is inadequate to meet the instream water quality standards more stringent discharge permits must be issued. Thus the effectiveness of the Act relied on the coupling of national uniform effluent standards and instream water quality standards.

The "intent" of the water quality standard is subject to two conflicting interpretations. One is that the standard is the minimum (or maximum) acceptable instream concentration of a constituent and what is truly desired are conditions superior to the standard. An alternative interpretation is that the water quality standard means what it says, and better water quality is not necessary to maintain a healthy aquatic environment. In this case achieving the standard assures protection of the multiple uses of the stream. This distinction may be further clarified by examining the dissolved oxygen standard used by many states.

Dissolved Oxygen

Historically, dissolved oxygen concentrations have been considered significant as a stream quality indicator. Dissolved oxygen has been used as an index to protect aesthetic qualities of water as well as for the maintenance of fish and other aquatic life. While it is recognized that dissolved oxygen cannot and does not reflect or reveal the myriad of constituents influencing the quality of a water, dissolved oxygen remains as the most widely recognized indicator of water quality available today.

Insufficient dissolved oxygen in a stream will lead to septic conditions including malodorous emissions. Anaerobic decomposition of organics produces methane and hydrogen sulfide gas (26). Dissolved oxygen is essential for a healthy and varied fish population. The reduced ability to extract oxygen by fish in embryonic and larval stages, coupled with their inability to move away from adverse conditions makes them vulnerable to reduced oxygen concentrations (22). Severe dissolved oxygen depletion may also adversely affect aquatic insects and other fish prey (54).

Dissolved oxygen levels in streams to be used as public water supplies also function as quality indicators. High dissolved oxygen concentrations in streams may indicate a satisfactory water quality in terms of low residuals of biologically available organic materials in water supplies (26). Chemical reduction and subsequent leaching of sedimentary iron and manganese is inhibited by the presence of oxygen (22). The biochemical oxidation of ammonia to nitrates in natural waters require oxygen. The depletion of ammonia reduced the chlorine demand of a water supply and increases the efficiency of chlorination (42).

The perception of good water quality is often associated with streams having adequate dissolved oxygen. A major emphasis of water pollution control is managing dissolved oxygen concentrations. The depletion and replenishment of oxygen in rivers depends on the interactions of physical, chemical and biological processes; despite all these processes monitoring and evaluating water quality is often accomplished by assessing dissolved oxygen. The standard setting process can be very complex. Defining beneficial uses and the supporting criteria to enable those uses may be quite controversial.

Despite the complex nature of dissolved oxygen, the applicable standards are usually stated as simple threshold values which are not to be violated. Such standards, which may facilitate administrative ease, are often unable to reflect the natural variability and complexity of some water quality parameters. The Massachusetts dissolved oxygen standard is a threshold standard concerned with a single dissolved oxygen concentration at a single flow (10). It stipulates that at critical low flow, the 7Q10, the minimum dissolved oxygen concentration shall be 5.0 mg/l in waters supporting warm water fisheries and 6.0 mg/l in waters supporting cold water fisheries.

Excess Assimilative Capacity

In general as flow increases stream quality increases (25). This is demonstrated by Figure 10 on page 59, which clearly shows that highest dissolved oxygen concentrations are associated with the highest streamflows. Although dissolved oxygen does not increase linearly with streamflow, for simplicity the following discussion assumes a linear relationship. This is a severe oversimplification, but it will serve the illustrative purposes of the following paragraphs. Relaxation of this assumption does not alter the argument, but would make it more difficult to follow. For the purposes of this discussion it will be assumed that the dissolved oxygen concentration to be met in the stream is 5.0 mg/l.

The standard is specified to be met at some critical low flow, typically the 7Q10. (Figure 3). Waste discharge limits are set assuming that the amount of water available for dilution is the 7Q10 and that the critical values of other parameters used in water quality modeling are those that are experienced at the time of the 7Q10. This is most likely to be a worst case analysis. The stream is protected during all but extreme low flow conditions. However, the instream dissolved oxygen concentration is greater than that required by the standard almost continually since the 7Q10

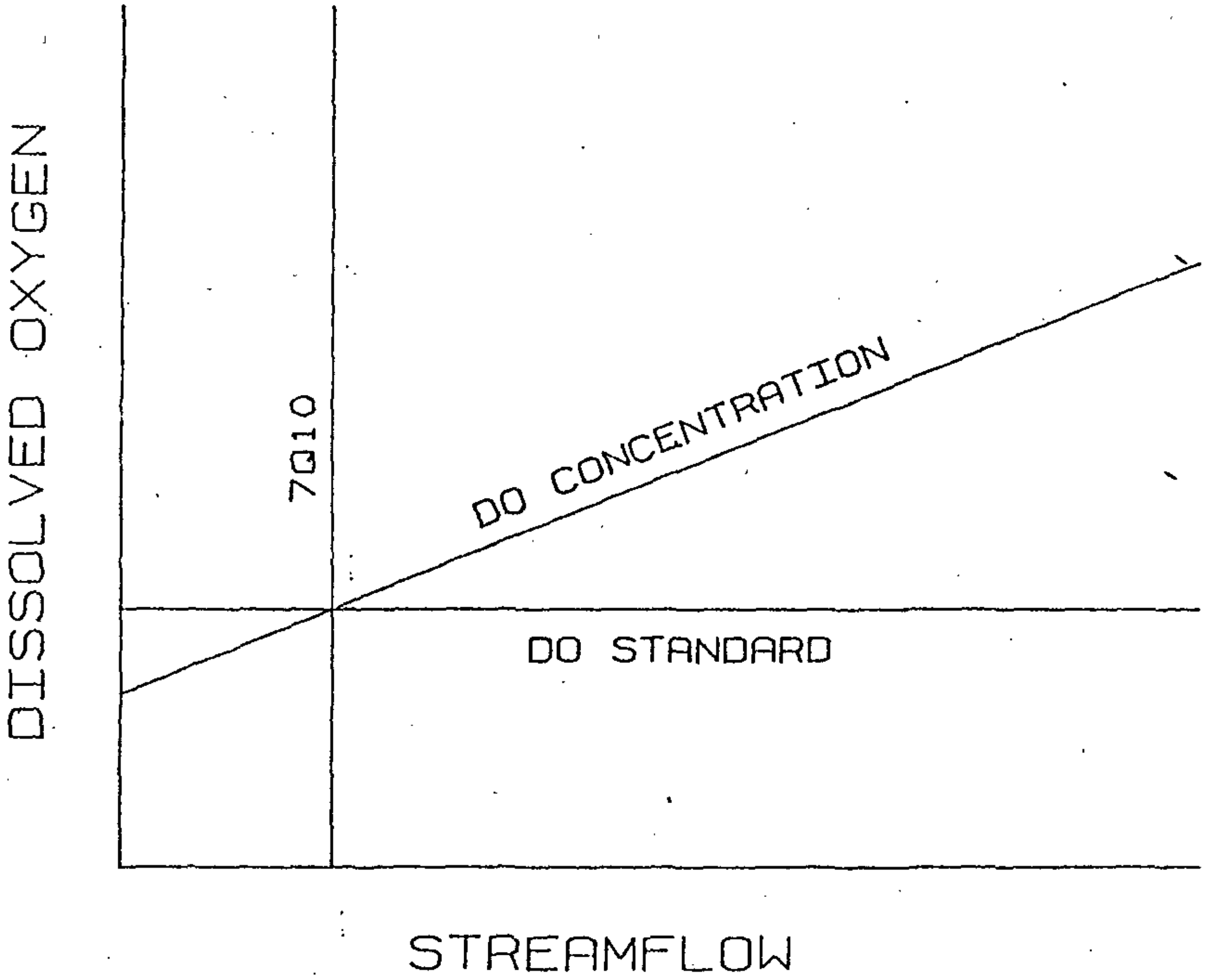

Figure 3. Relationship between 7Q10, dissolved oxygen standard and dissolved oxygen concentration.

is exceeded more than 99% of the time. At all flows below the 7Q10 the the standard will not be met, but at all flows greater than the 7Q10 the dissolved oxygen concentration is greater than 5 mg/l. This may be represented as the area of the graph bounded on top by the dissolved oxygen curve and below by the standard (Figure 4). This quality in excess of the standard represents the excess assimilative capacity of the stream, and this is where the distinction between the two interpretations of the "intent" of water quality standards is crucial. The criteria specified in a standard should be commensurate with the intent of the standard. A condition of minimal acceptability may be stipulated at low flow and a more suitable criteria designated at higher streamflows. The standard may vary with flow, becoming more stringent as flow increases. In either case there is an excess capacity to assimilate wastes at higher flows relative to the goal level specified by the current threshold standards.

Water quality standards have been developed to allow humans to utilize the assimilative capacity of a waterway while minimizing the human impact on the other beneficial uses. They are the water quality goals of each state. All water quality planning and management activities should be targeted at attaining and protecting these goals. If the goal of the standard is to protect a healthy aquatic

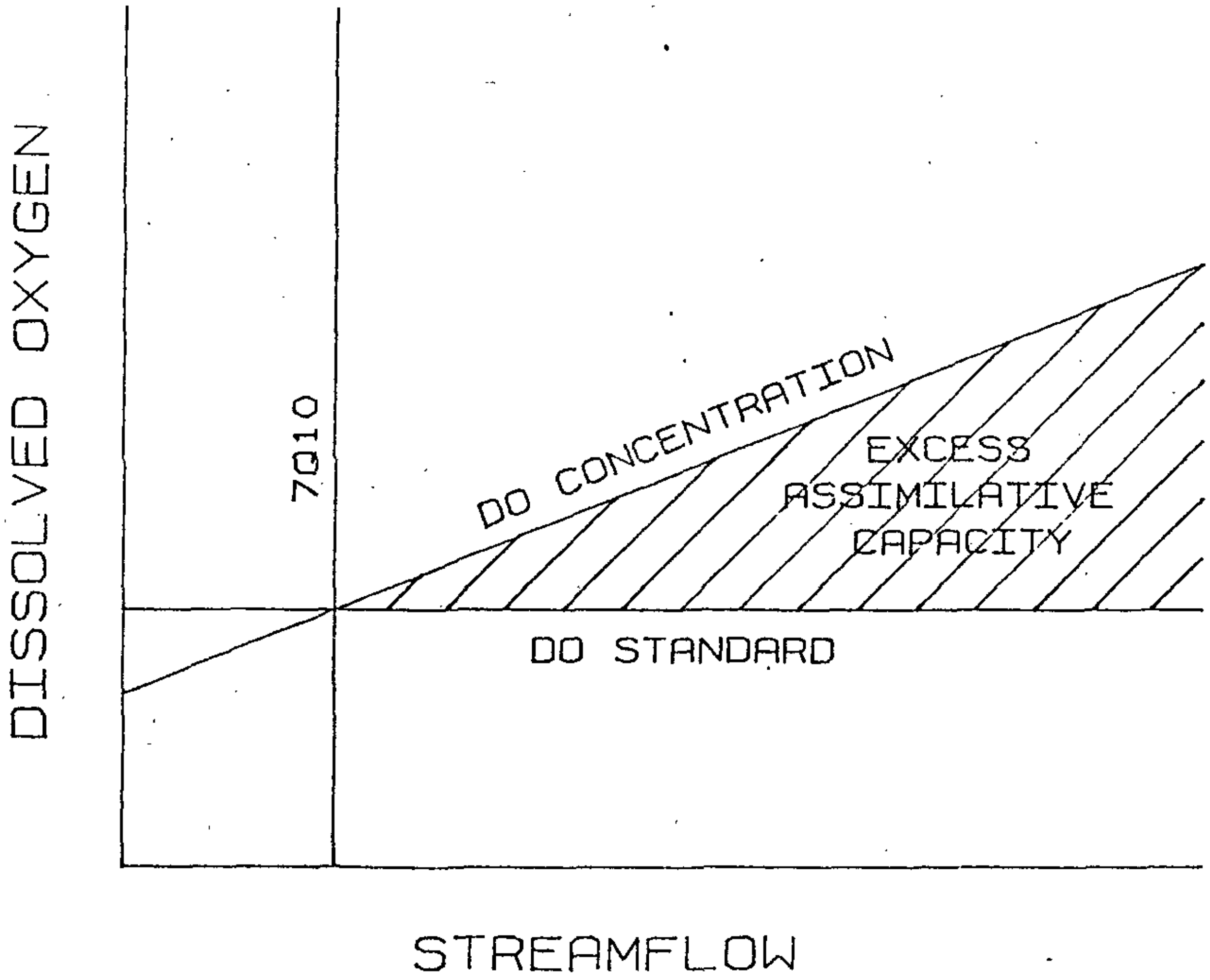

Figure 4. Excess assimilative capacity implicit in the dissolved oxygen standard.

environment then the criteria specified should do just that. Once the river's requirement are determined, the available assimilative capacity may be allocated as long as the water quality standards are not violated.

The present practice of national uniform effluent standards as the predominant method of water pollution control disregards this excess assimilative capacity of higher flows. Uniform effluent standards do not account for the fact that each stream is unique in its capacity to assimilate wastes. Effluent standards are technological standards. The objective of prescribing technological standards is that they appear to be "determinate and objective (24)." Proponents of uniform effluent standards assert their advantages include administrative ease, presumed equity among discharges and the elimination of the need to calculate, distribute and depend on the assimilative capacity of streams. However, effluent standards ignore the "practicability of restrictions, the impact on other resources, and the effects on both the individual discharger and on society as a whole (24)."

In effluent limited streams all discharges must meet the uniform effluent standards. The standard is not based on any local or site specific conditions such as biological, chemical, physical or economic consequences in a given instance. The effluent standard may be what is needed to secure a healthy stream or it may be dramatically overprotective of all the beneficial uses of the waterway at a very high cost.

Dorcey and Fox (12) assess the overprotection of beneficial uses and the consequential over investment in wastewater treatment facilities in an investigation of the Wisconsin River. Their study examined a portion of the Wisconsin River with 27 significant point sources; 12 municipalities, and 15 pulp and paper mills. Ninety percent of the organic waste load was contributed as industrial waste load. The annual cost of initiating secondary treatment was estimated at $7,000,000.

> Suitable oxygen levels for the preservation of fish life (5 mg/l) with a 1.0% risk of violating the standard can be achieved at an estimated cost of $5,300,000 assuming that municipalities would require to have a minimum of primary treatment plus chlorination; if the risk increased to 10% this estimated annual cost diminishes to $4,500,000. In the case of the Wisconsin River the level of dissolved oxygen is the critical parameter to be controlled if fish life is to be preserved, since degradation of the water quality results form the organic waste loads of pulp and paper mills...This [all municipalities and mills instituting secondary treatment or its equivalence] will involve costs greater than those required to preserve fish life and make the river safe for swimming. The difference in annual cost can, of course, only be approximated and will depend on the degree of risk accepted. Annual cost differences will be of the order of $2,500,000 at the 10% risk level and $1,700,000 at the 1% risk level (12).

This situation is an example of implementing a standard that will not significantly improve the quality of the river at a high economic cost.

An interim goal of the FWPCA (66) is that wherever attainable water quality should "provide for the protection of fish, shellfish, and wildlife and...for recreation in and on the water." Standards were established from criteria necessary to protect specified designated uses. Assuming the water quality criteria were correct then when the standard is met the goals embodied in the standards have been achieved. What is the purpose of producing regulations which are much more stringent than needed? This would amount to "treatment for treatment's sake (2)."

The intent of the standard must be clear. If what is implied is to do much better than the standard, then this is what should be stipulated in the standard. The standard would have to be written in a format that would state the water quality desired at all points, at all times and during all possible conditions. If the regulator insists that a threshold standard implies the achievement of quality better than the standard why even bother designating an achievable standard or an attainable goal? Nothing but zero discharge is suitable. Setting a goal them becomes deceptive to all parties concerned.

CHAPTER IV

DATA ANALYSIS

Literature Review

The utilization of excess assimilative capacity in developing water quality standards is dependent on a definable relationship between streamflow quantity and water quality. There is substantial literature identifying quantity/quality relationships examining both short and long term trends. These patterns have often been drawn using mineral quality.

Most of the matter in water is dissolved solids and consists mainly of inorganic salts, small amounts of organic matter and dissolved gases (51). The principle inorganic anions dissolved in water are the carbonates, chlorides, sulfates and nitrates. The principle cations are sodium, potassium, calcium and magnesium (22).

The log linear relationship between dissolved solids and specific conductance is well accepted (Figure 5), and it has been demonstrated many times, in many river basins (13, 31, 53). Electrical conductance is the ability of a substance to conduct an electrical current. Specific

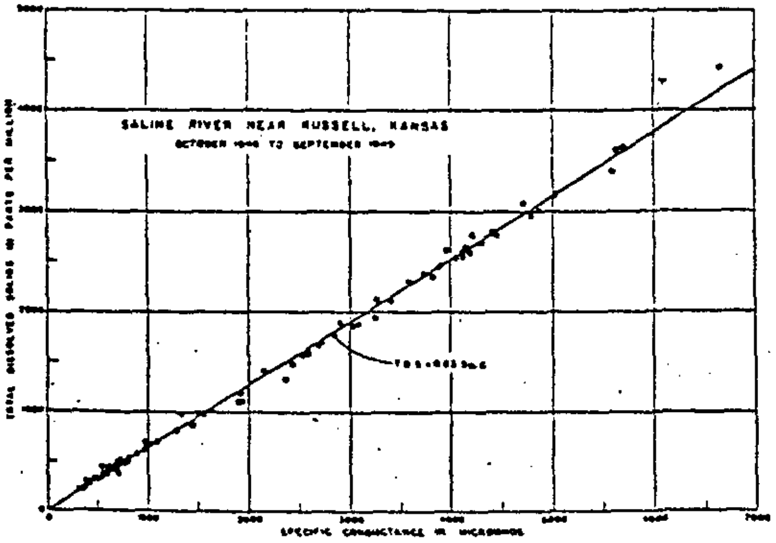

Figure 5. Relationship between dissolved solids concentration and specific conductance (13).

conductance is defined as the "reciprocal of the resistance in ohms measured between opposite faces of a centimeter cube of an aqueous solution at a specified temperature [25 C]" (26).

Hem (31) points out that studies of surface waters have demonstrated that the dissolved solids concentration at any point in a stream varies with time. In addition, these variations in mineral content may be associated with variations in stream discharge.

Lenz and Sawyer (34) presented one the the first plausible approximations of the inverse relationship between mineral concentration and streamflow. Their graphical presentation demonstrated this inverse relationship between alkalinity and discharge.

Gunnerson (25) modified the then common practice of fitting a quality/quantity curve to a hyperbola on arithmetic paper. He presented specific conductance and streamflow data as either a straight line on logarithmic paper, or, by incorporating time, as an elliptical function. This cyclic nature of specific conductance and discharge has been supported by other river basin studies (28, 46, 59, 71).

This cyclic pattern has been explained by Hendrickson and Krieger (29). An idealized curve presented in Figure 6 is a plot of mean daily conductance versus mean daily discharge, with the points connected chronologically. In this idealized curve the intial conditions represent base flow characteristics.

