THESIS

EVALUATION OF ALTERNATIVE DESIGN FLOW CRITERIA FOR USE IN EFFLUENT DISCHARGE PERMITTING

Submitted by

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MASTER OF SCIENCE.

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ABSTRACT OF THESIS

EVALUATION OF ALTERNATIVE DESIGN FLOW CRITERIA
FOR USE IN EFFLUENT DISCHARGE PERMITTING

A design flow is the value used to represent upstream or dilution flow in the calculation of effluent permit limits under the National Pollutant Discharge Elimination System (NPDES). The 7Q10 low-flow statistic, or the 7-day moving average low flow that occurs once every ten years on the average, has traditionally been used for design flows. Recently, alternative approaches to conventional NPDES permitting techniques have been investigated. The objective of this study was to research alternative design flows that would maximize use of the assimilative capacity of receiving waters while also maintaining water uses.

This study addressed two major aspects of design flows. The first was the definition of a set of recommended methods to use in the calculation of design flows. These methods were gathered from the literature or developed in the process of the study. The second aspect was a comparison of alternative design flows and recommendation of guidelines to use in selecting appropriate values. Data at eight sites on streams along the Front Range of Colorado were analyzed. Three types of analysis were applied to define design flows for acute and chronic conditions. Traditional frequency/duration statistics were calculated

on an annual, monthly and seasonal basis. An empirical, distribution-free approach developed by the U.S. EPA, called the biologically-based method, was also applied. A simplified version of this method, termed excursion analysis, was developed to augment the information supplied by the biologically-based approach. Design flows calculated with these methods were related to acute or chronic durations and allowable frequency criteria recommended by the U.S. EPA for the protection of aquatic life.

The results of the research highlighted the need to establish a standard set of methods to use in the calculation of design flows. Some methods were recommended while other areas requiring more research were pointed out. The lack of long flow data records above effluent discharge points, where NPDES permit limits are calculated, is a major problem. The results of the flow analysis showed that distribution-based frequency statistic flows do not relate as directly to aquatic life criteria as biologically-based design flows. The level of protection provided by frequency statistic flows varies widely from site to site, while biologically-based flows provide relatively consistent levels of protection. Seasonal or monthly design flows can be used to increase the use of stream assimilative capacity. However, it was shown that the number of excursions, or flows below a given design flow, was substantially higher for monthly frequency statistic flows than annual values. The implication of this result is that more stringent design flows may be required on a monthly basis, depending on the seasonal needs of aquatic life populations, and other water uses.

The critical importance of design flow criteria, based on aquatic life protection, was emphasized in this study. Once criteria have been chosen, the selection of an appropriate annual design flow is relatively straightforward. The biologically-based method, or a similar approach that relates directly to use criteria, is recommended as a better alternative than the 7Q10. Seasonal or monthly flows are also recommended, but will require further research.

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The value traditionally used for the design flow in National Pollutant Discharge Elimination System (NPDES) permits has been the 7Q10. The 7Q10 is defined as the 7-day moving average low flow that is equaled or not exceeded once in every ten years on the average. This statistic was chosen rather arbitrarily at the inception of the NPDES in the early 1970's and has no strong water quality basis (U.S. EPA, 1986). The design flow value used in NPDES permitting can have a significant effect on the quality of our nation's waters as well as on the costs of wastewater treatment in this country. Recently, the U.S. EPA and a number of the states have begun to experiment with alternatives to the 7Q10. Two reports have been published as part of this research effort in Colorado - the Interim Report (Low Flow Project Team, 1986) and the Final Report (Paulson and Sanders, 1987) Evaluation of Design Flow Criteria for Effluent Discharge Permits in Colorado.

The annual 7Q10 flow statistic is a questionable design flow for a number of reasons. The 7Q10 flow occurs infrequently, on less than 1% of all days in most streams, and is considered overly restrictive by many (Reheis, 1982). One major problem with an annual 7Q10 is that it is based on extreme low flows which occur only during certain times of the year. The assimilative capacities of streams at higher flows which occur at other times of the year are not recognized by a procedure which uses only the annual 7Q10 as the design flow. To take advantage of these higher assimilative capacities, monthly or seasonal design flows could be applied. Frequency/durations flow statistics have two major drawbacks that apply to both annual and seasonal flows, however. The first is that frequency statistics provide inconsistent levels of protection from one stream to another. Frequency analysis does not reflect the variety of flow patterns that can occur in natural and regulated streams. The number of days with flows lower than the 7Q10 annual design flow may vary significantly from one river to another (U.S. EPA, 1983g). A second drawback is that the 7Q10 frequency statistic is not directly related to instream water quality conditions. Frequency analysis, which is based on extreme value flows, does not reflect less severe low-flow events and potential cumulative effects on water quality and aquatic life. The problems with the annual 7Q10 and other frequency/duration flow statistics warrant research into better alternatives.

The objectives of this study were twofold. The first objective was to develop a set of recommended methodologies for the calculation of design flows. The second was to investigate alternative design flows that would reduce wastewater treatment costs by using the assimilative capacity of streams more fully, while maintaining existing downstream water quality.

The scope of this research included an evaluation of methodologies used to calculate design flows and the application of some of these procedures to flow data in Colorado. The evaluation of methodologies included a summary of the techniques currently applied in design flow analysis, development of a few new methods, and recommendations for future research. The set of proposed guidelines for calculating design flows, given in chapter four, represent the current state-of-the-art and include lessons learned from this research. The guidelines are not meant as the final answer to the problem of design flows, but rather as a base for future research and development of improved methods. Low flows were analyzed at eight sites on four rivers along the Front Range in Colorado. The scope of the research was limited to the analysis of low flows for use in discharge permitting under the NPDES. Although water quality and effluent characteristics are also vital aspects of NPDES permitting, analysis of these factors were beyond the scope of this project. The analysis of alternative design flows included seasonal and monthly frequency/duration statistics and values calculated with an empirical, distribution-free approach. Criteria used to evaluate various alternatives were based on the protection of aquatic life as defined by the U.S. EPA (U.S. EPA, 1985). Economic implications of various design flows were not considered.

The study organization included five stages to provide a scientific basis for the analysis of design flows and then to evaluate alternatves in Colorado. The steps were as follows:

1) review of the literature
    a. federal and state regulatory requirements and procedures used in NPDES discharge permitting;
    b. alternative approaches currently applied to discharge permitting throughout the nation;
    c. methodologies used to calculate design flows;
2) evaluation of analytical methods used to calculate design flows;
3) analysis of the flow data;
4) comparison of alternative design flows;

5) recommendation of guidelines for the calculation of appropriate design flows.

Chapter 2 - Literature Review

A review of the literature was made in three major areas to provide a base for this study. Federal and state water quality legislation and regulations were investigated to give a legal framework for the research of alternatives under the existing system. Special emphasis was placed on effluent discharge permits issued under the Colorado version of the National Pollutant Discharge Elimination System (NPDES). A review of currently applied alternative approaches to discharge permitting was made to see what had already been done in this area. Finally, the methods used in the analysis of design flows were reviewed to ensure that the methods applied in this study would be appropriate.

LEGISLATIVE AND REGULATORY BACKGROUND

Water pollution control in the United States is based primarily on the Federal Water Pollution Control Act of 1972 as amended in 1977 by the Clean Water Act and by subsequent amendments. The objective of the Clean Water Act is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (1977). To achieve this objective, the Act requires that water quality standards be established for the Nation's waters and provides for the National Pollutant Discharge Elimination System (NPDES) to enforce these standards. Implementation of the Clean Water Act occurs mainly at the state level wherein lie the "primary responsibilities and rights to prevent, reduce, and eliminate pollution" (Clean Water Act, 1977). The states receive guidance and approval from the U.S. Environmental Protection Agency, which holds final authority for the administration of the Act.

<u>Colorado Water Uses and Water Quality Criteria</u>

In the state of Colorado, water pollution control is governed by the Colorado Water Quality Control Act of 1973, as amended. A major policy declaration of the Colorado Act is "to prevent injury to beneficial uses made of state waters, to maximize the beneficial uses of water, and to develop waters . . . to achieve the maximum practical degree of water quality" (1973). The Colorado Water Quality Control Commission (WQCC) holds primary authority to enact this policy, and has delegated the responsibilities for the actual implementation of state water quality programs to the Water Quality Control Division of the Colorado Department of Public Health.

The state surface water quality regulatory program includes three major elements: use classifications, water quality criteria, and effluent discharge permits. Colorado state surface waters have been divided into segments which have been classified according to "present and potential future beneficial uses" as described in The Basic Standards and Methodologies (Colorado WQCC, 1984). Use classifications must protect all current uses, must not jeopardize any downstream uses, and should aim for the highest water quality obtainable. On this basis, five major use classifications have been established for Colorado waters as follows: 1) existing high quality, class I and II; 2) aquatic life, cold or warm water class I and II; 3) recreation, class I and II; 4) water supply; and 5) agriculture (Colorado WQCC, 1979). Waste transport and waste assimilation has been explicitly denied as an acceptable designated use in federal water quality standards (U.S. EPA, 1983c). Waters may be classified for more than one use. Water quality regulation for a given water segment is generally controlled by the most sensitive use, which is often the aquatic life classification.

Water quality criteria corresponding to each of the use classifications have been developed by the Colorado WQCC to define the maximum permissible levels of pollutants necessary to protect and maintain designated uses (1984a). Six categories of water quality variables are addressed by the criteria, and include: physical, biological, inorganic, organic, metal, and radioactive constituents. Tables of suggested values for water quality criteria are given in the state standards to serve as guidance for the determination of actual numeric limits in specific stream segments throughout the state. Site specific criteria may follow these guidelines or may vary to reflect unique ambient conditions for a particular water that differ significantly from laboratory testing conditions.

Federal water quality standards include an antidegradation policy that is superimposed over use classifications and water quality criteria to provide further protection of the Nation's waters. The policy includes a three tiered approach to maintain and protect various levels of water quality and uses (U.S. EPA, 1983c and 1983d). The first tier requires that the level of water quality necessary to protect existing uses be maintained and protected. Where actual water quality exceeds the levels necessary to protect existing uses, a second tier provides protection of that higher quality. The only exception to this requirement is allowed if a state finds that allowing lower water quality is "necessary to accommodate important economic or social development" (U.S. EPA, 1983c and 1983d). A third tier provides special protection of waters that are classified as outstanding national resource waters, including waters that are important, unique, or sensitive ecologically.

The Colorado NPDES

Colorado surface water use classifications and corresponding water quality criteria are enforced through the state version of the National Pollutant Discharge Elimination System, called the Colorado Discharge Permit System (Colorado WQCC, 1984b). The Colorado NPDES requires all "point sources" discharging "pollutants" into state waters to obtain effluent discharge permits. A point source has been defined as "any discernible, confined, and discrete conveyance . . . from which pollutants are or may be discharged" (U.S. EPA, 1983a). This definition specifically excludes return flows from irrigated agriculture and most other forms of non-point source pollution, but it may be applied to include stormwater drains. Pollutants to be regulated by the NPDES include liquid and solid wastes of chemical, biological or physical nature that are discharged into water.

An effluent discharge permit issued under the Colorado NPDES includes two main elements: specific effluent limits for each regulated pollutant being discharged, and effluent monitoring requirements. The permits must be reviewed by the state and renewed every five years.

Effluent limits in NPDES permits reflect two levels of treatment requirements. The first level is based on technological treatment capabilities and provides the minimum degree of treatment required before discharge. For municipal wastewater treatment plants, this level is defined as "secondary treatment" which consists of the following for

Colorado: 1) five-day biochemical oxygen demand - 30 mg/l for a 30-day average and 45 mg/l for a 7-day average; 2) total suspended solids - 30 mg/l for a 30-day average and 45 mg/l for a 7-day average; 3) residual chlorine - less than 0.5 mg/l: 4) pH - 6.0-9.0; and 5) fecal coliforms - varying levels depending on water use (Colorado WQCC, 1979). Technology-based effluent limits for industrial point sources are generally based on industry specific federal guidelines. A second level of treatment requirements may be imposed on municipal and industrial dischargers if technology-based limits are insufficient to protect and maintain designated water uses. These water quality-based limits are defined by "total maximum daily loads" (TMDL's), which are the maximum quantities of pollutants that can be carried by a receiving water without adversely affecting water uses (Federal Water Pollution Control Act, 1972). The TMDL's are proportioned among dischargers on a given segment through a waste load allocation procedure (U.S. EPA, 1983c and 1983d). Water quality-based limits have been applied widely throughout Colorado.

The determination of water quality-based effluent limits is based on a steady state mass balance equation of the general form:

$$C_e = \frac{(Q_d)(C_d) - (Q_u)(C_u)}{Q_e}$$

where:

Q_u = upstream low flow or design flow (cfs)

C_u = upstream pollutant concentration (mg/l)

Q_e = effluent flow (cfs)

C_e = allowable effluent concentration (permit limit, mg/l)

Q_d = downstream flow (Q_u + Q_e, cfs)

C_d = allowable downstream concentration (water quality criteria, mg/l)

The general form of this equation may be modified to reflect additional factors required for non-conservative variables such as dissolved oxygen and un-ionized ammonia. The mass balance equation is solved independently for each regulated water quality variable to determine allowable effluent concentrations or permit limits (C_e).

The input values to the equation used to determine water quality-based effluent limits are fixed to a large extent by site-specific conditions, but may vary according to data availability and interpretation. The upstream pollutant concentration (C_u) is generally taken from historical water quality data, when available. Either average or maximum "worst case" values from historical data may be used. Where data are insufficient, assumptions may be made about upstream quality (C_u) based on the literature or other sources of information. The value chosen for effluent flow (Q_e) has commonly been the maximum design capacity of the plant, used to represent a worst case scenario. More recently, actual effluent flow values, based on historical records and projections, have been used and updated with each permit renewal. The allowable downstream concentration (C_d) is based on established site specific water quality criteria. If more than one discharger is present on a given segment, TMDL's proportioned through a waste load allocation are used to define the maximum allowable downstream concentration that may be contributed by each discharger.