As streamflow increases specific conductance decreases through the first few days of peak discharge. Then as streamflow declines specific conductance increases until the next stream rise. Hendrickson and Krieger (29) divide the cycle into three phases. The slow decrease in specific conductance, phase AB, is the intial discharge rising stage and may be attributed to the washing of readily soluble material into the stream by new runoff. This dissolved material comes from the soil, the stream, and shallow groundwater. These materials tend to retard the rate of decrease in dissolved material matter of the stream even though the discharge is increasing rapidly. In the second phase, BC, the water entering the stream has a decreasing amount of dissolved materials. This water is almost all "fresh" runoff. The final phase, CD, represents the decline in streamflow and an increase in specific conductance. As the stream stage decreases groundwater recharge, with its high dissolved solids content, becomes the principle mechanism of streamflow maintenance. First bank storage is

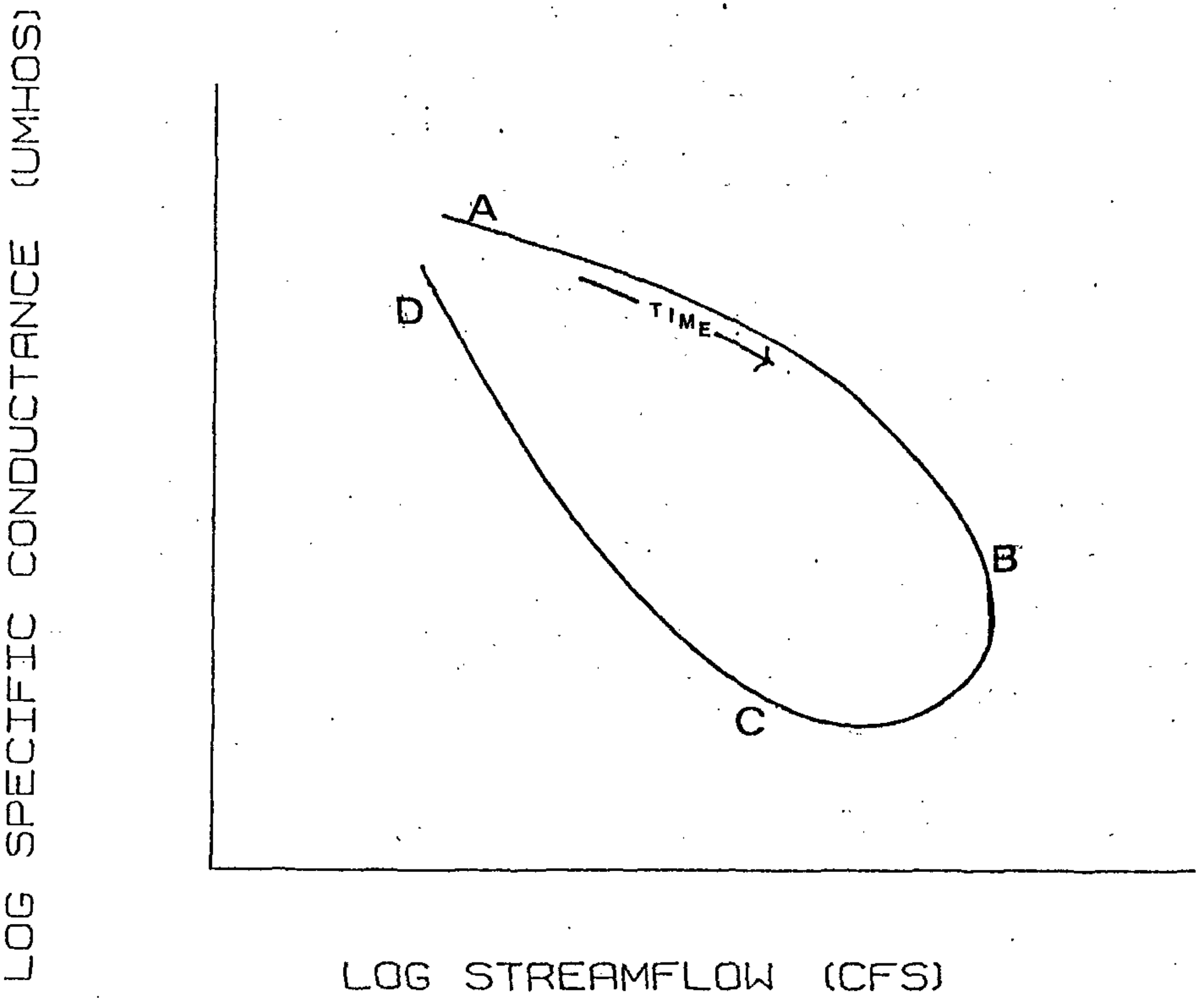

Figure 6. Cyclic relationship between specific conductance and streamflow (29).

released into the stream, followed by recharge from older groundwater. This water has a high mineral concentration. In time, streamflow is derived entirely from groundwater and the baseflow characteristics are resumed.

Regression analysis of the techniques may be used to analyze the quantity/quality relationships of data. Edwards (14) distinguishes between two time frames used in discharge concentration models. The first examines specific hydrological events, incorporating time. The second includes many hydrological events over a long period of time. *This second time frame may be used for successful* regression analysis. Edwards regressed specific mineral concentrations against stream discharge. The minerals included sodium, potassium, calcium, magnesium, silicon, chloride, bicarbonate, nitrate, phosphate and sulfate. Nitrate and sulfate concentrations increased with increasing streamflow. Magnesium, bicarbonate and phosphorus concentrations were diluted and decreased with increasing streamflow. Calcium and silicon showed no significant correlations with discharge. Regression techniques have also been successfully used by Anderson and Faust (1), Steele and Jennings (56), Tirsh (58). and Wang and Evans (72) to correlate streamflow and water quality.

Tirsh regressed specific conductance against streamflow for the Shoshone River Basin in Wyoming to verify the use of streamflow records as a substitution for water quality data (58). After performing a step forward multiple regression analysis including drainage area, precipitation, annual thunderstorm days, evapotranspiration and stream discharge, Steele and Jennings conclude that in the majority of cases simple regression analysis is adequate to describe the flow quality relationships for specific parameters (56).

The logarithmic transformation of streamflow and specific conductance data has been commonly used in analysis (56, 58, 72). These transformations have been used by Ledbetter and Gloyna (33) in predictive techniques to estimate quantity/quality relationships. In addition, Hardison (27) reports on improved correlations by using logarithms. The aforementioned authors also used logarithmic transformation in their regression analyses.

River Basin Description

To further substantiate the relationship between quality and quantity of streamflow and constituent concentrations, graphical and regression analyses were performed on the water data at the gauging station of the United States Geological Survey on the Quinebaug River, at

Dudley Massachusetts. The intent of the analysis is to present a data set which demonstrates the concept of excess assimilative capacity. Once this is done this data set will be used to illustrate the feasibility of flow variable discharge limitations.

The French and Quinebaug River Basin is located in south central Massachusetts (Figure 7) (37, 38, 39, 40). The source of the Quinebaug River is the Hamilton Reservoir in Union Connecticut. It flows north into Massachusetts through the towns of Holland and Brimfield. It turns east through Sturbridge and Southbridge, then flows through Dudley and re-enters Connecticut at Thompson. The French River begins in Leicester, Massachusetts and flows south through Oxford and Webster. It crosses the state line and joins the Quinebaug River in Thompson.

The Quinebaug River Basin, exclusive of the French River Basin, covers 744 square miles. The River flows 75 miles from its source to its confluence with the Shetucket River in Connecticut to form the Thames River. The Thames River ends in Long Island Sound. Within Massachusetts the Quinebaug River flows for 28 miles, draining an area of 143 square miles in Worschester and Hampden Counties.

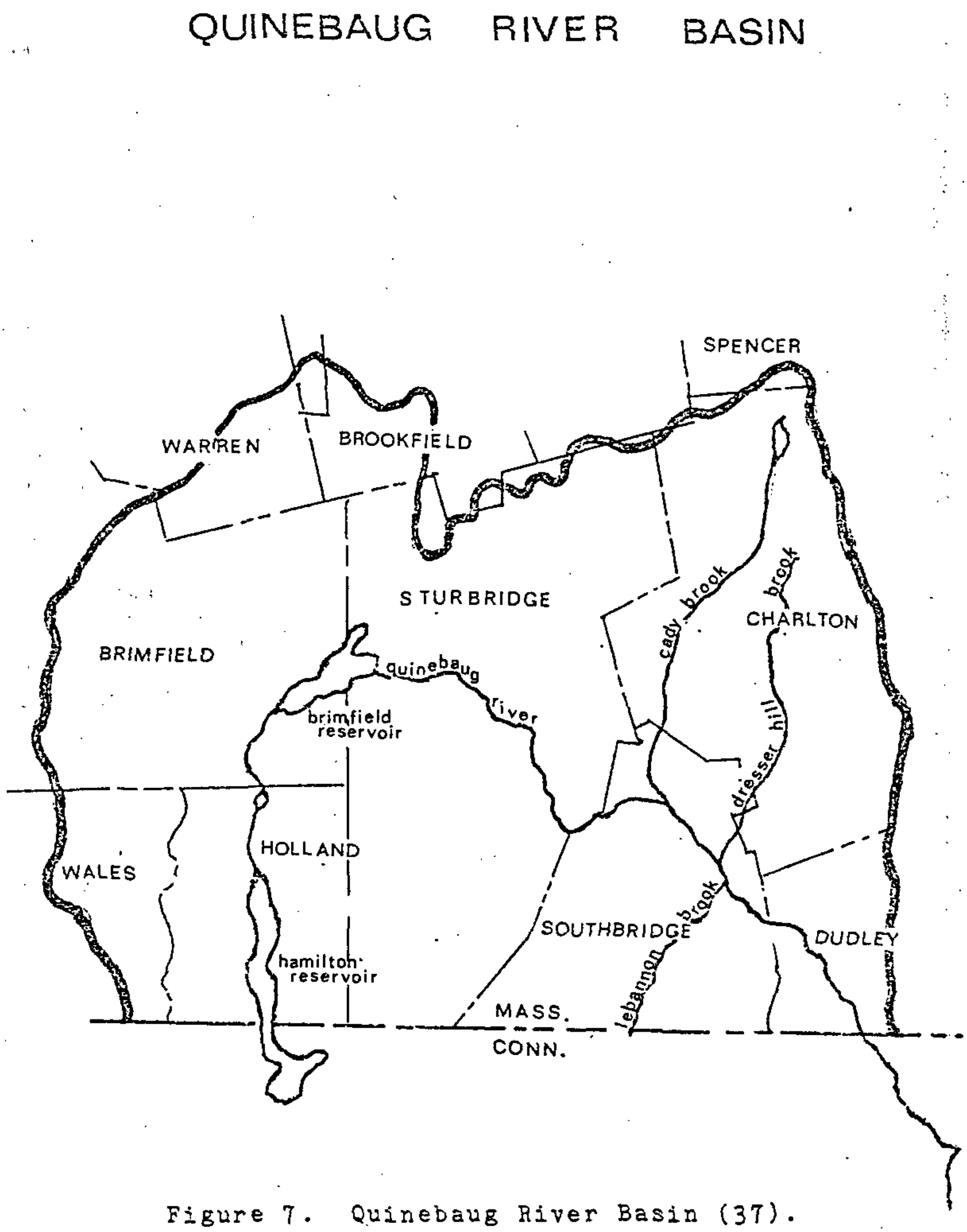

Figure 7. Quinebaug River Basin (37).

The Hamilton Reservoir is at an elevation of 683 feet. The Quinebaug River flows north from there through a very marshy area. The Mill Brook enters north of Brimfield. After meandering through a flat, swampy section the River proceeds eastward and enters the large Brimfield Reservoir--Long Pond in travelling over the next three miles it drops only three feet, to the East Brimfield Reservoir. As the Quinebaug River flows eastward it is joined by the outlet of Cedar Pond. The River then drops 45 feet over 4.8 miles to the Westville Army Corps of Engineers Dam. This section is totally undeveloped, and the Hamant, Hobbs and Hatchet Brooks enter the River. From the Westville Lake the Quinebaug River continues southeast through Southbridge, where it is impounded by two dams and resulting in cascades. This section of the River is characterized by rapids and a drop of over 100 feet.

The Cady Brook joins the Quinebaug River in Charlton, along with the McKinstry Brook from the north and the Leban and Cohasse Brooks from the south. Southeast of Southbridge the River enters a mile long impoundment behind the West Dudley Dam.

The reach above the impoundment is characterized by several shallow rapids over a mostly rocky bottom. After flowing through the impoundment the river flows unobstructed through an almost wholly wooded area to the West Thompson

Army Corp of Engineers Dam in West Thompson, Connecticut. The confluence with the French River is just beyond the Dam.

Recreational areas are spread along the River. The East Brimfield Reservoir and Holland Pond supports various activities. Excellent canoeing exists in the reaches below the Westville Dam and the West Dudley Dam.

The Quinebaug River has been divided into four reaches by the Massachusetts Division of Water Pollution Control for stream quality classification. All reaches are Class B (Table 4), suitable for primary and secondary recreation. In addition, they are restricted from new or increased discharges of pollutants.

Very few streams in Massachusetts have long term water quality records; therefore, the number of possible data sets available for investigation was limited. The Quinebaug River gauging station at Dudley, Ma. was selected because there are water quality records including temperature, specific conductance, dissolved oxygen, and pH since 1968. The station is the United States Geological Survey (USGS) gauging station No. 01123900 (68). It is located in Dudley, Ma. at a latitude of 42 01'40" and a longitude of 71 57'22". The streamflow is measured 0.4 miles downstream of the Dudley station at the USGS gauging station No. 01124000 (67) at Quinebaug, Connecticut. It located at a

Table 4

Classification of Quinebaug River Basin (10)

Boundry	Mile Point	Class	Designated Use	Other Restrictions
Hamilton Reservior to Sturbridge STP	30.7-19.7	B!	Cold Water Fishery Recreation	4.3!!
Sturbridge STP to Cady Broook Confluence	19.7-13.4	B	Cold Water Fishery Recreation	4.3
Cady Brook Confluence to Southbridge STP	13.4-12.2	B	Cold Water Fishery Recreation	4.3
Southbridge STP to State Line	12.2-0.0	B	Warm Water Fishery Recreation	4.3

! Class B Waters: Waters assigned to this class are designated for the uses of protectiron and propagation of fish, other aquatic life and wildlife; and for primary and secondary contact recreation.

!! Regulation 4.3: Protection of Low Flow Waters. Certain waters will be designated...for the protection under this section...New or increased discharges of pollutants to water so designated are prohibited unless a variance is granted by the Division [of Water Pollution Control].

latitude of 42 01'40" and a longitude of 71 57'22".

Data Analysis

The following presentation and analyses of data are meant to provide an example of the relationships between water quality and streamflow and to demonstrate the availability of excess assimilative capacity at higher streamflows. The objective is not to conduct a complex statistical analysis nor is it to develop a water quality model, but to provide a data set which substantiates the concepts presented in the above discussion. This is necessary since it is fruitless to discuss policy issues if they are only theoretical, and if the feasibility of applying them to naturally occurring situations is minimal.

The examination of the behavior and properties of the Quinebaug River at the Dudley gauging station first entailed graphical analysis of dissolved oxygen concentrations. Trends in streamflow and the variations of constituent concentrations are readily discernable. Extensive statistical analysis of instream dissolved oxygen concentrations are beyond the scope of this discussion since complex models incorporate not only streamflow but temperature, temperature dependent constants (ie. reaeration coefficients), biochemical oxygen demand and benthic demand. However, an appreciation for the variation of dissolved oxygen levels with season and streamflow may be gained by means of pictorial representation. Plotting dissolved oxygen against time by considering each water year illustrates this point (Figure 8). The dissolved oxygen concentration varies between approximately 2.5 mg/l and 15 mg/l and demonstrates the dramatic seasonal variations in dissolved oxygen concentration. (It must be recalled that this is prior to the extensive pollution abatement program mandated by the Federal Water Pollution Control Act Amendments of 1972, and the dissolved oxygen level is substantially below that now required by Massachusetts Division of Water Pollution Control.) The dissolved oxygen concentration is highest during the winter month (corresponding to the lowest water temperatures) and remains at levels during the spring. The concentration of dissolved oxygen falls off dramatically during the late summer and early autumn. These trends may also be explained in part by the variations in streamflow (Figure 9). The stream at higher flows, with its associated lower temperatures, has more assimilative capacity than at low flows (Figure 10). The same plots of a later water year (Figures 11, 12 and 13) show the same seasonal and streamflow changes without the extreme low dissolved oxygen levels during low flow periods. (This improvement in water quality is probably a result of the pollution control measures implemented in the interim.)

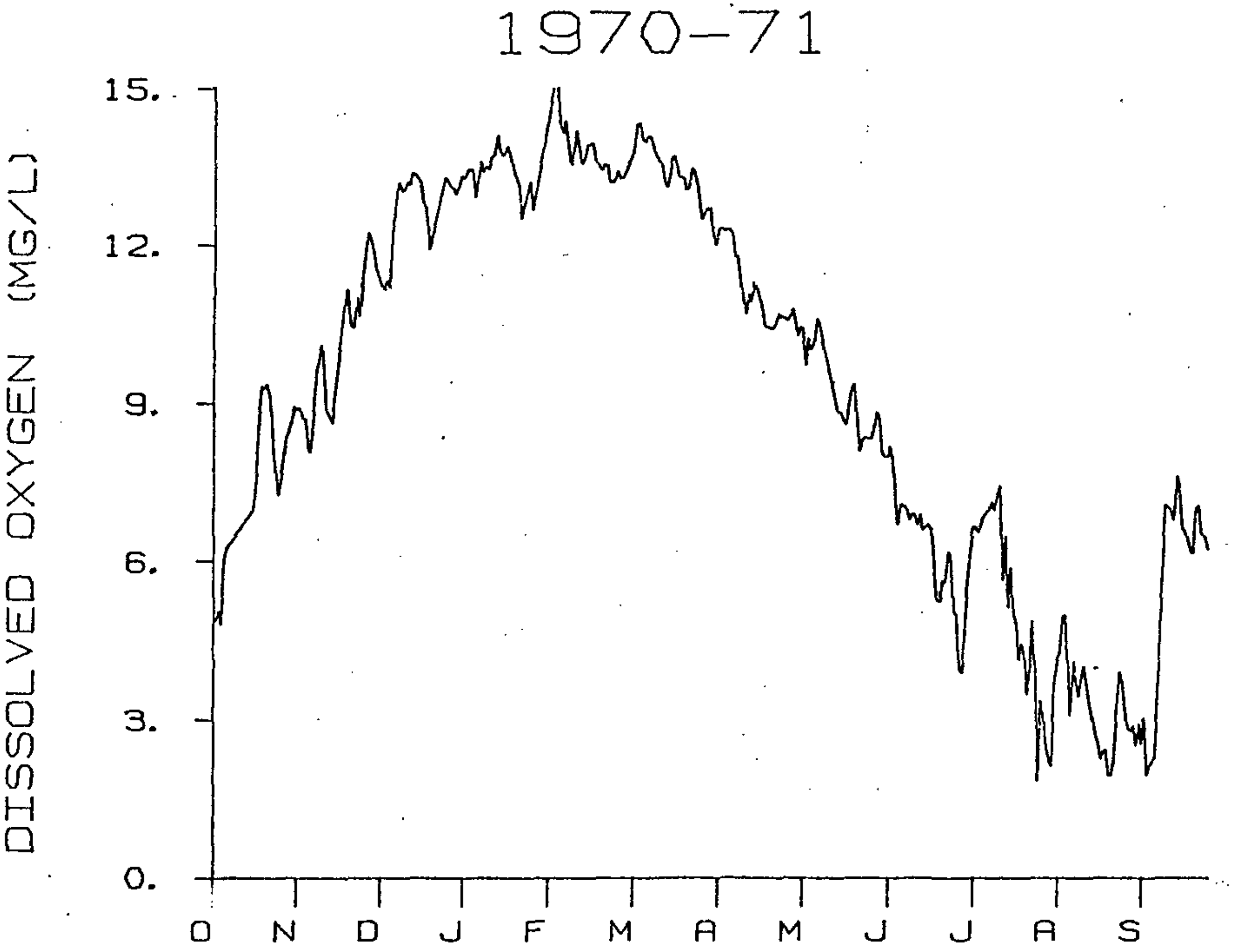

Figure 8. Variation in dissolved oxygen concentration throughout water year 1970-71.

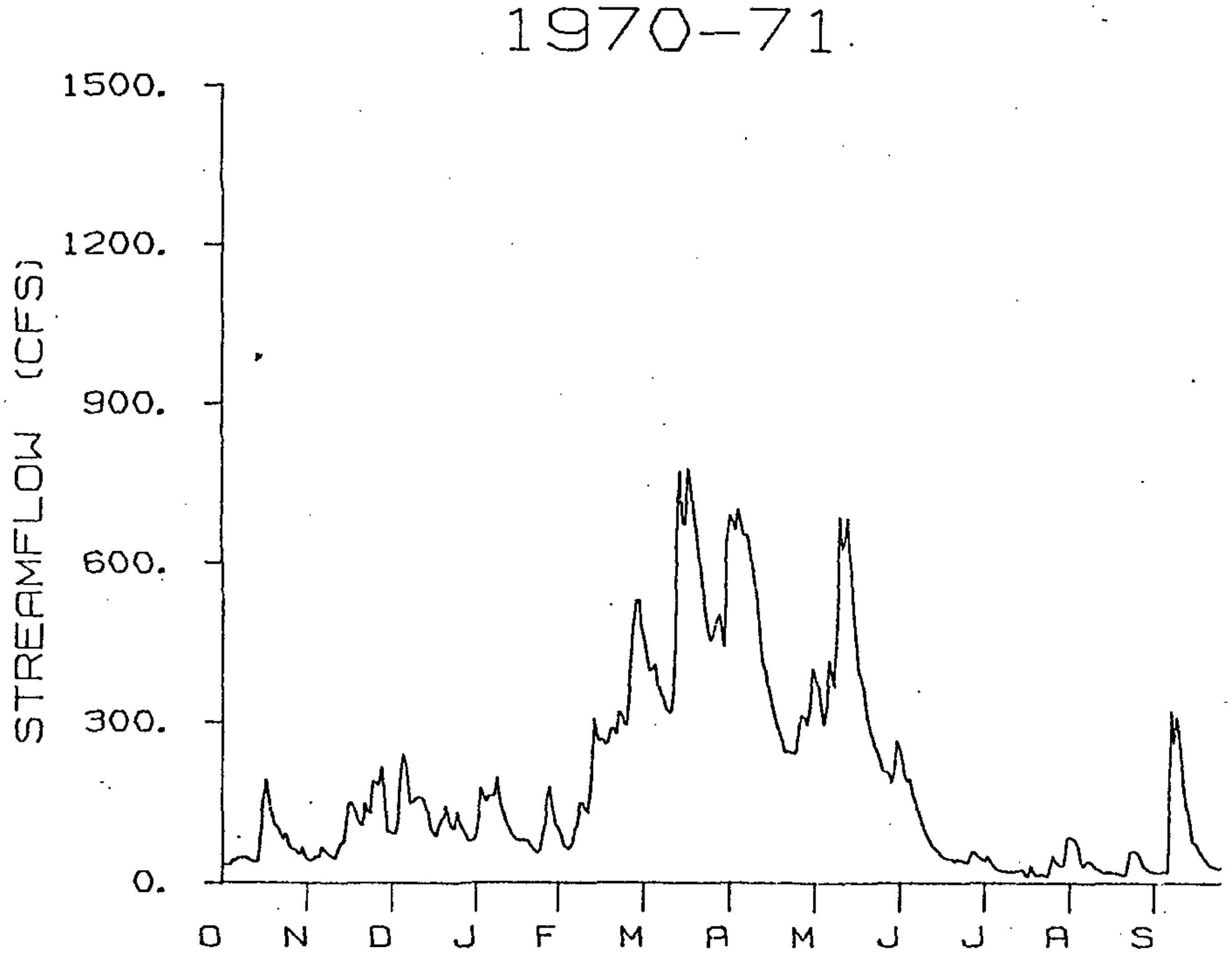

Figure 9. Variation in streamflow throughout water year 1970-71.