Possibly the most significant input to the determination of water quality-based effluent limits is the upstream design flow. This value may be varied to correspond to given levels of water quality protection desired. In general, water quality standards are not applicable under extreme low-flow conditions, defined as flows below the designated upstream design flow. The protection of water uses, therefore, is provided only for flow conditions equal to or greater than the design flow value. Design flows may be defined to provide protection for aquatic life from short-term, acute, or long-term, chronic, exposures to pollutants.

Historically, the statistical value for the upstream design flow "commonly accepted" for use by the state of Colorado has been the 7Q10 (Colorado WQCC, 1984a). The 7Q10 value represents the 7-day moving average low flow that is equaled or not exceeded once in every ten years on the average. Although the use of the 7Q10 has been accepted in Colorado and throughout the United States, the Federal Clean Water Act makes no specific provision requiring the use of the 7Q10, but rather provides flexibility for the states to develop individualized water quality management programs. A recent U.S. EPA report has stated that "a review of the literature fails to reveal a strict water quality basis for establishing 7Q10 as the stream design flow" (U.S. EPA 1983b). Alternatives to the 7Q10 design flow, more firmly based on water quality considerations, could be more cost effective for point source dischargers and still protect and maintain designated water uses.

The implementation of the Colorado NPDES is built largely upon self-enforcement procedures. Point source dischargers are required to monitor the quality and flow rate of their effluent routinely and to submit the results to the state and the U.S. EPA in monthly Discharge Monitoring Reports (DMR's). The reports are checked for violations of the permit limits and other forms of noncompliance. Significant noncompliance may be subject to enforcement actions ranging from warning letters to restraining orders or injunctions to shut down plant operation (Colorado WQCD, 1984). Currently, there are approximately one thousand active NPDES permits in Colorado, about one-half of which are municipal wastewater treatment facilities.

Summary

To summarize, the legal framework for this study allows for alternatives to the 7Q10 for use in effluent discharge permitting under the NPDES. Alternatives must meet the goals of the federal and state water quality acts to maintain the chemical, physical, and biological integrity of the Nation's waters and to protect beneficial uses of these waters. A change in the design flow criteria from the annual 7Q10 must protect existing water uses and high quality waters as defined by the U.S. EPA antidegradation policy.

ALTERNATIVE APPROACHES TO NPDES PERMITTING

Compliance with surface water quality regulations and National Pollutant Discharge Elimination System (NPDES) permit requirements can be costly for point source dischargers. Recently, the U.S. EPA Office of Policy, Planning and Evaluation and individual states have sought innovative approaches to water pollution control permitting that will maintain or improve existing water quality while reducing treatment costs. Two major types of innovations in NPDES permitting have been tried. The first type involves increasing the use of stream assimilative capacity for wastes and the second involves redistributing allowable waste loads among dischargers, or discharge trading, to achieve the most economical allocation.

Increased Use of Assimilative Capacity

Increased use of stream assimilative capacity can be achieved by reducing various factors of safety that have historically been included in the determination of NPDES permit limits. Three major inputs that may be varied to reduce factors of safety include upstream design flow, water quality standards, and values used for effluent flow rates.

The most significant input that can be varied is the upstream design flow. As mentioned in the review of NPDES regulations, the 7Q10 flow statistic has traditionally been used as the upstream design flow in discharge permits. In many streams the 7Q10 flow occurs less than 1% of the the time and thus may be considered a conservative measure (Reheis, et al., 1982; Ferrara and Domino, 1985). Alternative low-flow statistics of different frequency and/or duration from the 7Q10 (7-day duration, one in ten year frequency) have been evaluated in a number of recent reports. The U.S. EPA looked at five river reaches across the nation, including the Arkansas River at Canon City, Colorado, and compared the 30Q10, 30Q5, and 7Q2 flows to the 7Q10 (1983g). The annual statistics were based a Log Pearson Type III distribution. It was found that the 7Q2 low flows for the reaches in the study were generally 1.5-1.7 times larger than 7Q10 flows, and that 30Q10 and 30Q5 flows were between the 7Q10 and 7Q2 flows. In Texas and a number of other dry, southwest states the 7Q2 has been applied, instead of the 7Q10, to determine discharge permit limits (U.S. EPA, 1983e). The use of design flow criteria larger than the 7Q10 will obviously allow higher effluent permit limits and lower treatment costs. At the same time, however, larger design flow criteria will also provide less protection of water uses with more days occurring when flows fall below the design flow value and when water quality standards do not apply.

A major drawback of annual frequency/duration flow statistics is that they provide unequal levels of protection from one stream to another. A single, arbitrary flow statistic cannot accurately reflect the entire range of potential flow patterns in natural and regulated streams. The number of days on which flows fall below a given annual statistic, like the 7Q10, may vary significantly from one river to another. As an example, a comparison of the number of flows falling below the annual 7Q10 on five rivers across the United States showed a range of 0.12 days per year for the Cheyenne River to 4.3 per year for the Housatonic River, a difference on the order of 3500% (U.S. EPA, 1983g).

A second major disadvantage of annual design flow statistics is that the values are based on extreme low flows which occur only during certain times of the year. The assimilative capacities of higher flows which occur at other times of the year are ignored by annual design flows. To use this capacity more fully, monthly or seasonal design flows may be applied. Seasonal water quality may also be factored into effluent permit limits in place of annual values. A seasonal 7Q10 is defined in a similar manner as the annual 7Q10 statistic except that the period of analysis may be one to several months rather than a year. Different 7Q10 values are defined for each month or season. A recent survey found that seasonal design flows are currently being applied to some extent in 42 states and monthly flows are being applied in 14 states (Lamb, 1985).

Significant increases in waste loadings for biochemical oxygen demand (BOD) and ammonia were reported in a number of cases where design flows were based on two seasons, winter and summer (Ferrara and Domino, 1985; Schaughnessy, et al., 1984; U.S. EPA, 1983; Lamb, 1982a and 1982b; Reheis, et al., 1982; Boner and Furland, 1982; Epp and Young, 1981; and Hargett and Seagraves, 1980). In one study, values for summer BOD effluent limits were approximately doubled by the use of a winter design flow (Hargett and Seagraves, 1980). The use of monthly 7Q10 flows rather than annual 7Q10 values in one study resulted in allowable discharge loads that were more than ten times higher in the winter than the annual allowable load (Lamb 1982). Use of monthly 7Q10 flows in Buffalo, Wyoming recently abated the need to construct advanced treatment facilities which would have cost $2-4 million (Willey and Benjes, 1985). The state of Georgia has adopted monthly 7Q10 design flows and has estimated annual operating cost savings of 2-19% and capital cost savings of 4-16% (Reheis, et al., 1982).

Water quality control regualtions in the state of Colorado currently provide for the use of seasonal 7Q10 design flows (Colorado WQCC, 1984a). The regulations state that each season will "normally consist" of a minimum of three months. Although other options are permitted, the year is generally divided into three periods - a six month winter low-flow period (November-April), and two shorter seasons (May-July and August-October).

The next step beyond monthly or seasonal design flows is a daily time varying permit limit which is based on actual real time river conditions of flow and water quality. With this method, flow and water quality monitoring data are used to determine the allowable wasteload a discharger may release on a given day (Herbay and Smeers, 1983; David and David, 1983). Several states, including Wisconsin, North Carolina, Iowa, and Colorado have implemented daily time varying permits to some extent (U.S. EPA, 1983e, 1983f, and 1984c).

Seasonal, monthly or daily design flows have a number of potential drawbacks. The first is that the level of protection provided for designated water uses may be reduced from that achieved with annual design flows. The overall assimilative capacities of receiving waters are more fully used with seasonal or time-varying permits which may result in lower water quality over the long term (Reheis, et al., 1982). Research done by the U.S. EPA has shown that the use of seasonal design flows increases the probability of violation of water quality criteria and could result in lower water quality unless standards are made more stringent (U.S. EPA, 1983g). A second drawback is based on increased data required to calculate permit limits based on seasonal, monthly or daily design flows. In addition, implementation of these short-term limits is more complex and may be more expensive for regulatory agencies. The benefits of varying permit limits may be restricted by the ability of dischargers to start up and shut down treatment processes on short notice. Finally, varying permit limits may not result in overall treatment costs savings because lower costs during some periods may be offset by higher costs during other periods. Given all of these potential drawbacks, it still appears that cost savings in construction and operation of treatment facilities using seasonal or monthly design flows may be significant. Reheis, et al. (1982) reported a potential savings of over $1 billion if monthly design flows were applied nationwide. However, corresponding effects on water quality must also be carefully assessed.

An alternative to frequency-duration flow statistics has recently been developed by the Office of Research and Development of the U.S. EPA (1986). This alternative, called the "biologically-based" method, is an empirical distribution-free approach that utilizes historical records of daily flows to select appropriate design flows. The selection criteria include an allowable frequency of occurrence of flows below the design value and flow durations that reflect acute and chronic conditions. Values recommended by the U.S. EPA (1985 and 1986) for these criteria are a frequency of once in three years, and durations of one day for acute and four days of longer for chronic flows. The biologically-based design flow is determined by ordering the low flows of historical record and choosing the highest flow that allows no more than the allowable number of excursions.

Water uses and water quality criteria may also be varied to raise NPDES permit limits and increase the use of stream assimilative capacity. Although water quality standards are generally constant over time, they may be adjusted to reflect water uses that vary with the seasons. For example, dissolved oxygen criteria could be varied to provide better protection for fish during spawning seasons and less protection with relaxed limits during non-critical periods (U.S. EPA, 1983g). Seasonal criteria have already been applied to protect recreation uses in the state of Nebraska where chlorination to control fecal coliforms is required only during the summer season (Lamb, 1980).

Site specific water quality criteria may replace the recommended values where local conditions are unique. The state of Colorado has developed site specific criteria for a number of waters using two techniques (Foster, 1983). The first approach is based on the use of bioassay testing to define appropriate instream water quality requirements to protect indigenous populations given ambient stream quality. The second approach, which is much less expensive, involves a statistical analysis of historical water quality data. Water quality criteria are set equal to the value of the mean plus the standard deviation of the sample data.

The value used to represent the quantity of effluent flow from a discharger may also have a significant effect on NPDES permit limits. In the past, plant design capacities have been used to represent the maximum possible effluent flows. However, the use of anticipated flows over the five-year life of the NPDES permit is an acceptable option. Two studies reported average annual effluent flows equal to about 50% for the majority of treatment facilities investigated (Ferrara and Domino, 1985; Boner and Furland, 1983). The use of actual effluent flows rather than rated values could allow higher permit limits and provide significant savings in treatment costs while still maintaining water uses. In one case, the use of actual flow values relaxed ammonia limits from 10.9 mg/l at a flow of 10 MGD to 16.0 mg/l at a flow of 5 MGD (Ferrara and Domino, 1985). A reduction in the effluent flow value could actually produce lower limits for ammonia in some cases, however, depending on the pH and temperature conditions of the discharge and the receiving water.

Prudent timing and location of pollutant discharges may be used to help increase the use of stream asssimilative capacities. Effluent may be retained temporarily in holding ponds or lagoons during critical low flow or water quality conditions and released later under more favorable conditions (Zitta, 1979). The "controlled release" approach allows a discharger to take advantage of high flow events and provide better protection during critical times. One disadvantage of this method is the capital cost required to construct holding facilities, but this may still be significantly less than the cost of building new treatment facilities. The point of effluent discharge may also be varied over time to protect water quality during critical conditions if alternative locations are available. The City of Fort Collins, Colorado has developed a system to bypass discharge to the receiving stream and release into an irrigation ditch when conditions are critical. This program could save the city $140,000 a year in reduced nitrification requirements (Kuchenrither, 1983).

Discharge Trading

The second major group of alternative NPDES permitting techniques is based on a redistribution of allowable waste loads. On stream segments with more than one discharger, a waste load allocation is performed to proportion the allowable total maximum daily load among the the dischargers. Waste load allocation rights may be exchanged among point sources to achieve a more economical distribution of the waste load.

Point source trading allows dischargers with more efficient, less expensive treatment capabilities to treat their waste to a greater degree than required and apply the savings in waste load to another discharger on the same segment which may use more expensive treament processes. Cost savings are shared among all the dischargers involved in the transaction. Secondary treatment requirements must be met at all times, however, even if not necessary to meet the allowable waste load. Cost savings from point source trading can be significant, particularly when the construction of new treatment factilites is avoided. Potential cost savings for a group of twelve point source dischargers on the Delaware Estuary were estimated to be in excess of $4 million a year (Schaughnessy , et al., 1983). Transferable discharge permits have been used to some extent between domestic wastewater treatment facilities discharging in Dillon Reservoir in Summit County, Colorado (NWCOOG, 1984). One major limitation of the point source trading option is that it requires extensive planning and cooperation among competing dischargers, which may be difficult to achieve.

Waste load trades may be made among non-point as well as point source dischargers. Generally, pollutant discharges from non-point sources have not been regulated and are considered as part of the ambient stream conditions in determining allowable loads. However, it may be that non-point sources of pollutants can be treated more effectively with less cost than point sources requiring expensive advanced treatment. The advanced treatment policy of the U.S. EPA requires states to consider controlling discharges from non-point sources before imposing advanced treatment requirements on publicly owned treatment works. Point/non-point source trading has been used very effectively on Dillon Reservoir in Colorado to control phosphorous runoff from local developments and ease the phosphorous limits on point source dischargers (NWCOOG, 1984). The use of point/non-point source trading may be limited by the fact that most pollutants released from non-point sources are not discharged by point sources, with the exception of phosphorous. In addition, non-point sources are difficult to regulate.