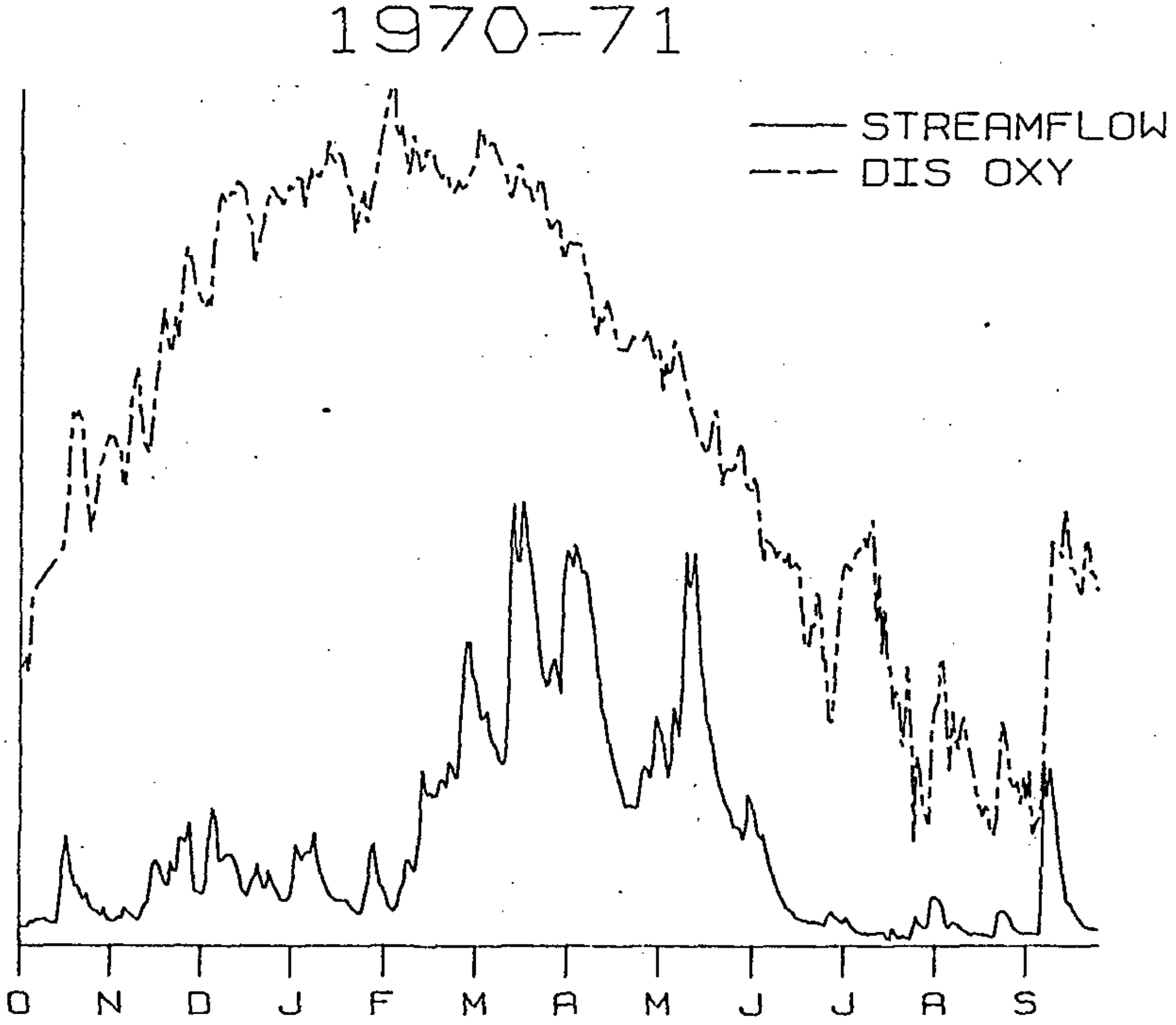

Figure 10. Variation in dissolved oxygen concentration and streamflow throughout water year 1970-71.

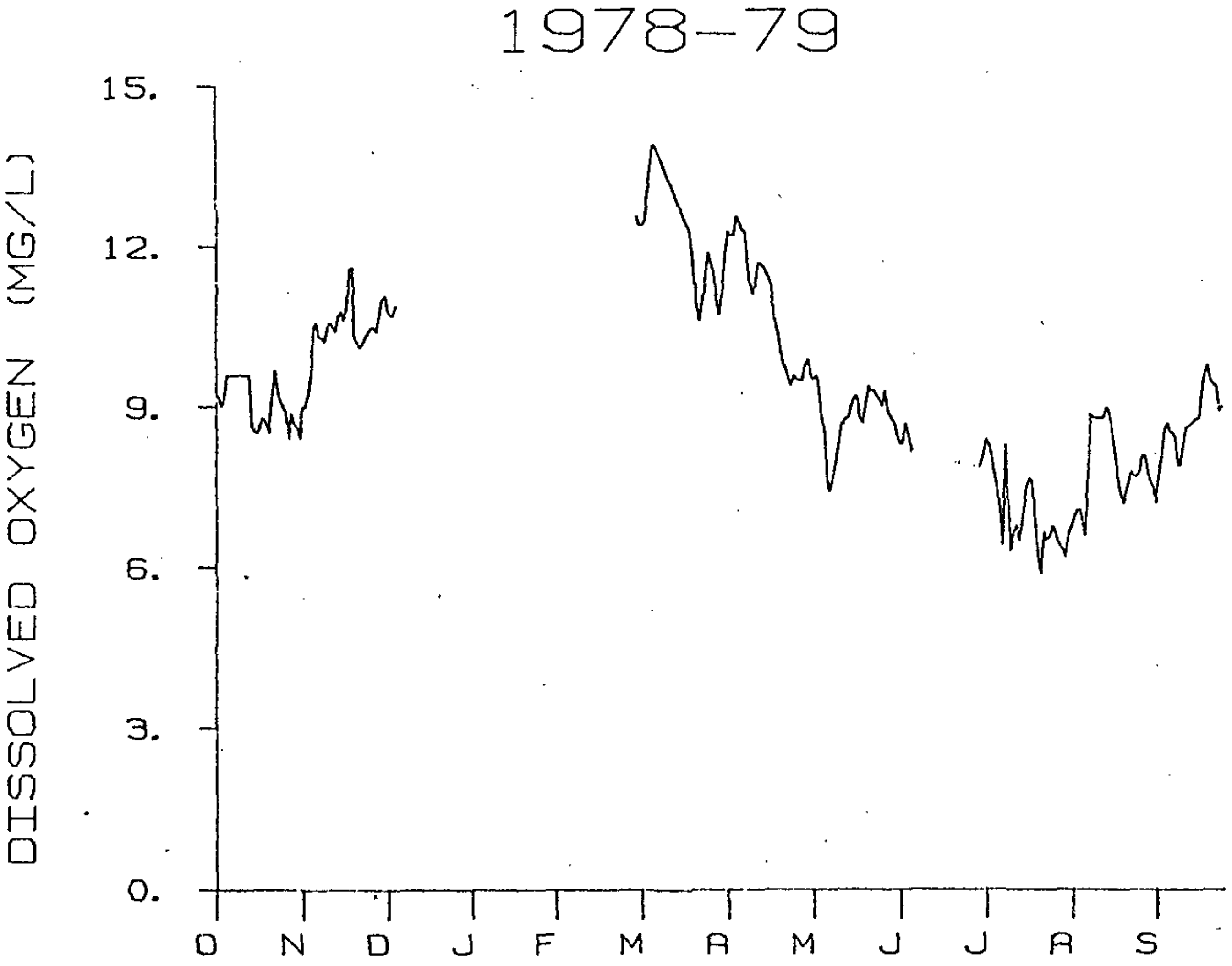

Figure 11. Variation in dissolved oxygen concentration throughout water year 1978-79.

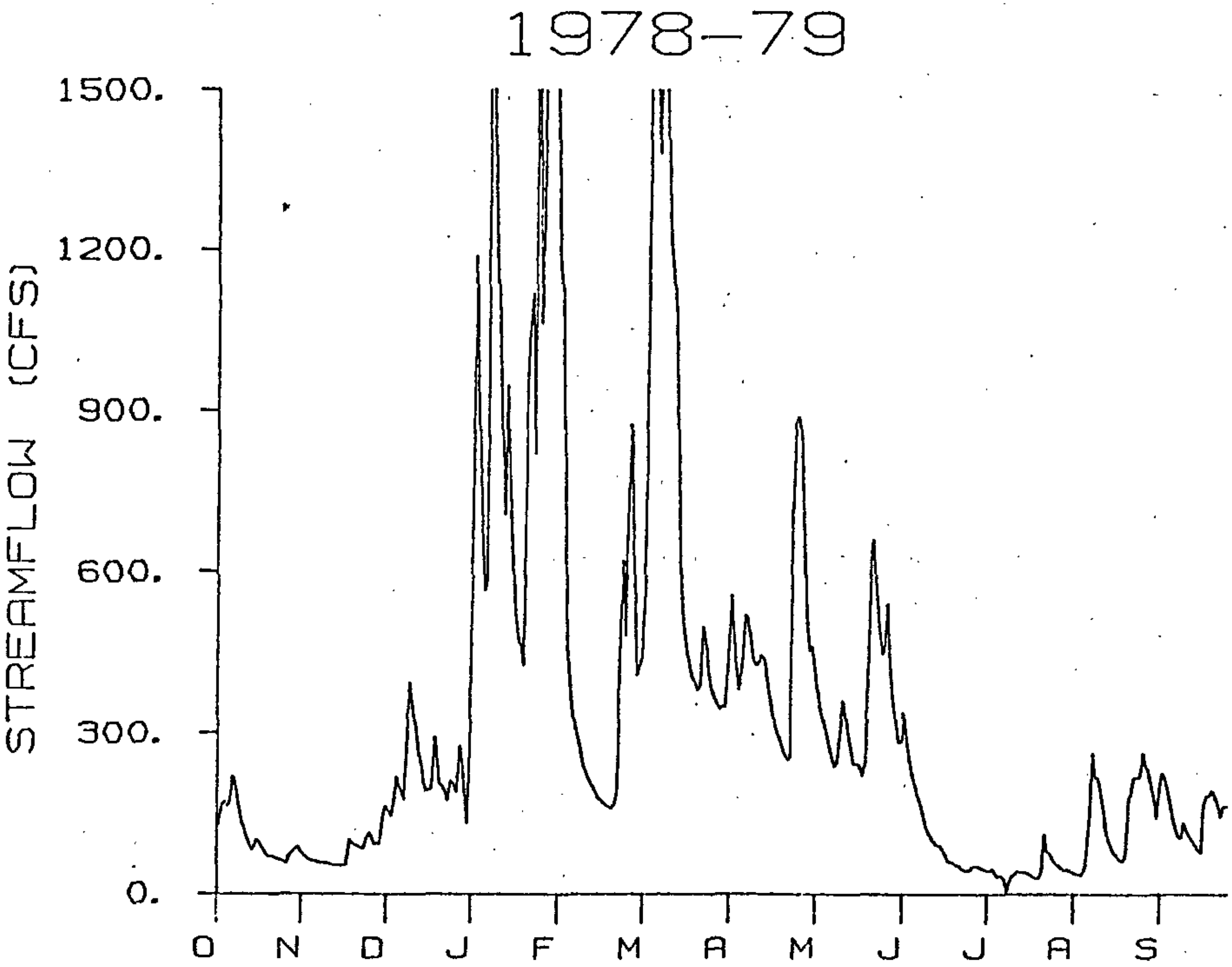

Figure 12. Variation in streamflow throughout water year 1978-79.

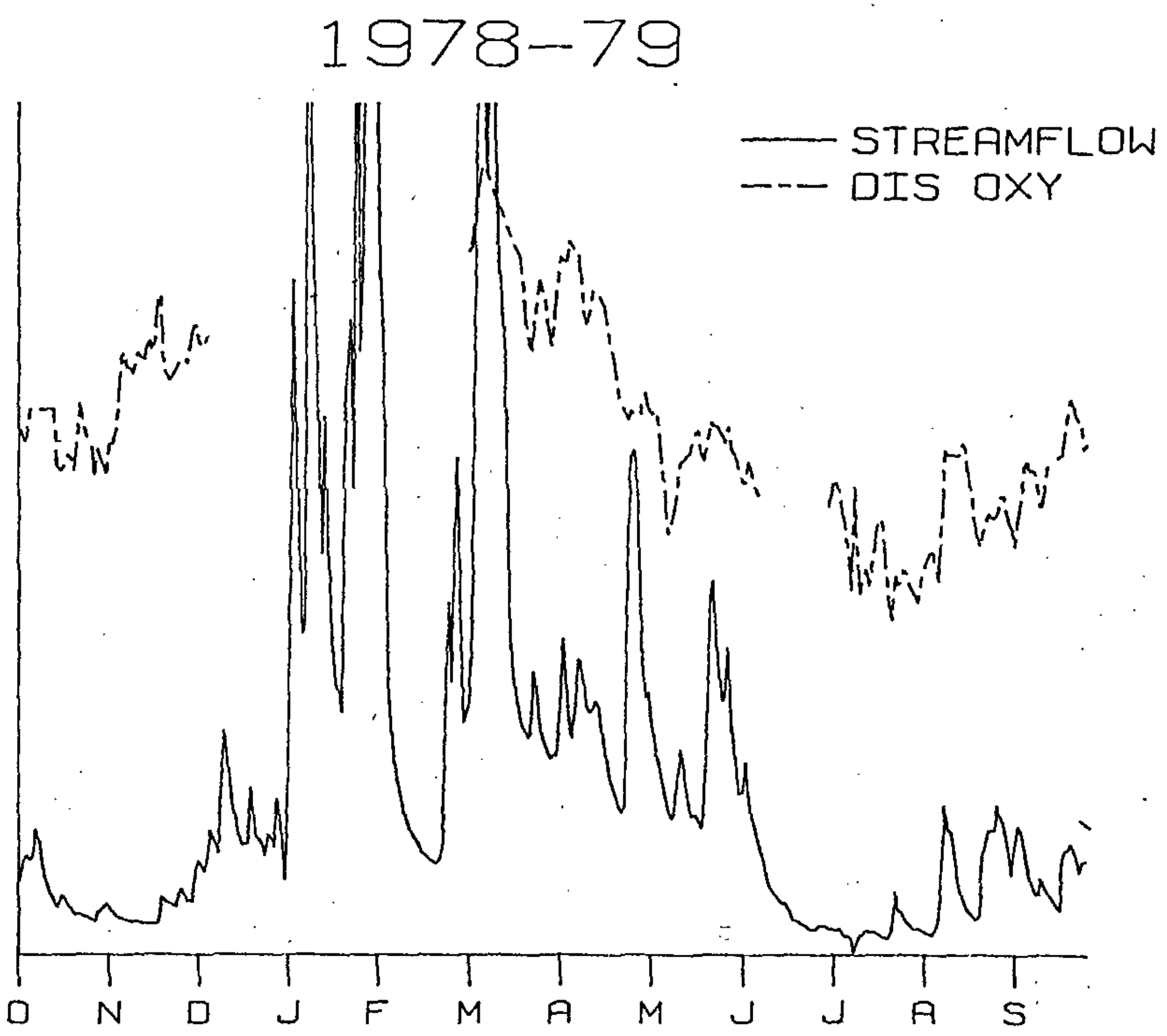

Figure 13. Variation in dissolved oxygen concentration and streamflow throughout water year 1978-79.

Specific conductance also exhibits a clear relationship with streamflow. The inverse relationship between specific conductance and streamflow is well accepted. The variations in specific conductance throughout the year may be seen by plotting specific conductance against time. The variable behavior of the parameter is concisely illustrated over the water years 1969-70, 1970-71 and 1971-72 (Figure 14). These graphs show consistently that specific conductance is at a minimum during the spring and at a maximum during the late summer. The extreme values of specific conductance in September 1970 begins to fall off in November. The measurement remains fairly constant throughout the winter (except for one high point in February 1971) decreasing to its minimum in April 1972. Again the specific conductance peaks during the late summer but returns to approximately the same level as early winter 1970 in the early winter of 1971. It should be pointed out that extraneous sources and highly variable sources of ionized pollutants may cause intermittent variations from the general relations being demonstrated here.

The seasonal variations in specific conductance coincide with the seasonal variations in streamflow. Examining the streamflow of the same three water years (Figure 15) and then graphing both the streamflow and specific conductance as functions of time (Figure 16) shows

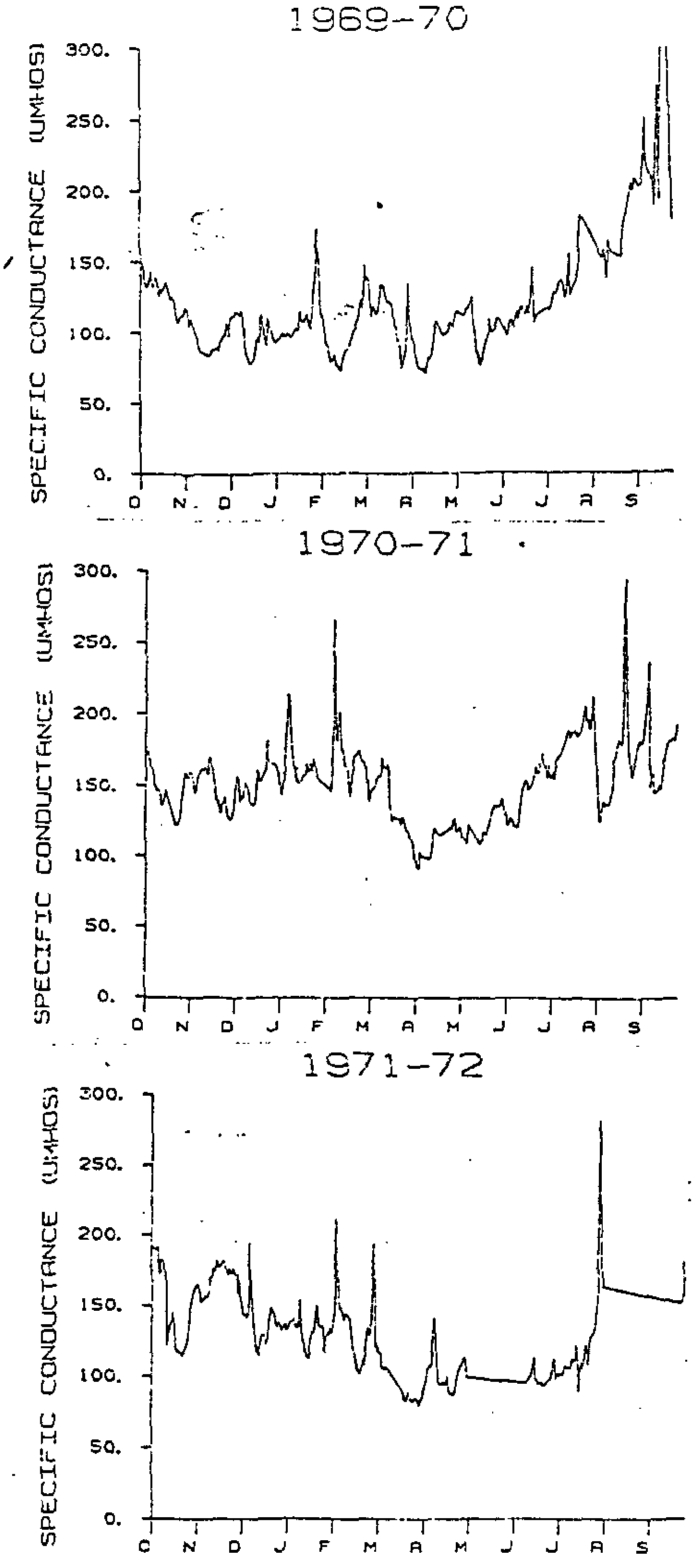

Figure 14. Variation in specific conductance throughout water years 1969-70, 1970-71 and 1971-72.