Summary

Innovative approaches are currently incorporated into approximately one-fourth of all disharge permits issued in Colorado. Alternative permitting techniques have been applied in Colorado in four major areas: seasonal design flows, site specific water quality standards, permit trading, and controlled release. Considerable potential exists for future use of alternative NPDES permitting in the state of Colorado, particularly as applied to waters of environmental and economic importance.

METHODOLOGIES USED TO CALCULATE DESIGN FLOWS

Flow Durations and Moving Averages

Low flows may be calculated for durations of one day or longer, depending on the degree of protection required for a given use. The U.S. EPA has recommended that dual design flows be used to protect aquatic life from both acute and chronic effects. The rationale for acute and chronic design flows is given in the 1985 U.S. EPA Guidelines for Developing National Water Quality Criteria (Stephan, 1985). Acute design flows are generally based on maximum concentration levels, which are intended to protect aquatic life from unacceptable short-term effects. The acute concentration used by the U.S. EPA is the Criterion Maximum Concentration (CMC), which is equal to one-half of the Final Acute Value (FAV). The FAV is a value based on laboratory toxicity test results (i.e. 48- or 96-hour LC50). The CMC is intended to provide a "reasonable level" of protection for aquatic life. This level has been defined by the EPA as protection of all except a small fraction of the taxa present (or 50 percent of the population of the most sensitive 5 percent of the species present) (Stephan, 1985). The duration of exposure deemed by the U.S. EPA to be appropriate for acute levels is one hour, a short enough period to avoid large fluctuations in pollutant concentration. In practice, the duration used is one day, because discharge data are not often readily available on an hourly basis.

Chronic design flows are generally based on a concentration lower than the acute level, and are designed to protect ecosystems from unacceptable effects due to long-term exposure. The chronic concentration used by the U.S. EPA is the Criterion Continuous Concentration (CCC), which is equal to the Final Acute Value divided by the Final Acute-to-Chronic Ratio. Acute-to-Chronic ratios have been determined in the laboratory and range from one to more than a thousand, depending on the toxicity characteristics of the water quality variable. The duration of the chronic design flow is longer than one day, usually taken as a moving average of four to thirty days. Four days is the duration that has been recommended initially by the U.S. EPA, but longer durations (7-day or 30-day) may be justified for relatively stable flow and downstream water quality conditions. The criterion used by the U.S. EPA to justify the use of a 30-day average for chronic design flows is that the coefficient of variation (mean discharge divided by the standard deviation) based on the complete record of daily flows be approximately one or less. Other criteria that may be more appropriate include the coefficient of variation based on flows below a given level, instream water quality variations or effluent quantity and quality variations. It should be noted that the difference between a 4-day duration chronic flow and a 30-day duration flow will be less in a stream with relatively stable flows than in other streams.

Low flows of durations longer than one day are generally calculated as moving averages of a series of daily flows. The moving average acts as a smoothing function for a daily flow record to reduce the effects of extreme variability, particularly of zero or very low instantaneous flows. An x-day moving average is calculated by averaging daily flow values for days 1 to x, 2 to (x+1), 3 to (x+2) etc. For an annual period of record, 365 daily values would be smoothed to (365-x)+1, x-day moving averages.

Period of Record

The recommended period of record for low-flow frequency/duration analysis is 30 years or more of daily flows (McMahon, 1985). If 30 years is not available, a minimum of 10 years of daily flow data may be used to produce valid results (U.S. Interagency Advisory Committee, 1982). Frequency analysis of a period of record shorter than 30 years could produce results with larger probable errors and may introduce bias if the short-term record includes a predominance of wet or dry years (McMahon, 1985; Searcy, 1959). The period of record for biologically-based low-flow analysis may be shorter than 30 years and still produce results with a good level of confidence (U.S. EPA, 1986). Since biologically-based analysis considers all days within the period of record and not just the single extreme low flow for each year, the sample size is much larger than that of frequency analysis and a shorter record is sufficient.

One important consideration in the determination of an appropriate length of record to use is the homogeneity of flow data. If data are non-homogeneous, then the advantage of a longer, more representative record is offset by the disadvantage of inconsistent data. Both homogeneity and representativeness should be weighed in the determination of the period of record for analysis. These factors are discussed further in the section on data assumptions.

Frequency/Duration Analysis

Frequency analysis is used in hydrology to relate the magnitude of flows to their expected frequencies of occurrence. Often, the analysis is concerned with flow durations longer than a single day (e.g. 4-, 7- or 30-day). The frequency of occurrence for annual events is defined statistically by the probability of occurrence each year and is equal to the inverse of the recurrence interval. The recurrence interval is defined as the period of time in which one occurrence is expected. To illustrate, a flow with a 10 percent probability of occurrence has a frequency of 0.10 per year and a recurrence interval of 10 years. The allowable frequency of acute or chronic flow events recommended by the U.S. EPA is once every three years, although this value may vary depending on the aquatic ecosystem being considered. Justification given by the U.S. EPA for the three year period is that it has been deemed sufficient for most aquatic ecosystems to recover from damage caused by adverse water quality conditions (Stephan, 1985). The three years recommended by the U.S. EPA is actually meant to be longer than the average recovery period so that ecosystems are not in a constant state of recovery (U.S. EPA, 1986). Frequencies more often than once every three years may be justified on a site-specific basis for particular aquatic ecosystems.

In the case of a prolonged drought with many single low-flow events, a frequency of once every three years or once every two years may not be appropriate. For instance, if a string of 10 low-flow events occurred in a single year, then the frequency of once in three years would require a recovery period of 30 years without another single low-flow event. To account for extreme low-flow periods, the U.S. EPA has recommended that a maximum time of 15 years be provided after a drought period. The justification for 15 years is that an ecosystem requires between five and ten years to recover after a severe stress like a drought, and an ecosystem should not be in a constant state of recovery. Thus, 15 years was deemed by the U.S. EPA as an "appropriate stress-free period of time" after a severe drought (U.S. EPA, 1986). In the case of a drought then, no more than 15 years can be required before the next allowable low-flow events that occurred during the drought. The maximum period required for recovery after a drought can vary and other values can be justified by site-specific analysis.

Frequency statistics for various duration flows are often denoted as (duration) Q (recurrence interval). Thus the 7Q10 is defined as the lowest 7-day moving average flow that occurs on the average once in every ten years. Low-flow frequency analysis may be made on the basis of either annual series or partial-duration series. Annual series frequency analysis is based on the minimum flow event of a given duration for each year of record. Frequency analysis may also be based on minimum flow events for shorter periods such as seasons or months.

There are several methods used to calculate annual low-flow frequency values. Two methods are graphical and mathematical. The graphical procedure includes the following steps:

1. Rank low flows. Moving average flows are calculated for given durations of x-days (e.g. 1-, 4-, 7- or 30-days). The minimum x-day flows for each year, season or month of record are ranked, with the lowest flow being ranked one.
2. Assign plotting positions. Plotting positions are assigned to each flow value using one of a number of available plotting position formulae. The formula most widely used and recommended is the common or Weibull plotting position (Riggs, 1974; McMahon, 1985) given as:

$$pp = \frac{m}{n + 1} = \frac{1}{T}$$

where pp = the plotting position and an estimate of the probability, P, of occurrence of an x-day flow that is less than or equal to a given ranked flow.

T = the estimate of the recurrence interval or the average period of time between years with an event less than or equal to the given x-day flow.

m = the rank of a given minimum annual x-day flow.

n = the number of years of daily flow data.

3. Plot points. Plot observed flows versus plotting position (probability of inverse of the recurrence interval) to show the magnitude and frequency of occurrence. Different types of probability paper may be used, including log-normal or log-extreme value paper.

4. Fit curve. A smooth curve may be drawn through the points to fit the data and estimate the model error.

Figure 2.1 provides an example of graphical analysis of frequency statistic flows.

The mathematical procedure for determining nonexceedence probabilities consists of estimating the parameters for a theoretical distribution from a set of low flows and using the estimated distribution to generate flow magnitudes for given recurrence intervals. A number of different distributions have been discussed for use in low-flow analysis, including: normal, log-normal, Gamma, Pearson Type III, log-Pearson Type III, Kritsky-Menkel, Extreme Value Type 1 (Gumbel), or extreme Value Type III (Weibull) (McMahon, 1985).

To evaluate the level of agreement between an observed sample of low flows and an assumed theoretical distribution, a statistical goodness of fit test may be used (McMahon, 1985). The Chi-Square and Shapiro-Wilk tests are two procedures that may be used for this purpose. One problem with the use of any goodness of fit test is that the analysis focuses on how well the entire distribution fits all of the data, including low and high flows. This sort of test is not heavily influenced by the tails of a distribution and thus may not be able to accurately define the level of agreement specifically for minimum flows (McMahon, 1985). Two other approaches have been used to evaluate the applicability of various probability distributions to flow data. The first is to compare observed minimum flows with the lower limit of the theoretical distribution, and the second is to compare the relation between skewness and kurtosis of the observed to the theoretical distribution (Matalas, 1963).

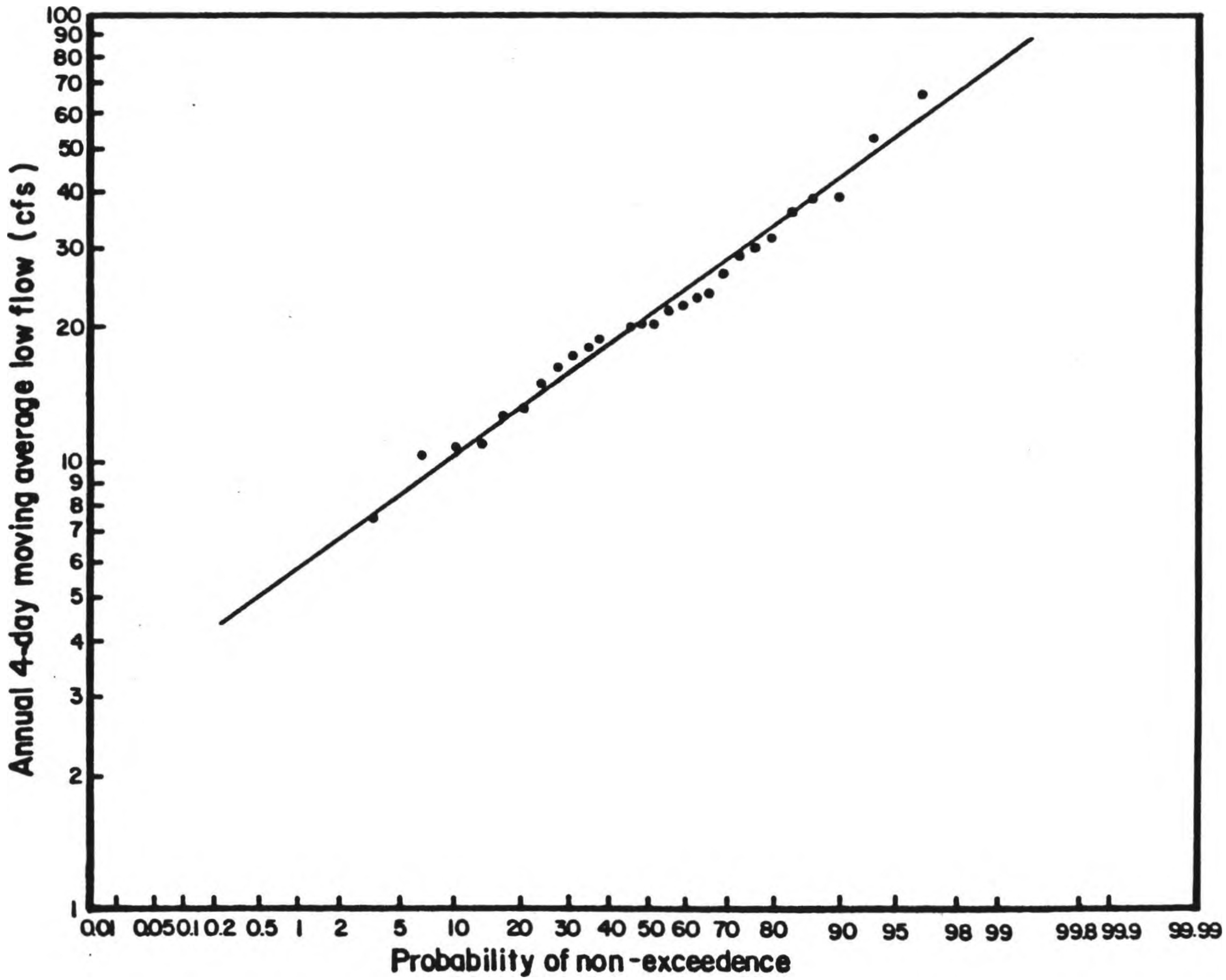


Figure 2.1 The graphical method of determining low flow frequency statistics at Littleton (1956-1985).

Of the methods to calculate low-flow frequency values, the graphical method has been recommended in a number of papers (McMahon, 1985; ASCE Task Committee, 1980; Riggs, 1974)). The graphical method is particularly useful for determining flows of recurrence intervals less than n/3 years (where n = number of years of data). Two reasons have been given for the superiority of the graphical over the mathemiatical method: 1) the graphical method requires no assumption as to the type or characteristics of a theoretical distribution and thus may better deal with a variety of low-flow regimes, 2) in some cases a purely statistical analysis may be misleading and provide less information than a graph (McMahon, 1985; Riggs, 1974). However, the mathematical method is more widely used for frequency analysis, probably because of its relative simplicity, compatibility with computer usage, and consistency of results between different investigators.