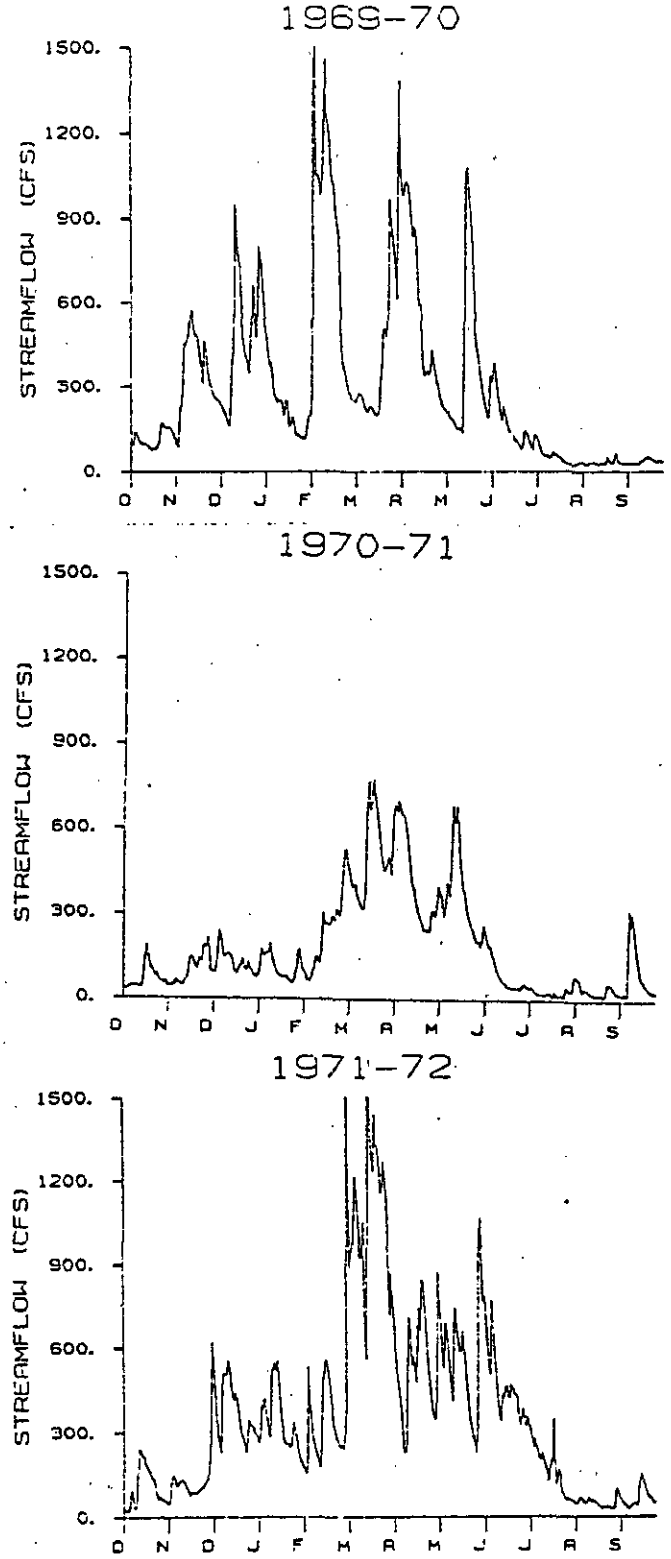

Figure 15. Variation in streamflow throughout water years 1969-70, 1970-71 and 1971-72.

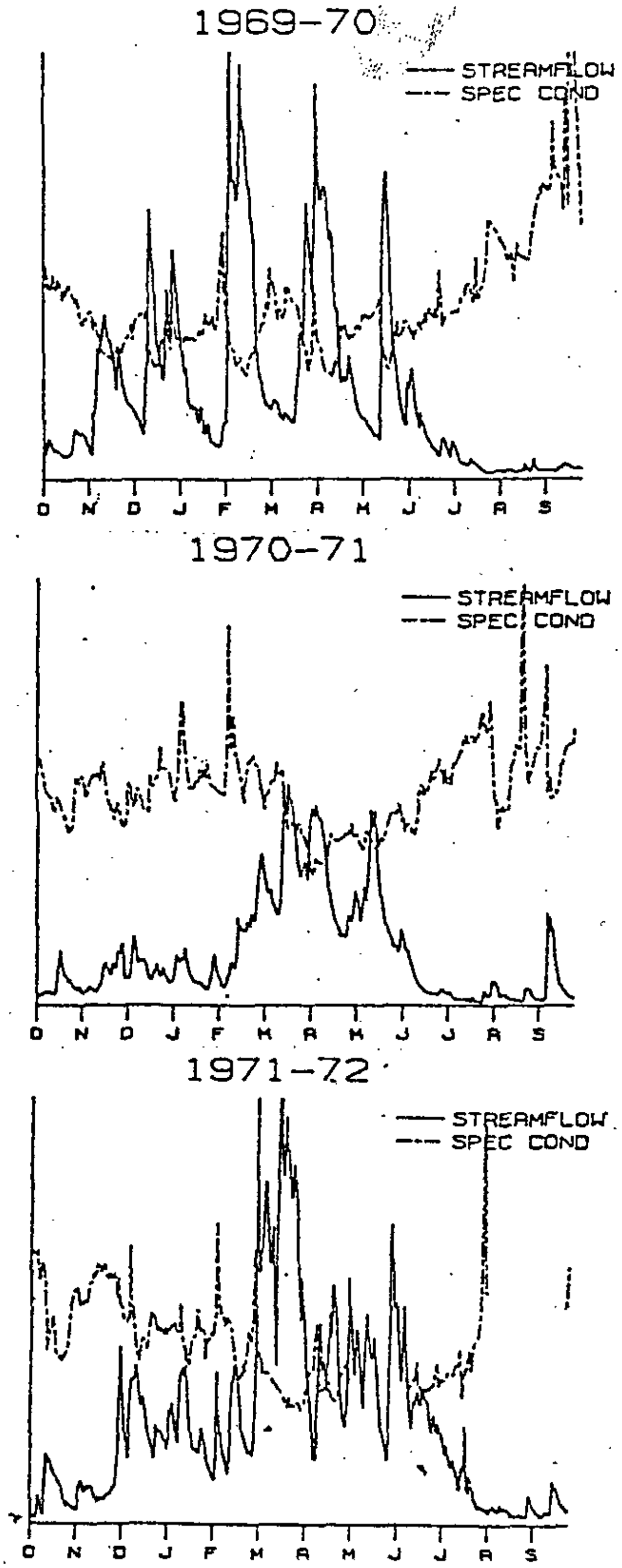

Figure 16. Variation in specific conductance and streamflow throughout water years 1969-70, 1970-71, 1971-72.

that the maximum specific conductance measurements occur at streamflow minimum, and conversely, the minimum specific conductance measurements occur at streamflow maximum.

An inspection of the streamflow specific conductance verses time graph within a season shows that the peaks of the specific conductance curve occurs simultaneously with the troughs of the streamflow curve (Figures 17 and 18). This occurs both high and low streamflows. The cyclic nature of specific conductance and streamflow is demonstrated during water year 1968-69. This cycle is apparent when the monthly averages (Table 5) of streamflow and specific conductance are plotted as logarithms in chronological order (Figure 19). Portion AB of the curve represents the winter and spring months, as the streamflow gradually increases the general trend is for the specific conductance to decrease. As discharge falls off during the summer months, portion BC, the specific conductance increases. The decrease in specific conductance at the end of the water year is associated with an increase in streamflow, portion CD. The overall trend is the decrease of specific conductance as the streamflow increases, returning to higher specific conductance as discharge decreases during the drier months.

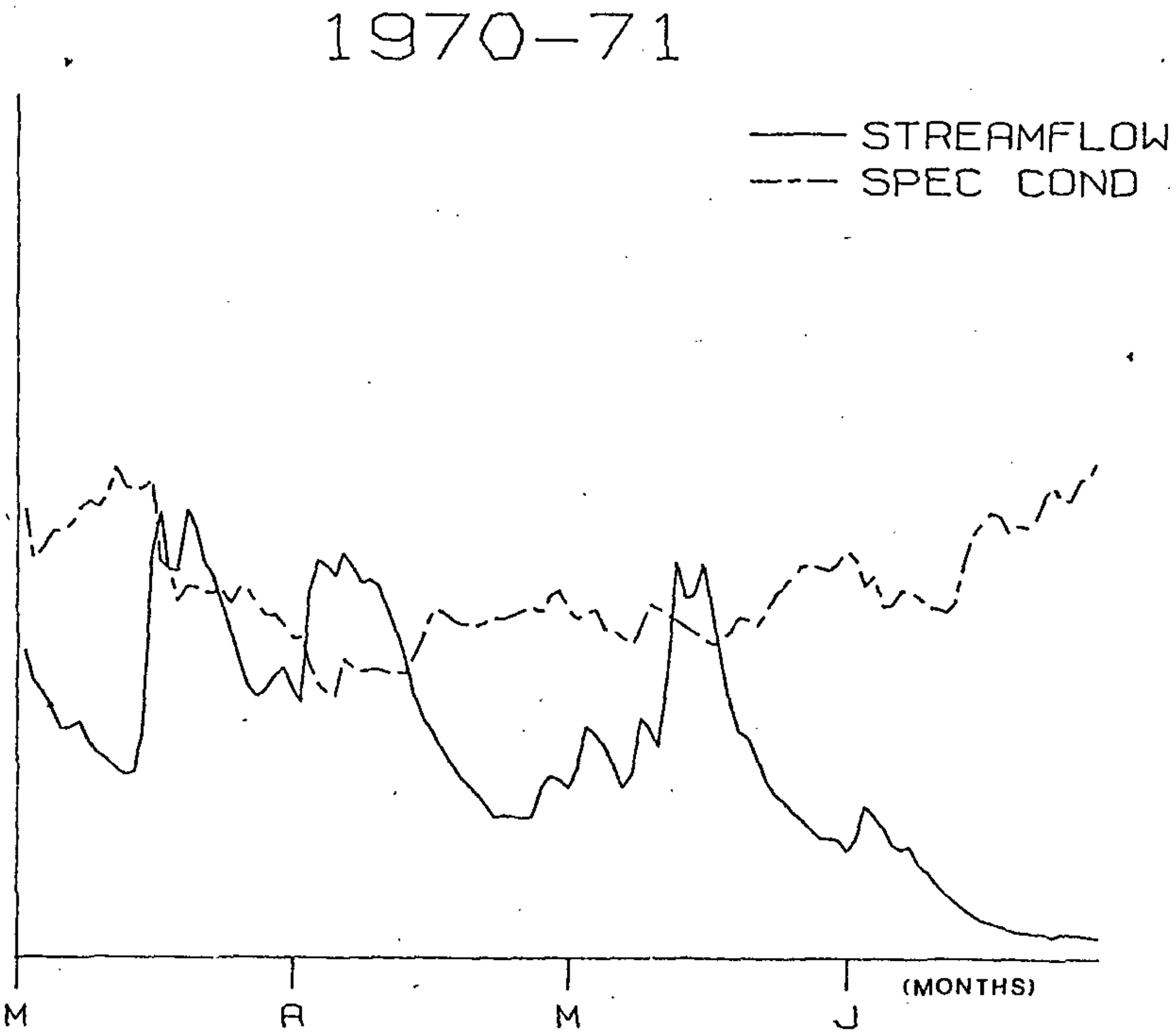

Figure 17. Influence of high streamflow on specific conductance.

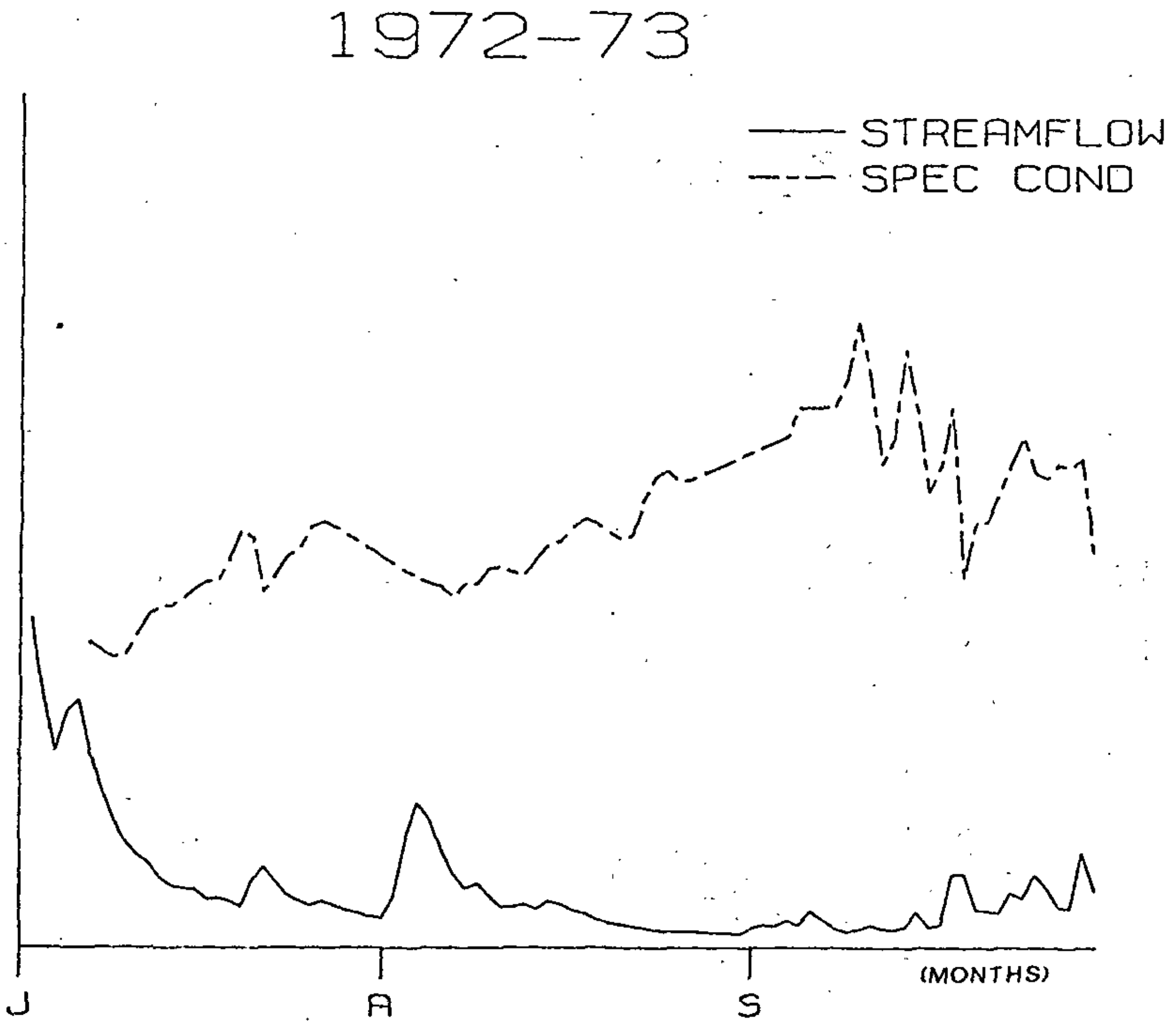

Figure 18. Influence of low streamflow on specific conductance.

Table 5

Monthly Averages of Streamflow and Specific Conductance

1968-1969

	streamflow (cfs)	specific conductance (umhos)
October	55	120
November	96	147
December	206	136
January	156	151
February	137	163
March	349	147
April	735	94
May	324	103
June	88	128
July	48	167
August	77	145
September	148	141

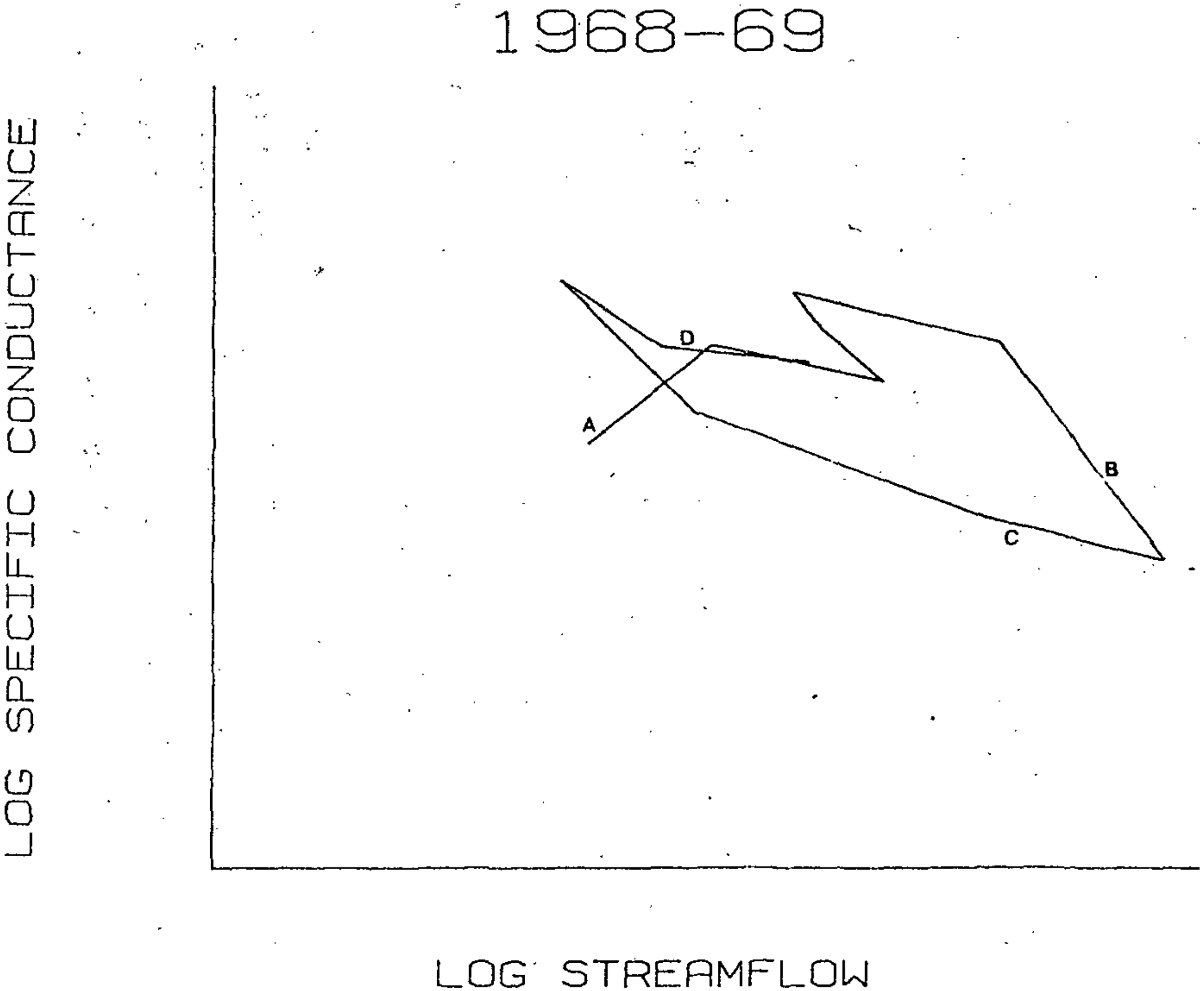

Figure 19. Cyclic relationship between specific conductance and streamflow during water year 1968-69.

The dependence of specific conductance on streamflow is apparent from an arithmetic plot (Figure 20) where streamflow is the independent variable and specific conductance is the dependent variable. A graph depicting all twelve years of data shows a wide envelope including most data points. Concise relationships are more evident if each water year is examined separately. Water years 1969-70 1974-75 and 1977-78 (Figures 21, 22 and 23) serve as examples. If the data is plotted on a log-log scale the scatter of points is minimized and a best fit line may be drawn (Figures 24, 25 and 26).

The relationship between specific conductance and streamflow may be quantified with a functional form and subjected to regression analysis. The simple regression analysis presented here is meant to solidify the qualitative relationship portrayed by the graphs. More sophisticated analyses could be performed to further quantify the relationship if desired.

The regression analyses examined two functional forms--arithmetic and log-log. In addition, each water year was regressed as a complete data set and as a partial data set, consisting of flows less than or equal to 500 cfs. (The examination of data less than 500 cfs was performed separately because of the concern for low flow conditions and water quality standards.) Flows greater than 500 cfs

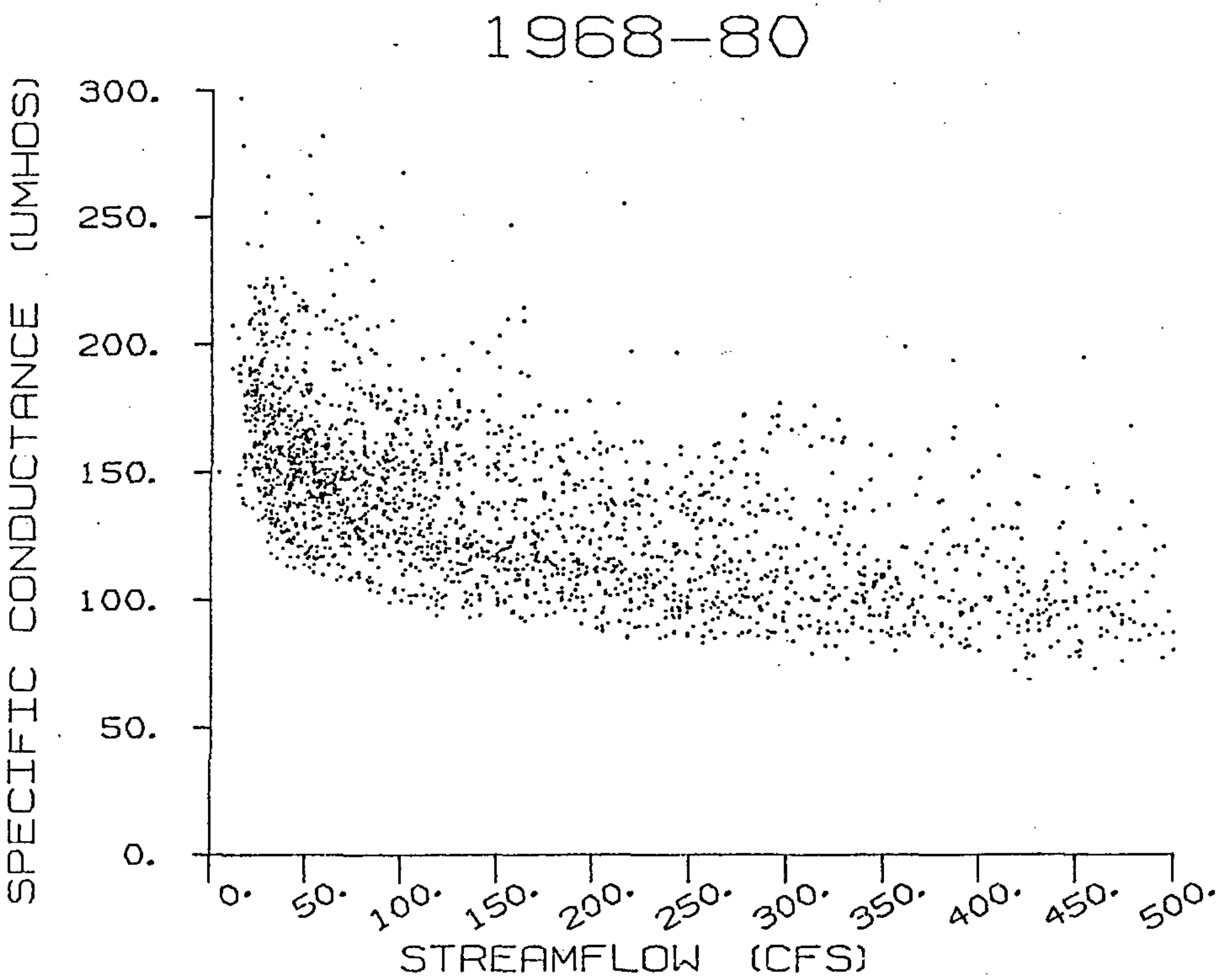

Figure 20. Influence of streamflow on specific conductance during water years 1968-80.

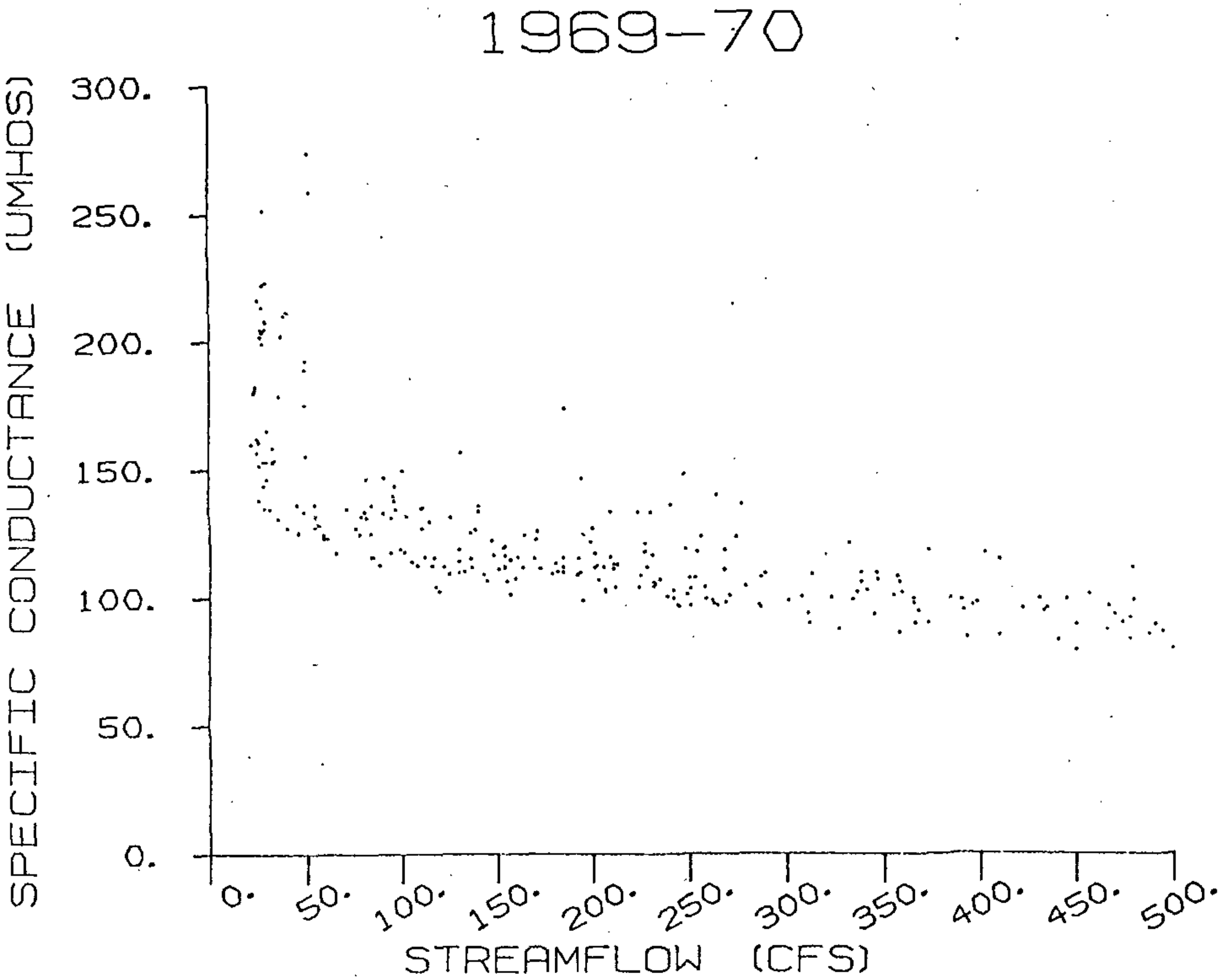

Figure 21. Influence of streamflow on specific conductance during water year 1969-70.

Figure 22. Influence of streamflow on specific conductance during water year 1974-75.

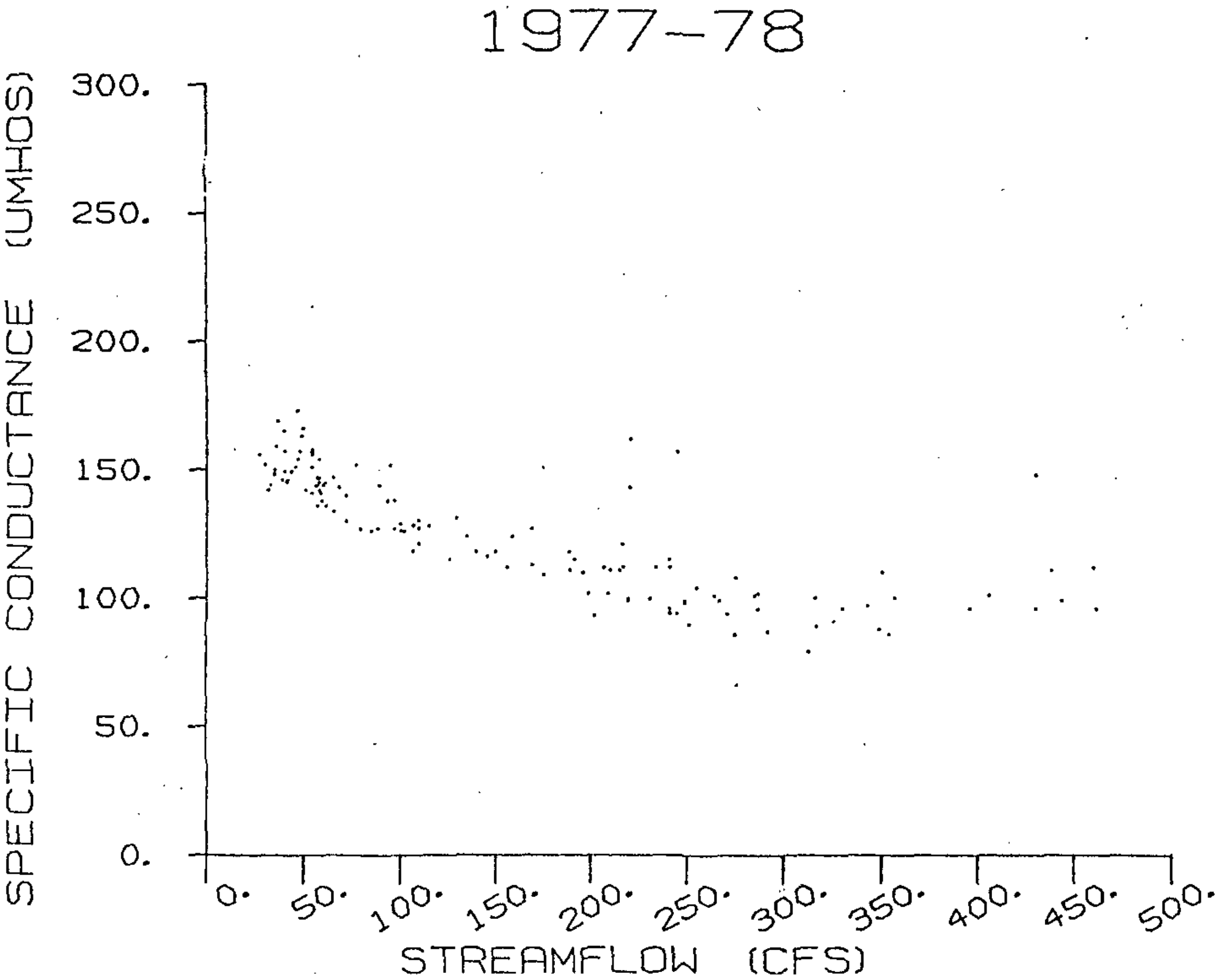

Figure 23. Influence of streamflow on specific conductance during water year 1977-78.

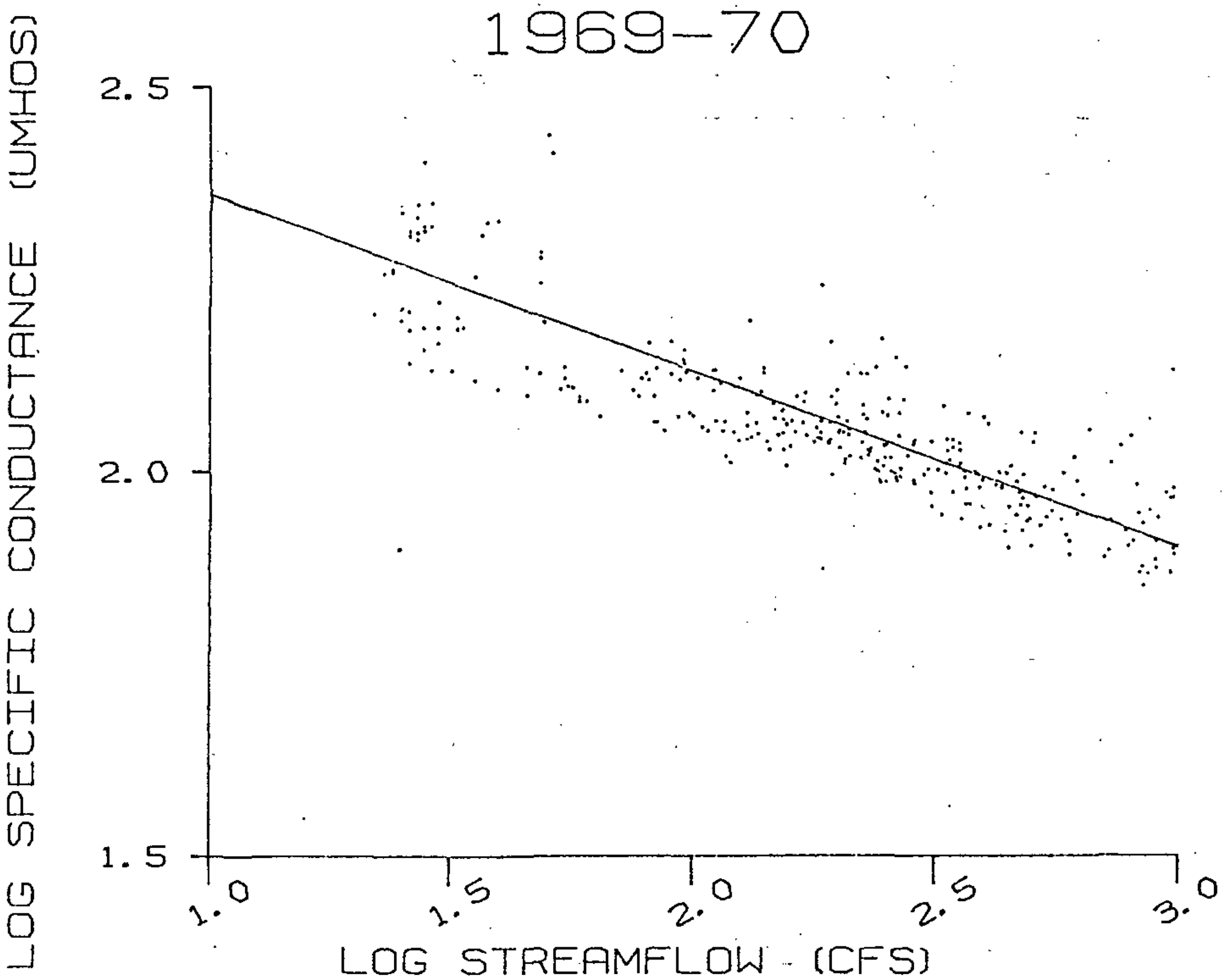

Figure 24. Influence of the log of streamflow on the log of specific conductance during water year 1969-70.

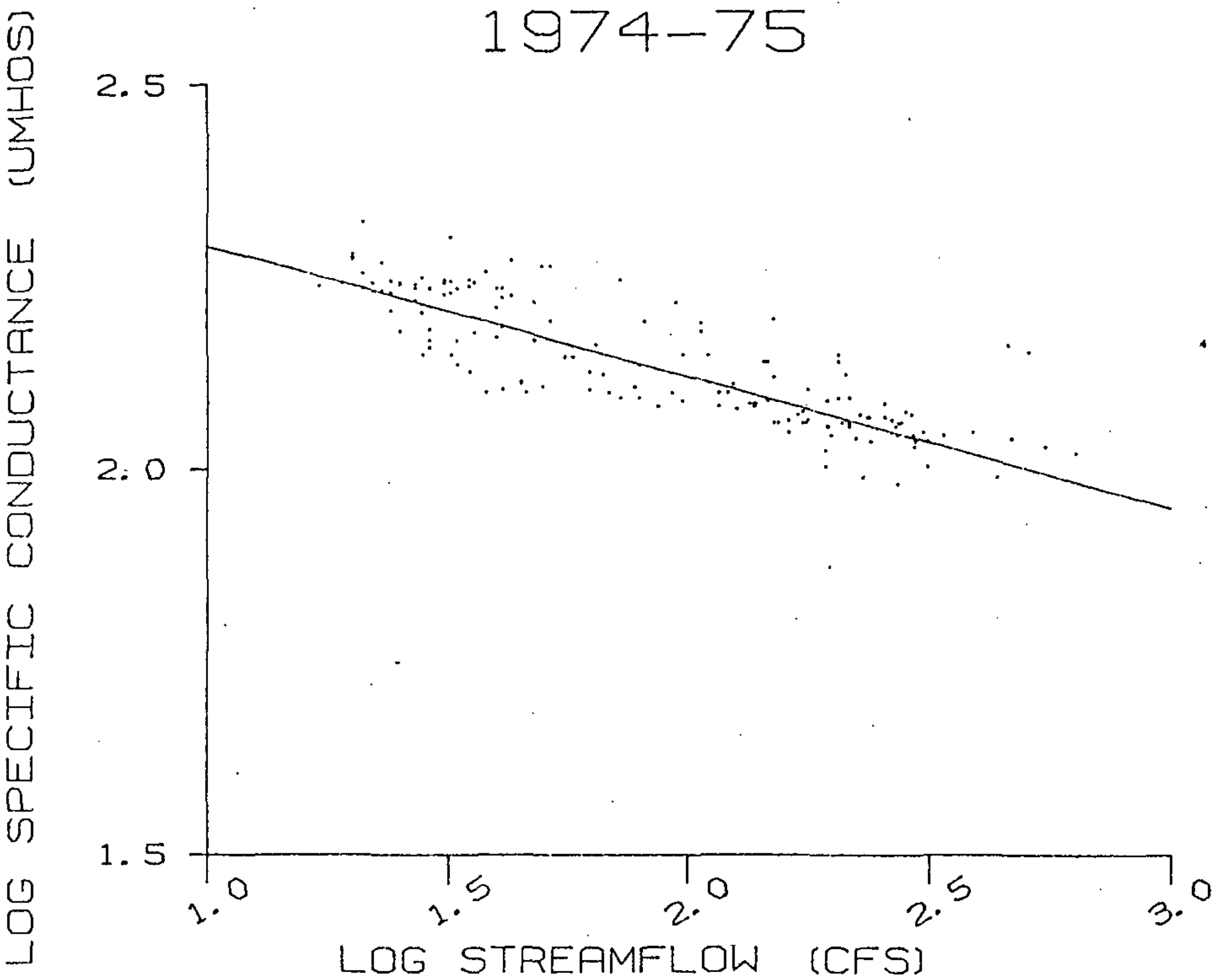

Figure 25. Influence of the log of streamflow on the log of specific conductance during water year 1974-75.

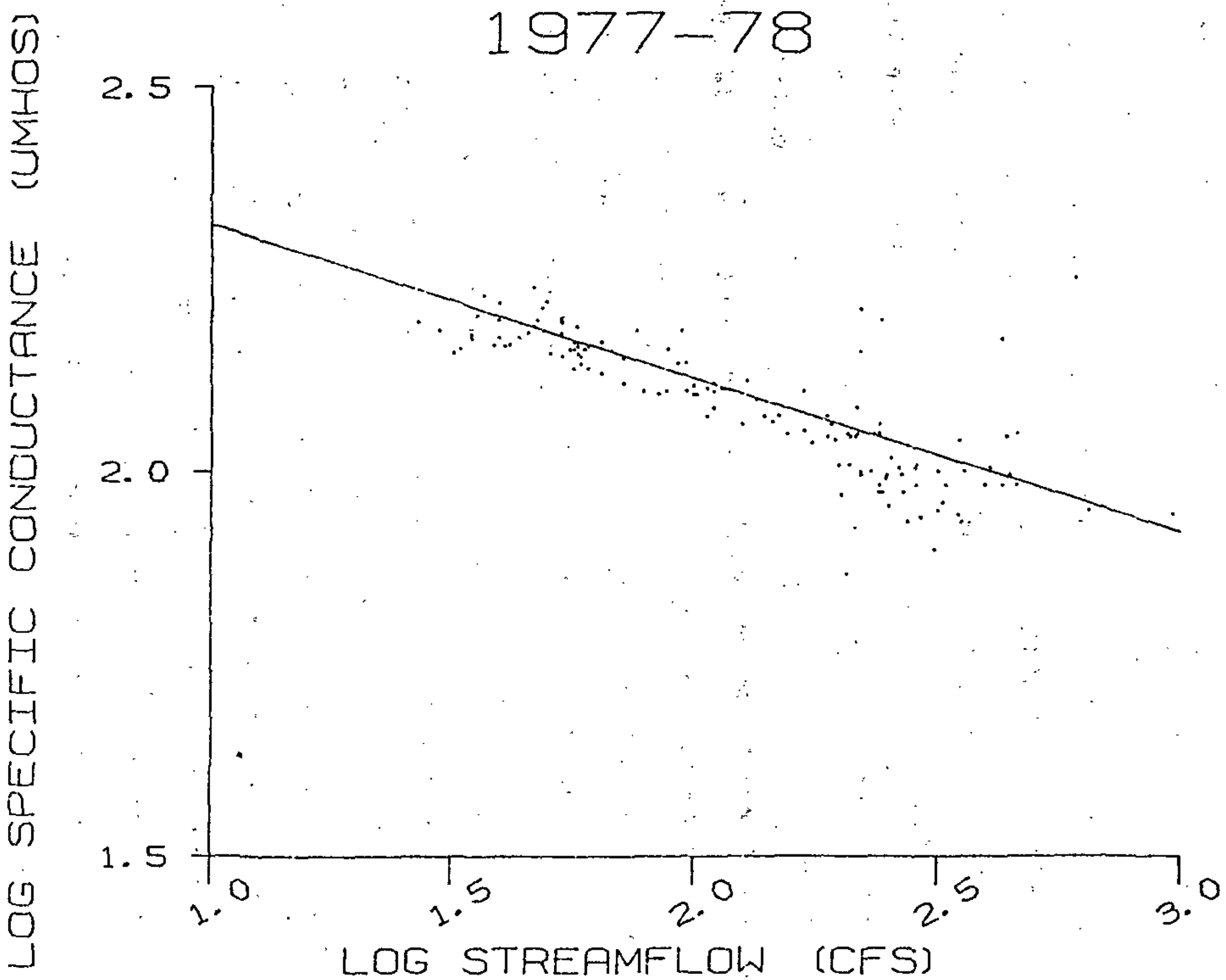

Figure 26. Influence of the log of streamflow on the log of specific conductance during water year 1977-78.

occured less than ten percent of the time (Table 6), and the development of standards can not depend on infrequently occurring events. In addition, pictorial representation is clearer with an upper limit that includes most of the data instead of one that must be extended only to include a few stray observations.