Annual, Monthly, and Seasonal Low Flows

Annual low-flow frequency analysis is based on the single lowest moving average flow for each year of record. Usually, the period of record is broken up into distinct year-long segments rather than analyzing the entire continuous period of record. A flow record may be separated into water years (October 1-September 30), climatic years (April 1-March 31) or calendar years (January 1-December 31). Both the climatic year and the water year are identified by the year in which the period ends (e.g., the climatic year April 1, 1955-March 31, 1956 is denoted as 1956). The period of annual low-flow analysis should be chosen so as to include the low-flow period entirely within a given year. Generally, flood flow analysis is made on the basis of the water year. The climatic year, however is more appropriate for low-flow analysis since a low-flow period rarely occurs in late March-early April (ASCE Task Committee, 1980; Riggs, 1972; Petsch, 1979). In some cases, other annual periods may be more appropriate than the climatic year, depending on the pattern and timing of low flows at a particular site.

Monthly low-flow frequency analysis is based on the single lowest moving average flow within each of the 12 months of the year for each year of record. Thus, there would be 12 different monthly low flows (April-March) as compared to one single annual low flow. The lowest monthly low flow for each year should be equal to the annual low flow for the same years. Other monthly low flows reflect wetter periods of the year and may be substantially higher than the annual low flow.

The procedure used to calculate monthly low flows is similar to that used for annual flows. Each month of the year is evaluated separately for minimum flows. The calculation of monthly or seasonal x-day moving average flows with the conventional annual approach presents certain problems because the period of analysis (e.g. 30 days) is short relative to the moving average duration (e.g. 7 days). Monthly moving averages calculated with standard techniques tend to be biased toward flow values occurring in the middle of the month, because values in the middle of the month are included in more moving averages than values occurring at the beginning and end of the month. Another inconsistency associated with the calculation of monthly flows is that fewer moving averages are calculated for 12 separate months than for a single whole year. For example, the calculation of monthly 7-day moving averages would produce 293 values in a monthly analysis as compared to 359 7-day moving averages calculated on an annual basis. These inconsistencies may cause some inaccuracies in the calculation of monthly frequency statistics.

For seasonal low-flow analysis, months can be grouped together to reflect flow and water quality variations throughout the year. Two to four groupings can be used to represent low, high and possibly transition months. Criteria used to group months may include seasonal variations in flow, ambient water quality, and effluent quality. The way in which months are grouped into seasons can have a significant effect on the values of the seasonal flows (Ferrara and Domino, 1985). An incorrect grouping of a transition month with a high-flow season may reduce the flows drastically, particularly if the low flows occur within the high-flow season for some years and in the transition month for the other years. The selection of seasons requires site-specific analysis because the patterns of low-flow events may differ significantly from one site to another. In addition, flow patterns may even differ from one duration flow to another (i.e. the ideal 1-day low-flow seasons may not be the same as ideal 7-day low-flow seasons). For practical purposes, one set of seasons should be chosen for each site by balancing all the factors involved.

EPA Biologically-Based Design Flows

A biologically-based method for determining design flows was recently developed by the Office of Research and Development of the U.S. EPA as an alternative to traditional frequency/duration analysis (1986). The biologically-based method is an empirical, distribution-free approach that utilizes historical records of daily flows. The method is empirical because it is based on the actual flow record, rather than on flows predicted by a statistical distribution. Design flows for both acute and chronic levels of aquatic life protection can be calculated with this method.

The design flow calculated with the biologically-based method is defined as the highest flow of a given duration that will not cause a given instream concentration to be exceeded with greater frequency than is allowable. The biological rationale for this new EPA method is found in 1985 EPA guidelines for deriving national water quality criteria (Stephan, 1985). The current national criteria are expressed as two levels, acute and chronic rather than the traditional one level, to reflect actual toxicological conditions more accurately, as described earlier. Three major factors are considered in design flow criteria: frequency (inverse of the average recurrence interval), intensity (concentration), and duration (length of averaging period). The allowable frequency of low-flow events recommended by the U.S. EPA is once every three years (U.S. EPA, 1985 and 1986). The concentrations used are the Criterion Maximum Concentration for acute flows and the Criterion Continuous Concentration for chronic flows. Durations are 1-day for acute flows and 4-day or longer for chronic flows. As mentioned previously, longer durations may be justified for relatively stable flow and water quality conditions.

Adjustment of Data Records

Daily flow data records may be incomplete or insufficient to enable the statistical analysis required to compute appropriate design flows. Certain adjustments of flow records can be made to provide more useful data sets. Frequently, flow records are missing data for a number of days. Estimates of the missing values can be made by interpolation between the surrounding flows just preceding and just following the missing data. If the gap of missing data is longer than several days, then interpolation may not be an appropriate method and another more advanced approach may be required.

Data records with zero flow values are difficult to analyze statistically because log-distributions do not fit data sets with zeros (Jennings, 1969). Two approaches may be used to transform zero flows to non-zero values. The first is to add a small amount (e.g. 0.1 cfs) to each of the discharges in a given flow record (Tasker, 1972; Jennings, 1969). One disadvantage of this method is that the arbitrary addition of a constant value may change the characteristics of the flow distribution. A preferred, though more complex, approach is to use conditional probability to determine appropriate values to replace zero flows. This method involves fitting a distribution to events greater than a given base flow (Q_b)and predicting values based on the ratio of the number of events greater than Q_b to the total number of flows (Jennings, 1969).

The estimation of low flows at a specific point of interest (an effluent discharge point) for use in discharge permitting is often very difficult and may require manipulation of data to produce a useful flow record. Rarely is there a set of discharge data of sufficient length available in the vicinity of the outfall that can be utilized. The problem is compounded in the western United States where the nearest gaging station may be many miles away from a discharge point and where there may be many unmeasured factors, including tributaries, irrigation diversions and groundwater flows that affect the flow. A number of methods have been used to extend short periods of record or to develop flows at ungaged sites for the analysis of low-flow characteristics.

Methods include: regression analysis, water balance procedures, and regionalized analysis (McMahon, 1985; Salas, 1980; Riggs, 1972; Searcy, 1959).

Regression analysis can be used to extend a short period of record at a site by developing a relation between flows at the point of interest and flows at one or more nearby gage sites with longer periods of record. The relation can be used along with the records at other sites to predict flows at the point of interest for ungaged periods.

A water balance procedure can be used to route flows from a gaged site to a site that is ungaged or has a short period of record. All sources and losses between the gaged site and the point of interest must be quantified and accounted for in the analysis. Sources may include tributary flows, effluent discharges, returns from irrigation, or groundwater recharge. Stormwater runoff may also act as a source, but is generally insignificant in low-flow analysis. Losses may include diversions, or groundwater outflows. Daily flow data are rarely available for all of these factors and estimates must often be made from monthly or even less frequent data.

A third approach, regionalized analysis, has been used with limited success to predict low flows at ungaged sites. The regionalization method is based on the premise that low flows can be predicted through an analysis of the regional factors affecting streamflows including: basin drainage area, precipitation, geology, groundwater flows, relief, and vegetation. This method is best applied to natural flowing streams.