The analysis in arithmetic form showed weak correlation between specific conductance and streamflow (Table 7). However, there was a marked improvement in correlation when the data was transformed by logarithms (Table 8). The improvement in correlation is typified during water year 1970-71. Figures 27 and 28 are the arithmetic and logarthmic plots respectively and pictorially demonstrate the superior correlation of the logarthmic plot. The addition of flows above 500 cfs improved correlations but did not dramatically change the regression coefficients.

The above data set describes the singular quality-quantity relationship. Although there is no criterion for specific conductance the application of the excess assimilative capacity concept to other water quality constituents may be inferred. The data demonstrates the effects of dilution and seasonal changes on the concentration of constituents and the potential for incorporating these variations into water quality standards is great.

Table 6

Percent of Streamflow Above 500 cfs

Wateryear	Total Occurances	Below 500 cfs	Above 500 cfs	Percent Above 500 cfs
1968-69	277	243	34	12.27
1969-70	330	261	69	20.91
1970-71	337	309	28	8.31
1971-72	262	206	56	21.37
1972-73	134	131	3	2.24
1973-74	132	130	2	1.52
1974-75	161	154	7	4.35
1975-76	172	157	15	8.72
1976-77	101	101	0	0.00
1977-78	134	129	5	3.73
1978-79	232	214	18	7.76
1979-80	245	212	33	13.47
1968-80	2517	2247	270	9.32

Table 7

Streamflow Specific Conductance Relationships

Water year	Regression Line	R^2
1968-69	SC = 156.78 - 0.08 DSCH	0.4249
1969-70	SC = 142.50 - 0.07 DSCH	0.3026
1970-71	SC = 169.68 - 0.09 DSCH	0.3457
1971-72	SC = 151.88 - 0.06 DSCH	0.3375
1972-73	SC = 158.88 - 0.15 DSCH	0.4555
1973-74	SC = 157.43 - 0.11 DSCH	0.2416
1974-75	SC = 153.43 - 0.10 DSCH	0.4149
1975-76	SC = 177.73 - 0.11 DSCH	0.2416
1976-77	SC = 172.21 - 0.23 DSCH	0.4149
1977-78	SC = 139.30 - 0.08 DSCH	0.3541
1978-79	SC = 136.73 - 0.08 DSCH	0.4787
1979-80	SC = 117.50 - 0.06 DSCH	0.5786

Streamflow Specific Conductance Relationships (Streamflow less than or equal to 500 cfs)

Water Year	Regression Line	R^2
1968-69	SC = 161.41 - 0.13 DSCH	0.2393
1969-70	SC = 164.99 - 0.19 DSCH	0.3878
1970-71	SC = 171.95 - 0.11 DSCH	0.2715
1971-72	SC = 168.42 - 0.14 DSCH	0.3530
1972-73	SC = 162.34 - 0.18 DSCH	0.4950
1973-74	SC = 165.41 - 0.18 DSCH	0.3095
1974-75	SC = 163.63 - 0.19 DSCH	0.5501
1975-76	SC = 184.74 - 0.16 DSCH	0.2418
1976-77	SC = 172.21 - 0.23 DSCH	0.4639
1977-78	SC = 151.19 - 0.16 DSCH	0.6180
1978-79	SC = 149.59 - 0.23 DSCH	0.6180
1979-80	SC = 127.56 - 0.12 DSCH	0.6436

Table 8

Streamflow Specific Conductance Relationships

Water Year	Regression Line	R^2
1968-69	log SC = 2.48 - 0.16 log DSCH	0.5028
1969-70	log SC = 2.55 - 0.21 log DSCH	0.6902
1970-71	log SC = 2.41 - 0.12 log DSCH	0.4633
1971-72	log SC = 2.55 - 0.19 log DSCH	0.4827
1972-73	log SC = 2.57 - 0.22 log DSCH	0.6664
1973-74	log SC = 2,45 - 0.16 log DSCH	0.5271
1974-75	log SC = 2.46 - 0.17 log DSCH	0.7265
1975-76	log SC = 2.52 - 0.16 log DSCH	0.3407
1976-77	log SC = 2.44 - 0.14 log DSCH	0.5136
1977-78	log SC = 2.48 - 0.18 log DSCH	0.6531
1978-79	log SC = 2.53 - 0.21 log DSCH	0.7084
1979-80	log SC = 2.40 - 0.19 log DSCH	0.9071

Streamflow Specific Conductance Relationships
(Streamflow less than or equal to 500 cfs)

Water Year	Regression Line	R^2
1968-69	log SC = 2.40 - 0.12 log DSCH	0.2526
1969-70	log SC = 2.59 - 0.23 log DSCH	0.6433
1970-71	log SC = 2.40 - 0.11 log DSCH	0.3895
1971-72	log SC = 2.55 - 0.18 log DSCH	0.4010
1972-73	log SC = 2.59 - 0.23 log DSCH	0.6676
1973-74	log SC = 2.46 - 0.16 log DSCH	0.5076
1974-75	log SC = 2.46 - 0.17 log DSCH	0.7189
1975-76	log SC = 2.44 - 0.13 log DSCH	0.1989
1976-77	log SC = 2.52 - 0.14 log DSCH	0.5136
1977-78	log SC = 2.53 - 0.20 log DSCH	0.7216
1978-79	log SC = 2.53 - 0.22 log DSCH	0.6589
1979-80	log SC = 2.38 - 0.17 log DSCH	0.8633

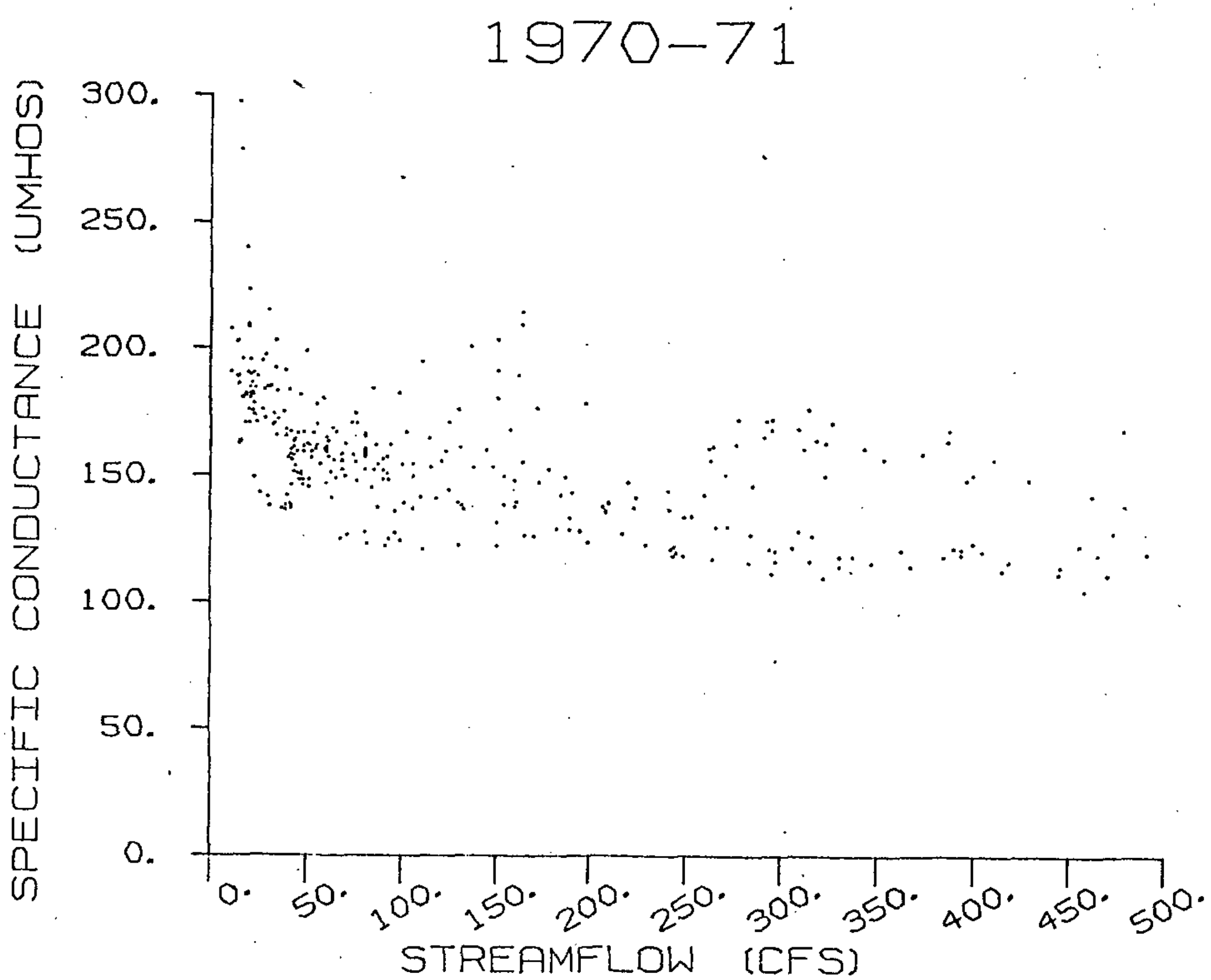

Figure 27. Arithmetic influence of streamflow on specific conductance during water year 1970-71.

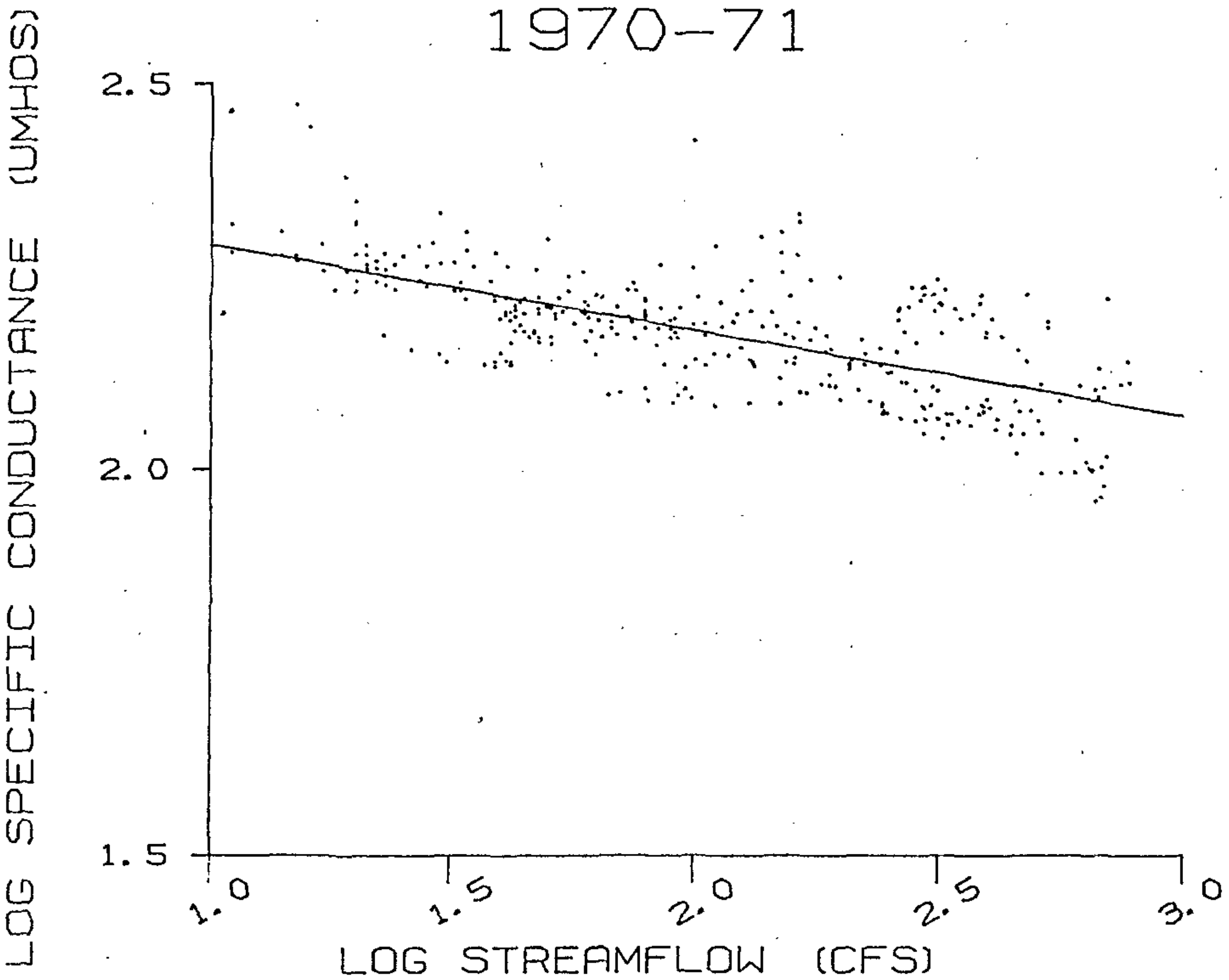

Figure 28. Influence of the log of streamflow on the log of specific conductance during water year 1970-71.

CHAPTER V

VARIABLE EFFLUENT DISCHARGE PERMITS

The approach to water pollution control presented in the Federal Water Pollution Control Act (FWPCA) Amendments of 1972 (66) radically changed the existing federal goals and policies. Previous to the Amendments, the role of the federal government in the regulation and enforcement of pollution abatement was minimal. Water quality action depended on water quality standards which were only advisory. Prior to 1972, legislation laid the burden of proof on the government to show that the beneficial use of a stream was impaired and that this impairment was caused by an individual discharger. Only after demonstrating this cause and effect relationship could enforcement measures be undertaken (2). This strategy was replaced in the 1972 Amendments by the requirement that technology based effluent limits be placed on all discharges into a receiving water. Now, after ten years, this method is also being reevaluated. The philosophy of the Act is sound, but it must be readjusted and refined to account for political and economic realities while incorporating the experience and knowledge acquired since 1972.

The question that must be addressed is if uniform effluent standards are always appropriate or even reasonable. It must be acknowledged that there has been a great deal of progress made since 1972. The trend of deteriorating waterways with the potential for septic conditions and the elimination of aquatic life has been reversed, and the water quality of many rivers has been restored or maintained to a "fishable and swimmable" condition. This has been accomplished, in part, by the expenditure of large amounts of capital for the construction of wastewater treatment plants. However, the resources for pollution control are finite, and the costs of operation and maintenance still continues.

Pragmatic adjustments of the uniform effluent standards system may be the key to an efficient use of resources. The requirement of uniform treatment at all times without any consideration of the environmental benefits derived may result in unnecessary expenditures which result in dramatic overprotection of a receiving stream.

Waste Load Allocations

Current methods of waste load allocation (WLA) may be modified by recognizing that all streams do not behave alike, and that their abilities to assimilate wastes are different. The distribution of the available stream capacity, in a water quality limited stream, is the waste load allocation process. The objective of a waste load allocation is to define the Total Maximum Daily Load (TMDL) of a pollutant. The TMDL as defined by the EPA regulation (62) is "the pollutant loading for a segment of water that results in an ambient concentration equal to the numerical concentration limit required for that pollutant by the numerical or narrative criteria in the water quality standard." An often cited advantage of uniform effluent standards is the "equity" of the load allocation amongst dischargers. However, there are many alternatives in waste load allocation methods (Table 9), and having so many different approaches actually implies multiple definitions of equity (7).

Waste load allocations are dependent on three factors: the critical streamflow, the instream behavior of a pollutant and the water quality standard to be met.

The critical streamflow most often used is the 7Q10. The 7Q10 is a conservative design parameter, since its flow will be exceeded approximately 99% of the time. Also, constituent concentrations are at a maximum at low flows. Concentration decreases with increasing flow by dilution.

Table 9

Potential Waste Load Allocation Methods (7)

---

1. Equal Percent Removal (equal percent treatment).
2. Equal effluent concentrations.
3. Equal total mass discharge per day.
4. Equal reduction of raw load (pounds per day).
5. Equal ambient mean annual quality (mg/l).
6. Equal treatment cost per unit of production.
7. Equal mass discharged per unit of raw load per day.
8. Equal mass discharged per unit of production.
9. Percent removal proportional to raw load per day.
10. Percent removal proportional to community effective income.
11. Effluent charges (dollars per pound, etc.)
12. Seasonal limits based on cost-effectiveness analysis.
13. Minimum total treatment cost.
14. BAT (industry) plus some level for municipal inputs.
15. Divide assimilative capacity to require an "equal effort among all discharges."

The instream reactions of pollutants affecting the mass of pollutants define the assimilative capacity of a receiving water. A combination of physical, chemical and biological processes will stabilize a quantity of pollutants without degrading the stream quality.

The waste load allocation process includes an estimation of the stream's assimilative capacity using the critical low flow and its associated parameters. This often results in an underestimation of the stream's assimilative capacity by using a worst case analysis.

Variable Discharge Permits

The most common water quality standard is the threshold standard. The threshold standard provides adequate protection at low streamflow conditions, but it does not utilize the excess capacity of the stream to assimilate wastes at high streamflows. The intent of a water quality standard is to protect the designated uses of a stream by maintaining an appropriate criterion. As long as that criterion is satisfied the designated uses are protected. The practice of stipulating a threshold standard at low flows and to mandate all discharge limits based on critical worst case conditions is overly protective. Since, if the standard truly protects the stream uses during low flow conditions then there is an excess capacity at higher flows which may be wisely utilized.

By examining the elements used in determining waste load allocations --streamflow, assimilative capacity, and water quality standards-- flexibility of the system may be developed. One modification of uniform effluent permits is a flow variable discharge permit. The flow variable discharge permit would take advantage of the dynamic nature of streamflow and its assimilative capacity. The level of treatment required would change as the available assimilative capacity changed and the discharge of oxygen demanding materials into the stream would be related to the instantaneous or daily streamflow rates.

The difficulties of using instantaneous or daily flow variable permits are obvious. They are impractical and probably infeasible given the processes involved in wastewater treatment. The biological processes which are the mainstay of most treatment facilities can not be instantaneously modified to account for the normally occurring increases or decreases in streamflow. In addition, accurate upstream gauging stations would be essential. Correlating effluent loads to instantaneous or daily streamflows would probably require either storage capacity for the effluent, for the influent, or a combination of both.

A viable alternative in using flow variable discharge permits is to base them on seasonal fluctuations. Seasonal flow variations are predictable, with the lowest flows occurring in the late summer and early autumn. Modifying treatment plant operations with the seasonal changes in flow and climate is already essential to maintain existing treatment standards. A seasonal variable discharge permit would define a different effluent standard for each distinct water season.

A water quality management scheme which allowed for the modification of the effluent standard would require a change in the water quality standard. If the intent of the standard is to guarantee adequate water quality at a critical low flow and higher quality at higher flows then that intent must be explicitly stated. (Although this is a judgement which is contrary to the assumption that the criteria are suitable to protect the designated uses outlined in a standard.) The point is that the water quality standard should be written as to clearly define the intent of the standard.

Modifying the water quality standard would enable the discharge from a point source to to change with changes in streamflow. At flows higher than the critical low flows the increase in discharge may parallel the increase (or decrease) in ambient constituent concentration. A maximum discharge level would be reached and maintained at that level so as not to rely on infrequently occurring high flow events.

A method of maintaining a threshold standard while decreasing the overprotection of a stream would be to use a dual threshold standard. A dual threshold standard would protect water quality during dry seasons by stipulating a critical low flow and single criterion for a pollutant. During wet seasons and high flows, a second threshold would specify a higher flow with the same criterion. In this way some of the excess capacity implicit in the definition of the critical low flow water quality standard is utilized during the high flow seasons. By establishing a second higher flow threshold standard a new region of unusable excess capacity is defined (Figures 29 and 30). However, this region would depend predominantly upon extreme high flow events and it would be unwise to depend on the assimilative capacity of infrequently occurring flood events. The effluent standard for discharges would be changed in accordance to the new seasonal water quality standard enabling the use of this excess capacity to assimilate wastes, while the criterion necessary to maintain good water quality is not violated. The effulent standard may take the form of a step function, the maximum discharge limit would change with increases in flow (Figure 31).

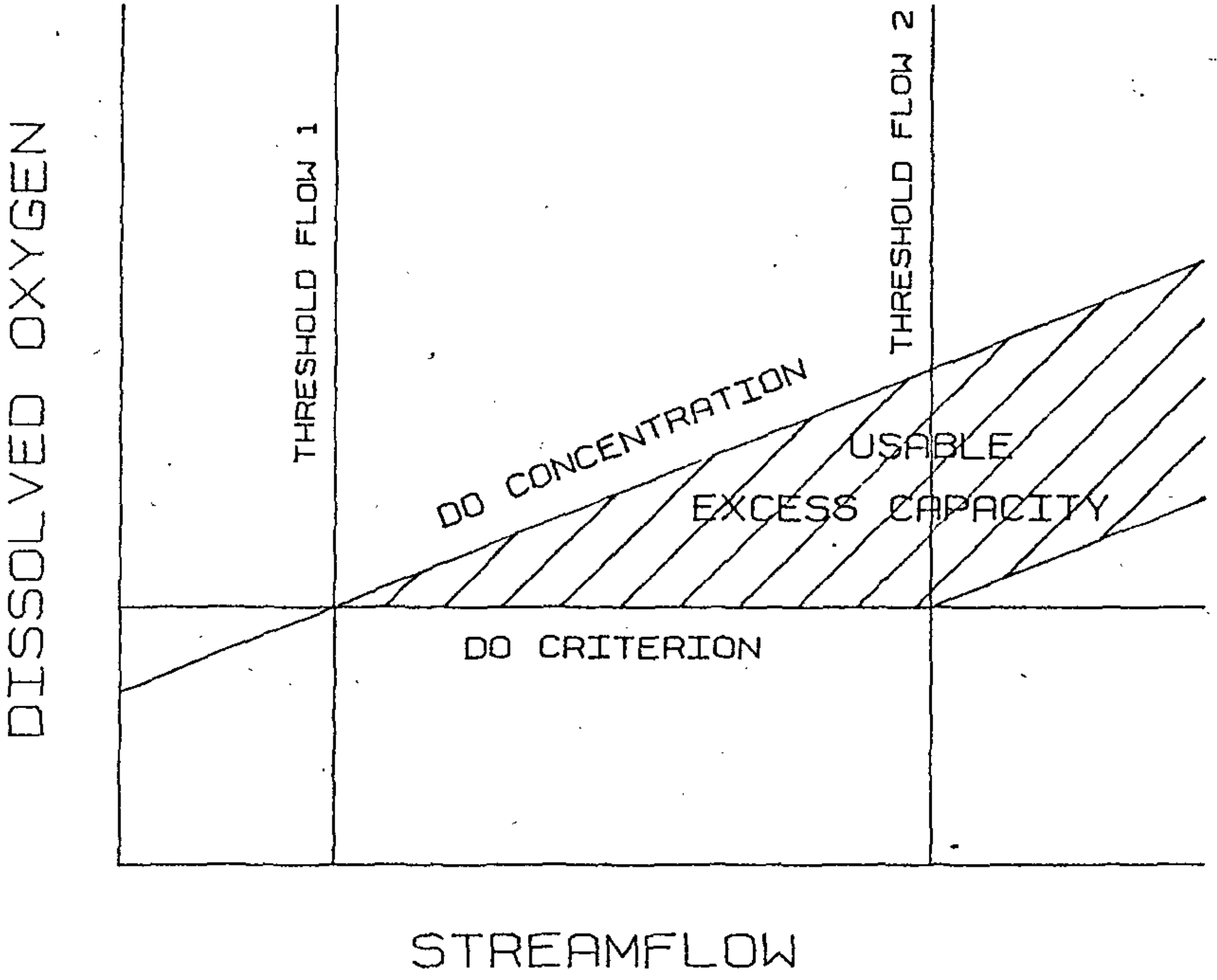

Figure 29. Dual threshold standard for dissolved oxygen concentration showing usable excess capacity.

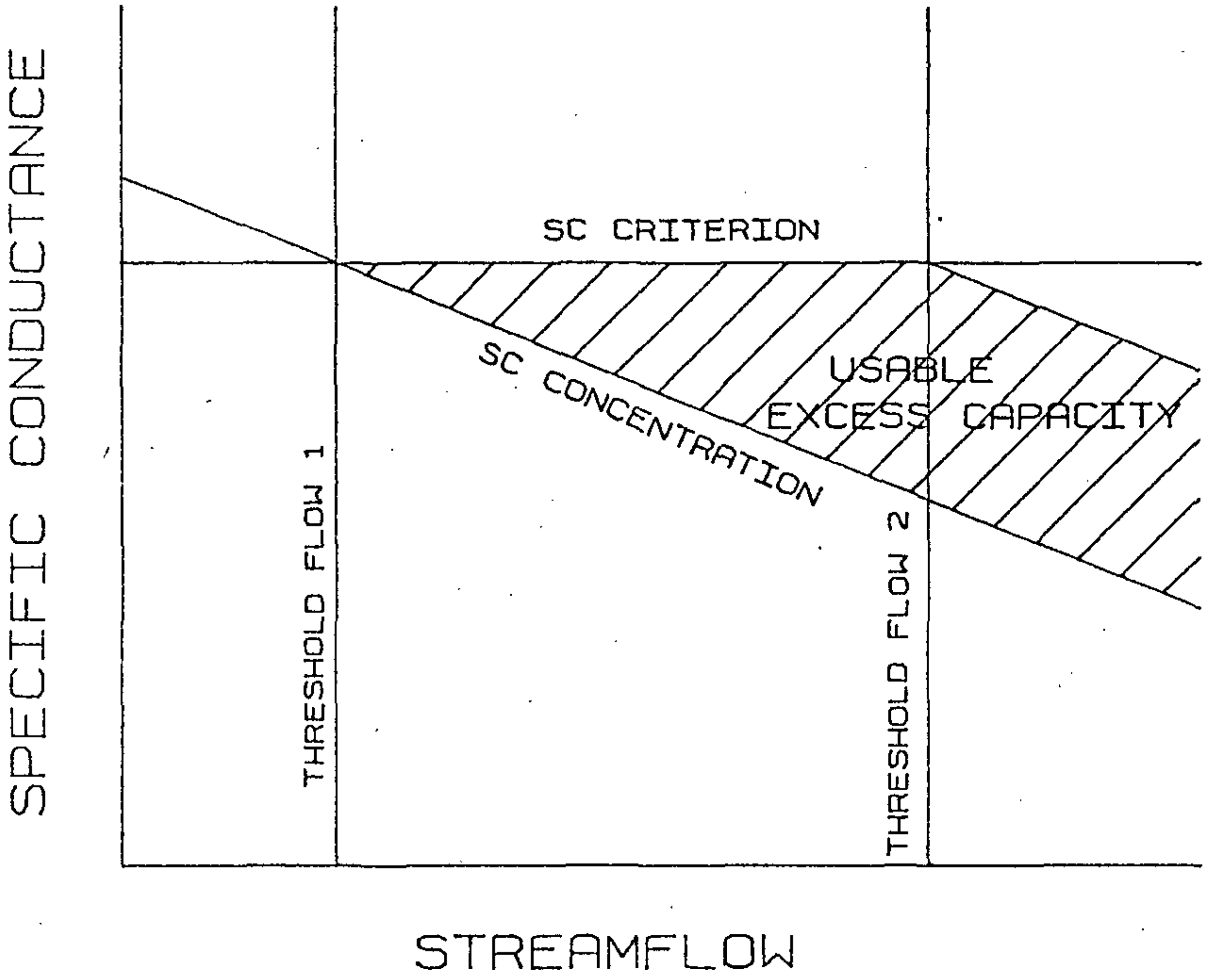

Figure 30. Dual threshhold standard for specific conductance showing usable excess capacity.

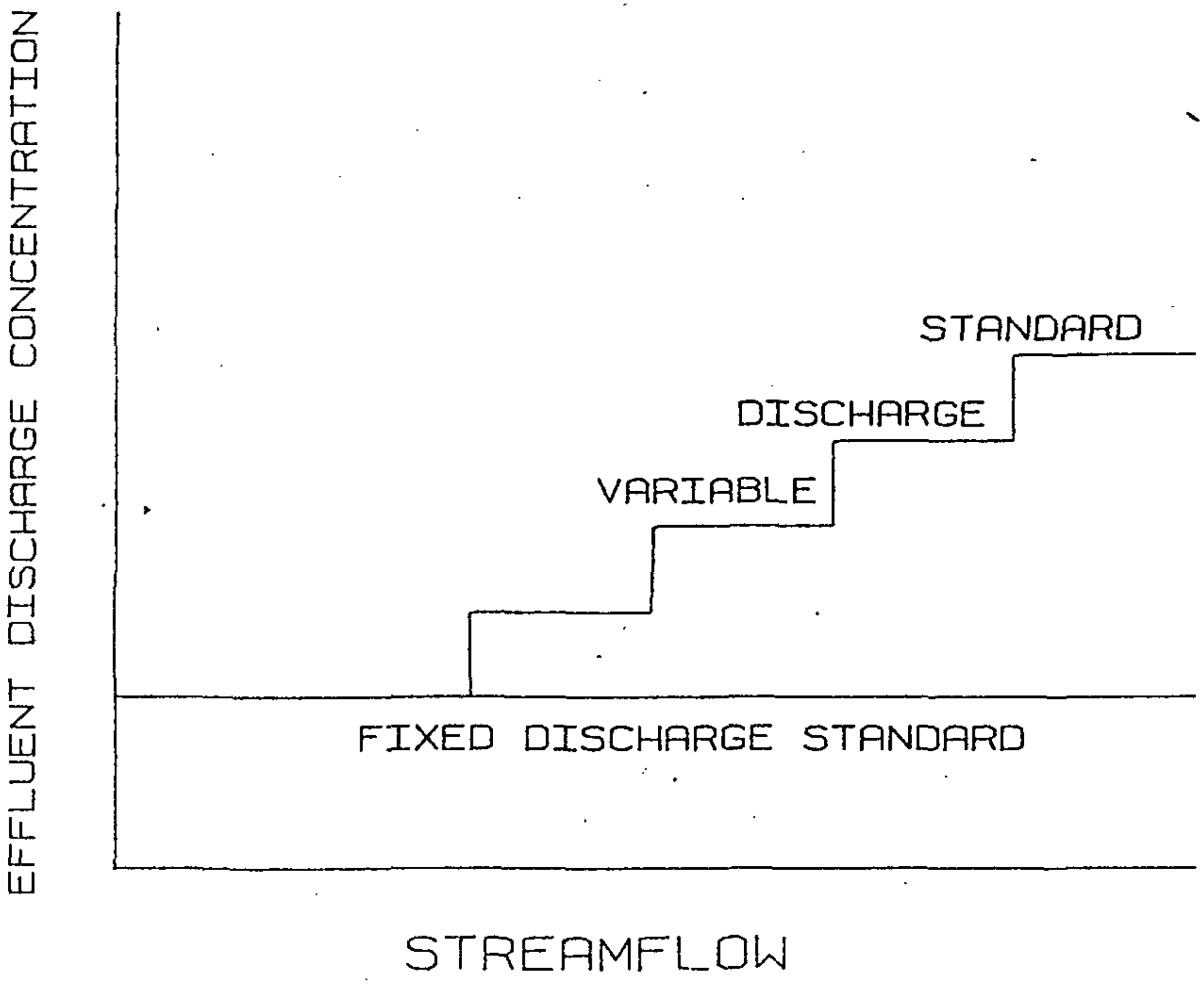

Figure 31. Variation in effluent discharge standards with increasing streamflow.

An alternative modification of the water quality standard would be a water quality criteria that increased with flow and/or seasonal conditions. In the case of dissolved oxygen, a standard based on a percent of oxygen saturation would account for higher dissolved oxygen concentrations during higher flows, since higher flows are typically associated with the colder seasons. It may be desirable to develop the water quality criteria with a margin of safety so that the assimilative capacity of the stream is not overtaxed. Again an upper limit on the criterion would be suitable at extreme high flows as not to depend on infrequently occurring flood events (Figures 32 and 33). Where the standard is regulating a constituent whose concentration is to be minimized, such as specific conductance, the standard may be written directly as a flow dependent curve.

For practical purposes the flow varying standards would probably be adapted to seasonal or monthly flows. A specified criterion would then be associated with a range of streamflows (Figures 34 and 35).

By using the assimilative capacity of a receiving water on a seasonal basis the intent of the water quality standard to protect the designated uses of a stream is upheld. Balanced with a variable water quality standard is the potential for extensive cost savings.

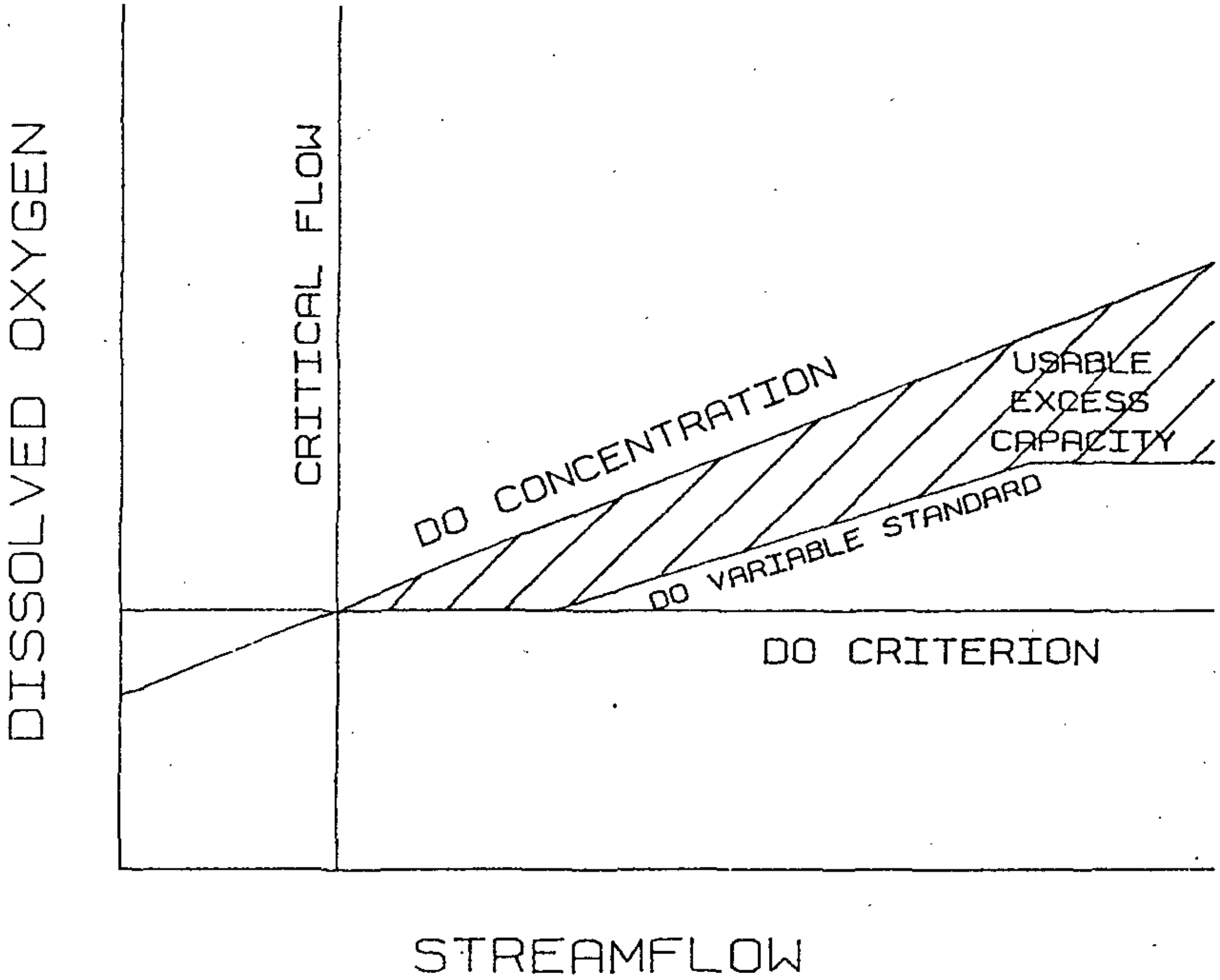

Figure 32. Flow variable standard for dissolved oxygen concentration showing usable excess capacity.

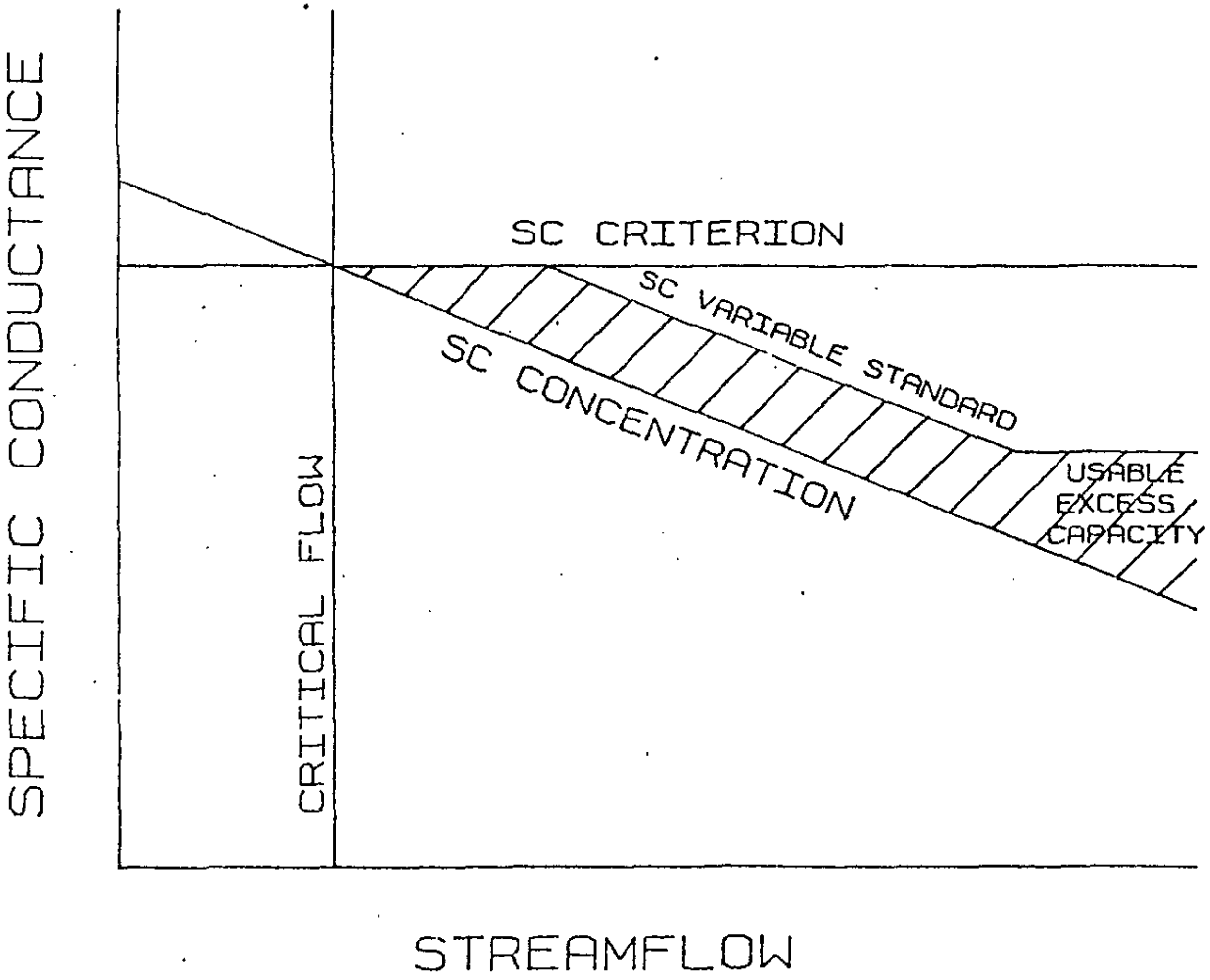

Figure 33. Flow variable standard for specific conductance showing usable excess capacity.

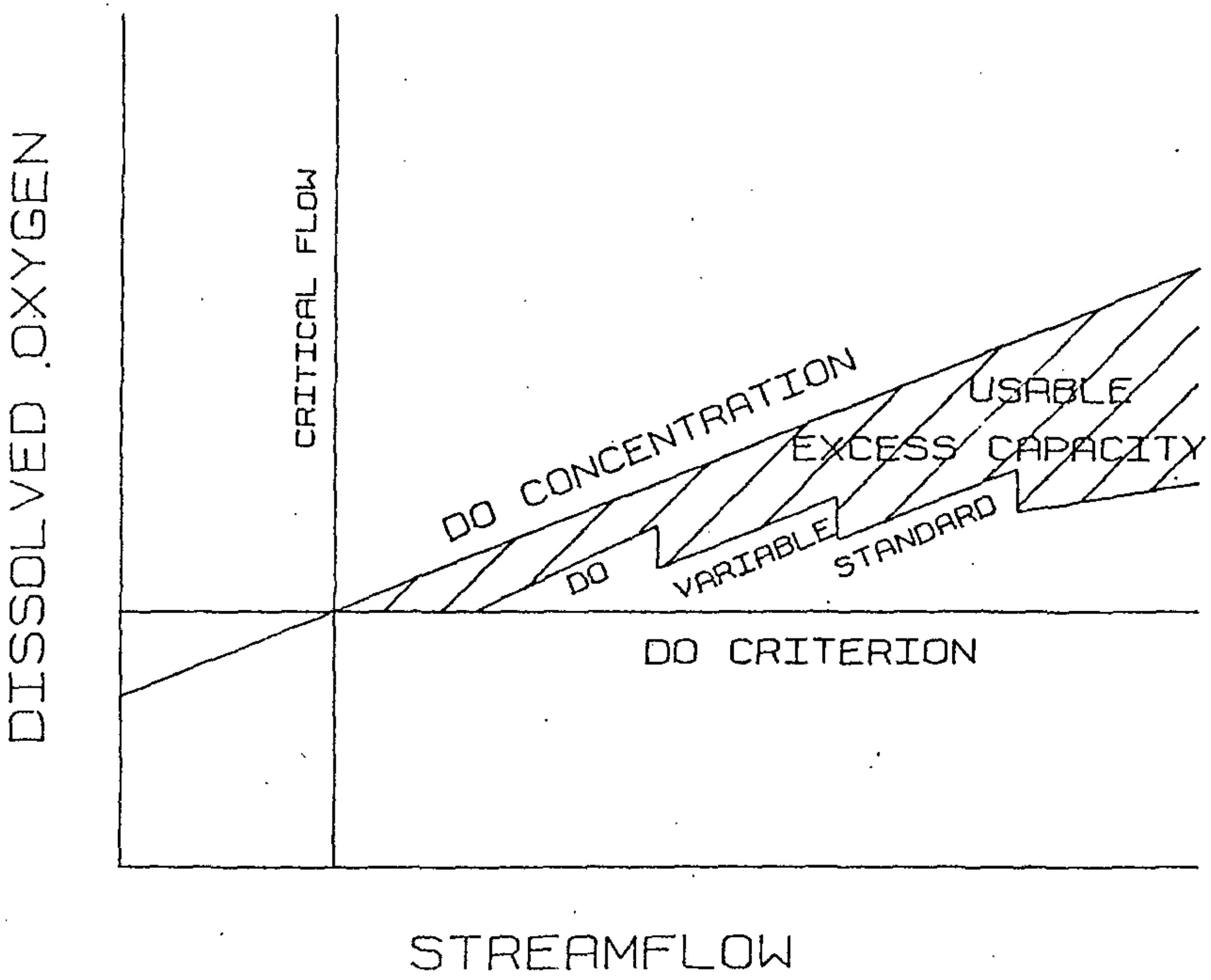

Figure 34. Flow variable standard defined over a range of streamflow for dissolved oxygen concentration showing usable excess capacity.

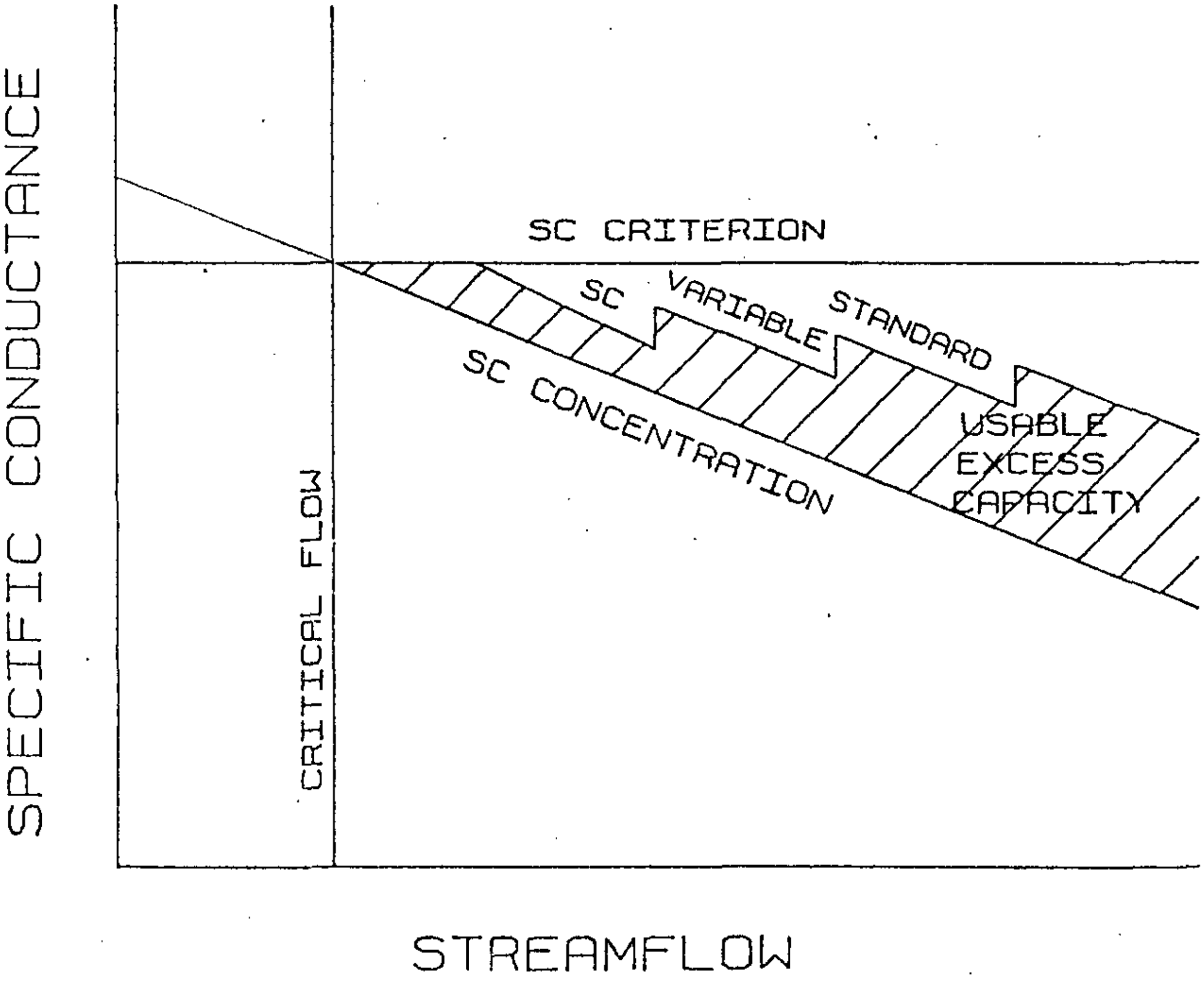

Figure 35. Flow variable standard defined over a range of streamflow for specific conductance showing usable excess capacity.

Potential Cost Savings

Georgia has initiated monthly variable effluent standards with respect to advanced wastewater treatment. (Treatment more stringent than that designated as secondary treatment.) Reheis, Dozier and et al. (49) have predicted the operating costs savings in Georgia if effluent limitations were readjusted monthly. Their estimates were based on the assumptions that secondary treatment requirements would be met at all times and:

1. Filters would not be operated in any month for which BOD5 limit is greater than 15 mg/l.
2. Post-aeration of effluents would be operated in any month for which the effluent dissolved oxygen requirement is greater than 2 mg/l.
3. Energy costs for activated sludge systems would be reduced by 23 to 30% below normal monthly costs for any month in which no nitrification of ammonia is required...
4. For facilities where rotating biological contactors (RBC) are proposed as the nitrifying process following activated sludge, the RBCs would not be used in any month for which no nitrification is required (49).

Based on the above assumptions they found that operating costs for the 19 facilities could be reduced anywhere from 2 to 19% per facility. The total annual savings would be $3.3 million or 8.9% of the operating costs for all facilities investigated.

Yaron (73) developed a multiseasonal mathematical programming model to examine the operating costs savings in seasonally adjusted wastewater treatment. The objective function was designed to minimize operating costs. He presents a case study to demonstrate the economic advantages of seasonal flow variable permits. The analysis examines BOD as the pollutant and dissolved oxygen as the measure of water quality. He considers three levels of BOD removal: L1 (<90.5%), L2 (90.5-95.2%), L3 (95.2-97.6%). The case study incorporated two river reaches.

In minimizing operating costs while maintaining stream quality standards Yaron concluded that:

1. During high flow season only the first of level treatment, L1, need be applied to the higher reach with both first and second levels applied to the lower reach.
2. During low flow season all treatment levels should be applied in both reaches.

With an operating cost of $595 per day in the high season and $1097 per day in the low season the potential for cost savings is $502 per day by operating in a modified mode during high flows. The high flow season consisted of 273 days. The potential cost savings by a seasonally adjusted effluent standard over a yearly effluent standard based on the critical low flow is $137,046. This savings comprises 34% of the cost if the plant was operated in the more stringent mode all year round ($1097 per day for 365 days = $400,405 per year) (73).

CHAPTER VI

CONCLUSIONS

The goal of the Federal Water Pollution Control Act Amendments of 1972 to eliminate discharge of pollutants into the nations waterways by 1985 is a noble ambition, but one that is quite clearly unattainable for the foreseeable future. It should not be abandoned. It serves as a statement of purpose and provides the direction for longterm water quality management planning. In the short run, however, policies must be formed that are technologically and financially reasonable.

The 1972 Amendments emphasize technology based controls for limiting water pollution. The next step in refining the pollution control program is to examine water quality standards. Water quality standards are legal entities which are defined by stipulation of the designated use of a waterbody and the associated criteria needed to attain that use. The reevaluation of the use of water quality standards in setting effluent limits can be an effective tool in the reallocation of limited water quality management resources.

The use of streams as receiving waters is inevitable. Waterways may still maintain their integrity as multipurpose resources by regulating the discharges wisely. Cost efficient solutions to discharge problems may be accomplished if water quality standards are written so as to attain the designated uses while utilizing the naturally occurring fluctuations in stream quality.

The use of statistical analysis to predict the frequency of low streamflows is essential in designing water quality standards. Low streamflows are the limiting situations for water quality protection, since it is during this time that the most adverse conditions occur. The 7Q10 is commonly used as the critical low flow of threshold standards. However, this flow is exceeded more than ninety-nine percent of the time, and a threshold standard based on the 7Q10 is therefore inordinately protective most of the time. This method of determining discharge limitations does not allow for an effective use of the stream or its available assimilative capacity.

The additional assimilative capacity during highflows permits flexibility in effluent standards. A viable alternative to a single year round effluent limitation is a variable discharge permit which takes into account the seasonal variations in streamflow. During low flow periods the effluent limitations based on the traditional load allocation process would be imposed. During periods of high flow, and higher assimilative capacity, protective measures may be relaxed to the extent permitted by the higher assimilative capacity. Due to the political and equity considerations involved in the mandatory minimum treatment levels required by the 1972 Amendments, this variable discharge approach id most suitable to streams which are water quality limited (ie., where additional treatment beyond the required minimum is necessary to meet the water quality standards). The varying seasonal water quality standard requires more stringent effluent limitations only when needed. In this manner the water quality of the nation's waterways will be improved and/or maintained at a reduced cost.

The use of variable discharge permits would mean additional responsibilities for both the regulator and treatment plant operator. Accurate modelling of the seasonal behavior of a stream and proper operation of wastewater treatment plants are essential. The advantage of variable discharge permits is that they enable the achievement of water quality suitable for the various designated uses while time permitting more efficient and cost effective operation of wastewater treatment plants.

REFERENCES

1. Anderson, P.W. and S.D. Faust, "Characteristics of Water Quality and Streamflow, Passaic River Basin Above Little Falls New Jersey," U.S. Geological Survey Water Supply Paper Number 1700, 1974.

2. Anonymous, "Changing the Clean Water Act: Reflections on the Longterm," Journal of the Water Pollution Control Federation, 55(2), Feburary 1983.

3. Bekers, C.C., S.G. Chamberlain and G.P. Grimsrud, "Quantitative Methods for Preliminary Design of Water Quality Surveillance Systems," EPA R5-72-001, 1972.

4. Berry, B.J.L., and F.E. Horton, Urban Environmental Management: Planning for Pollution Control, Prentice-Hall, Englewood Cliffs, New Jersey, 1974.

5. Cairns, J., "The Perspective of an Aquatic Ecologist," Proceedings of the Seminar on Development and Assessment of Environmental Standards, American Academy of Environmental Engineers, Annapolis, February 1983.

6. California State Water Quality Control Board, "Water Quality Criteria," (revised and expanded by J.E. McKee and H.W. Wolf), Publication 3-A, 1963.

7. Chadderton, R.A., A.C. Miller and A.J. McDonnel, "Analysis of Waste Load Allocation Procedures," Water Resources Bullentin, 17(5):760, October 1981.

8. Chow, V.T.E., Editor, Handbook of Applied A Hydrology: Compendium of Water Resources Technology, McGraw-Hill, New York, 1964.

9. Clark, J.W., W. Viessman, M.J. Hammer, Water Supply and Pollution Control, Harper and Row, New York, 1977.

10. Commonwealth of Massachusetts, Water Resources Commission, Division of Water Pollution Control, "Massachusetts Water Quality Standard," revised: April 1978.

11. Dallaire, E.E., "The U.S. Water Quality Program: Big Boost needed for R and D," Civil Engineering, 41(10):81, October 1971.

12. Dorcey, H.J. and I.K. Fox, "Critique of the Water Pollution Control Act," A.S.C.E. Journal of Environmental Engineering, 100(EE1):141, Feburary 1974.

13. Durum, W.H., "Relationship of the Mineral Constituents in Solution to Streamflow, Saline River near Russell, Kansas," Transactions of the American Geophysics Union, 34(3):435, 1953.

14. Edwards, A.M.C., "The Variation of Dissolved Constituents with Discharge in Some Norfolk Rivers," Journal of Hydrology, 18(1973):219, 1973.

15. Environmental Protection Agency, "Antidegradation Policies: Water Quality Standards, Criteria Summaries; A Compilation of State/Federal Criteria," 1980.

16. Environmental Protection Agency, "The Control of Pollution From Hydrographic Modification," EPA 430/9-73-017, 1793.

17. Environmental Protection Agency, "Designated Uses: Water Quality Standards, Criteria Summaries; A Compilation of State/Federal Criteria," 1980.

18. Environmental Protection Agency, "Dissolved Oxygen: Water Quality Standards, Criteria Summaries; A Compilation of State/Federal Criteria," 1979.

19. Environmental Protection Agency, "Guidelines for State and Areawide Water Quality Management Program Development, Chapter 5," November 1976.

20. Environmental Protection Agency, "Intermittent Streams: Water Quality Standards, Criteria Summaries; A Compilation of State/Federal Criteria," 1980.

21. Environmental Protection Agency, "Toward Cleaner Water: The New Permit Program to Control Water Pollution," January 1974.

22. Environmental Protection Agency, "Quality Criteria for Water, 1976," 1977.

23. Feliciano, D.V., "Water Qulaity Criterial and Standards Development," Journal of the Water Pollution Control Federation, 52(10):2418, October 1980.

24. Freeman, A.M., "Technology Based Effluent Standards: The U.S. Case," Water Resources Research, 16(1):21, February 1980

25. Gunnerson, C.G. "Streamflow and Quality in the Columbia River Basin," ASCE Journal of The Sanitary Engineering Division, 93(SA6):1, December 1967.

26. Hamilton, C.E., Editor, Manual Water, American Society for Testing and Materials, Philadelphia, 1964.

27. Hardison, C.H., "Prediction Error of Regression Estimates of Streamflow Characteristics at Ungaged Sites," U.S. Geological Survey Professional Paper: Number 750-C, 1971.

28. Hendrickson, G.E. and R.A. Krieger, "Geochemistry of Natural Waters of the Blue Grass Region, Kentucky," U.S. Geological Survey Water Supply Paper: Number 1700, 1964.

29. Hendrickson, G.E. and R.A. Krieger, "Relationship of Chemical Quality of Water to Stream Discharge in Kentucky," Report: International Geological Congrss, XXI Session, Part I, Norden, Copenhagen, 1960.

30. Hem, J.D., "Fluctuation in Concentration of Dissolved Solids of Some Southwestern Streams," Transactions of the American Geophysical Union, 29(1)80, February 1948.

31. Hem, J.D. "Study and Interpretation of Chemical Characteristics of Natural Waters," U.S. Geological Survey Water Supply Paper:, Number 1473, 1970.

32. Krenkel, P.A., "Problems in the Establishment of Water Quality Criteria," Journal of the Federation of Water Pollution Control, 51(8):2168, August 1979.

33. Ledbetter, J.O. and E.F. Gloyna, "Predictive Technicques for Water Quality Inorganics," ASCE Journal of The Sanitary Engineering Division, 90(SA1), 1964.

34. Lenz, A.T. and C.N. Sawyer, "Estimation of Streamflow form Alkalinity Determination," Transactions American Geophyscial Union, 25, 1944.

35. Linsley, R.K. and J.B. Franzini, Water Resources Engineering, McGraw-Hill, New York, 1979.

36. Male, J.W. and H. Ogawa, "Low Flows of Massachusettes Streams," Water Resources Research Center, University of Massachusettes, December 1981.

37. Massachusettes Department of Environmental Quality Engineering, Division of Water Pollution Control, "French and Quinebaug Rivers: Water Quality Data-Part A," 1976.

38. Massachusettes Department of Environmental Quality Engineering, Division of Water Pollution Control, "French and Quinebaug Rivers: Wasterwater Discharges-Part B," 1972.

39. Massachusettes Department of Environmental Quality Engineering, Division of Water Pollution Control, "French and Quinebaug Rivers: Water Quality Analysis-Part C," 1974.

40. Massachusettes Department of Environmental Quality Engineering, Division of Water Pollution Control, "French and Quinebaug Rivers: Water Quality Management Plan-Part D." 1975.

41. McGauhey, P.H., "Folklore in Water Quality Standards," Civil Engineering--ASCE, 25(6): ,June 1965.

42. National Academy of Sciences, National Academy of Engineers, "Water Quality Criteria, 1972," 1974.

43. National Technical Advisory Committee to the Secretary of the Interior, "Water Quality Criteria," 1968.

44. Nemeron, N.L., Scientific Stream Pollution Analysis, McGraw-Hill, New York, 1974.

45. Noss, R.R. and D.H Marks,"Improving the Development of Water Quality Standards," Journal Water Pollution Control Federation, 53(4):426, April 1981.

46. O'Connor, D.J., "The Concentration of Dissolved Solids and River Flow," Water Resources Research, 12(2):279, April 1976.

47. O'Neil W.B., "Pollution Permits and Markets for Water Quality," Ph.D. Thesis at the University Of Wisconsin-Madison, Department of Ecomomics, 1980.

48. Ray, W.C. and W.R. Walker, "Low Flow Criteria for Stream Standards," ASCE Journal of The Sanitary Engineering Division, 94(SA3):507, June 1968.

49. Reheis, H.F., J.C. Dozietr and et. al., "Treatment Cost Savings Through Monthly Variabe Effluent Limits," Journal of the Water Pollution Control Federation, 54(8):1224, August 1982.

50. Riggs, H.C., Chairman: Task Committee on Low Flow Evaluation, Methods and Needs of the Committee on Surface-Water Hydrology of the Hydraulics Division, "Characteristics of Low Flows," ASCE Journal of the Hydraulics Division, (HY5):717, May 1980.

51. Sawyer C.N., and P.L. McCarty, Chemistry for Environmental Engineers, McGraw-Hill, New York, 1978.

52. Sherwani, J.K., "Effects of Low Flow Hydrologic Regimes on Water Quality Management," North Carolina State University Resources Research Institution, March 1971.

53. Snoeyink, V.L. and D. Jenkins, Water Chemistry, John Wiley and Sons, New York, 1980.

54. Sprague, J.B., "Resistance of Four Freshwater Crustanceans to Lethal High Temperature an Low Oxygen," Journal of Fish Resources Board of Canada, 20(1963):387, 1963.

55. Stall, J.B. and J.C. Neill, "A Partial Duration Series for Low Flow Analyses," Water Resources Research, 66(12):4219, December 1961.

56. Steele, T.D. and M.E. Jennings, "Regional Analysis of Streamflow Chemical Quality in Texas," Water Resources Research, 8(2):460, April 1972.

57. Tarr, J.A. and F.C. McMichael, "Water and Wastes: A History," Water Spectrum, 10(4):18, Fall 1978.

58. Tirsh, F.S. "River Basin Water Quality Monitoring Network Design," Ph.D. Dissertation at the University of Massachusetts, Department of Civil Engineering, May 1983.

59. Toler, L.G., "Relation Between Chemical Quality and Water Discharge in Spring Creek, S.W. Georgia," U.S. Geological Survey Professional Paper: Number 525-C209, 1965.

60. United States, "The Clean Water Act Showing Changes Made by the 1977 Amendments," 1977.

61. United States, "Code of Federal Regulations," 40, Protection of the Environment, Parts 100 t 339, 158 (1976).

62. United States, "Federal Register, Vol. 43, July 10, 1978.

63. United States, "Federal Register, Vol. 43, December 28, 1978.

64. United States, "Federal Register, Vol. 45 November 28, 1980.

65. United States, "Federal Register, Vol. 47, Octobe 19, 1982.

66. United States, "Federal Water Pollution Control Act Amendments, 1972," 33USC abd 1271 et seq., 1972.

67. U.S. Geological Survey, "Water Resources Data for Connecticut: Water Year 1980," 1981.

68. U.S. Geological Survey, "Water Resources Data for Massachusetts and Rhode Island: Water Year 1980," 1981.

69. Velz, C.J., Applied Stream Sanitation, Wiley-Interscience, New York, 1970.

70. Viessman, W., J.W. Knapp, et. al, Introduction to Hydrology, Harper and Row, New York, 1977.

71. Walling, D.E. and B.W. Weber, "The Spatial Dimension in the Interpretation of Stream Solute Behavior, Journal of Hydrology, 47(1980):129, 1980.

72. Wang W. and R.L. Evans, "Dynamics if Nutrient Concentrations in the Illinois River," Journal of the Water Pollution Control Federation. 42(12):2117, December 1970.

73. Yaron, D., "A Model for the Analysis of Seasonal Aspects of Water Quality Control," Journal of Environmental Economics and Management, 6(1979):140, 1979.