Data Assumptions and Errors in Low-Flow Analysis

Certain assumptions about flow data must be achieved for most statistical analyses to be valid. Major assumptions are as follows: 1) the record is a representative time sample, 2) flow events are random and independent, and 3) the record is homogeneous (U.S. Interagency Advisory Committee, 1982). The violation of these assumptions may produce statistical results that are less reliable or even invalid, depending on the degree of violation. One of the first steps in low flow analysis should be to check the adequacy of the flow data and the applicability of specific statistical analyses.

Statistical analysis is usually based on a subset of measurements of the entire population, called a sample. A representative time sample requires that the flow record is complete and is long enough to include the full range of a characteristic flow regime. An adequate length of record has been recommended as 30 years or more (McMahon, 1985).

For a sample of flows to be random, each member of the population (or each flow for a given day) must have an equal and independent chance of being selected. Independent events require that the occurrence or nonoccurrence of one event has no bearing on the chance that the other will occur. Daily streamflow are usually not independent, but are usually positively serially correlated, meaning that a low flow one day is followed by another low flow on the next day. Serial correlation tests provide an indication of the degree of correlation, or non-independence, of flows. Annual minimum low flows, in contrast to daily flows, may be considered to be a sample of random and independent events (U.S. Interagency Advisory Committee, 1982). Annual events are generally not as highly correlated as daily events, although long-term persistence of drought may occur and upset this assumption. Monthly minimum flows may exhibit a higher degree of serial correlation than annual values and thus may not strictly be considered random and independent.

Homogeneity of a flow record implies that data samples are taken from the same population, or that the flow regime has remained relatively constant over the entire period of record. Non-homogeneity may often result from man-made developments or by the movement of a gaging station. It is recommended that only records that represent relatively constant watershed conditions be used for frequency analysis (U.S. Interagency Advisory Committee, 1982; Searcy, 1959).

A variety of techniques are available to test homogeneity of flow records. Double-mass analysis evidences non-homogeneities as changes of slope in the plot of massed flow at the point of interest against massed flow at an unaffected gage or gages in the general vicinity or against massed precipitation (Pitman, 1978). Other ways to detect non-homogeneities include examination of plots of annual 7-day low flows versus time, or comparison of annual 7-day low flows at the point of interest to a reference flow record (Riggs, 1976). One problem with these techniques is the possibility that the timing of wet and dry periods may introduce bias (Pitman, 1978). For example, if a flow record begins with a dry period (lower than average flows) and ends with a wet period (higher than average flows), then there will be a bias toward a trend of increasing flows. Another approach to detecting non-homogeneity of a flow record is to split the record into two groups defined by a suspected change in the flow regime, and to test for differences between the variances and between the means of each group. A variance ratio test, or F test, may be used to test differences in variances, and a two-sample t-test may be used to detect differences in the means of two sample groups (Zar, 1974). The groups should be chosen so as to reflect a suspected change in the flow regime, such as that resulting from the construction of a dam upstream from the gage. If both groups have the same variance and the same mean, then there is sufficient justification that the period of record may be said to be homogeneous.

Errors may be introduced to low-flow analysis from a number of different sources to produce estimates which may differ from the true values. The degree of reliability of flow estimates depends on the quality of the flow record and also on the applicability of various statistical analyses and validity of assumptions. The quality of a flow record for use in low-flow analysis may be affected by two major types of errors, measurement errors and rating curve errors (McMahon, 1985). Measurement errors may be either systematic, due to instruments of measurement methods, or accidental, due to observers. Rating curve errors may result from inaccurate rating curves based on insufficient low flow discharge measurements, or from changing stage-discharge relations due to shifting controls. Errors are generally considered a random process with a relatively small variance (U.S. Interagency Advisory Committee, 1982). Errors in statistical analysis of low flows can result from a number of sources. Whenever necessary statistical assumptions are violated, error is introduced. The magnitude of the error will be related to the degree of violation of given assumptions. Fitting a given flow record to some sort of underlying probability distribution to predict frequency statistic flows may also introduce errors. Parameter estimates may include errors, and a distribution may not always provide a good fit and may make inaccurate predictions of low flows.

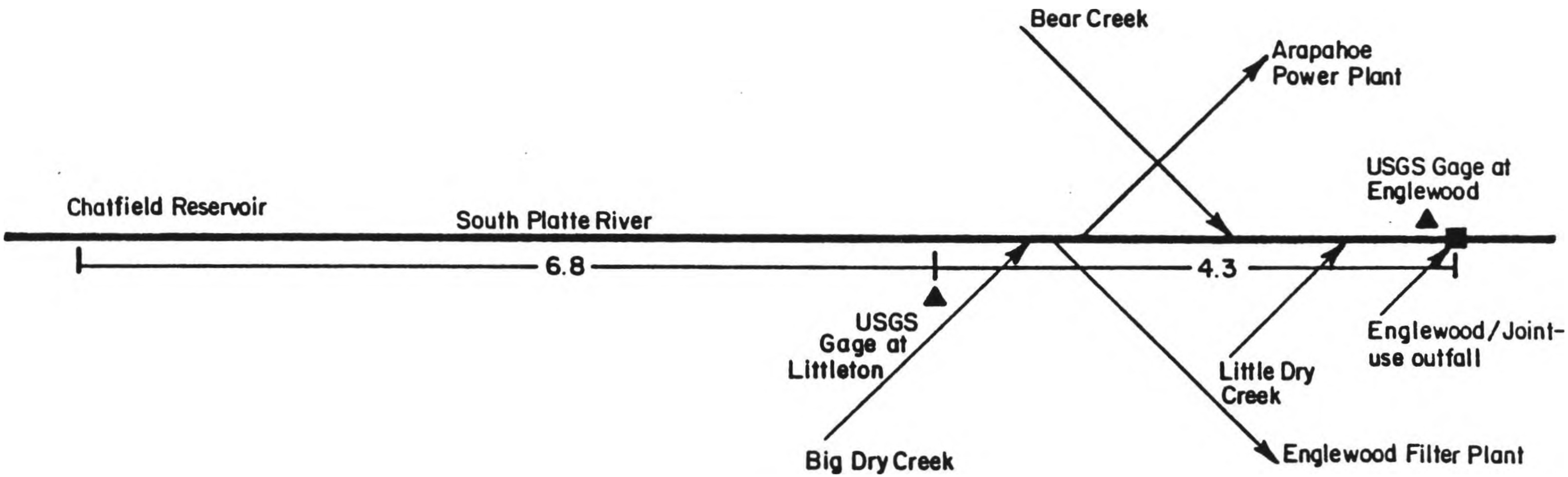
Chapter 3 - Methods of Design Flow Analysis

Methods of design flow analysis include procedures for the selection of an appropriate data set as well as techniques for the analysis of low flows. A description of the study sites, data base, and homogeneity testing is followed by discussion of each of the the three types of analysis applied to select appropriate design flows.

DESCRIPTION OF THE DATA SET

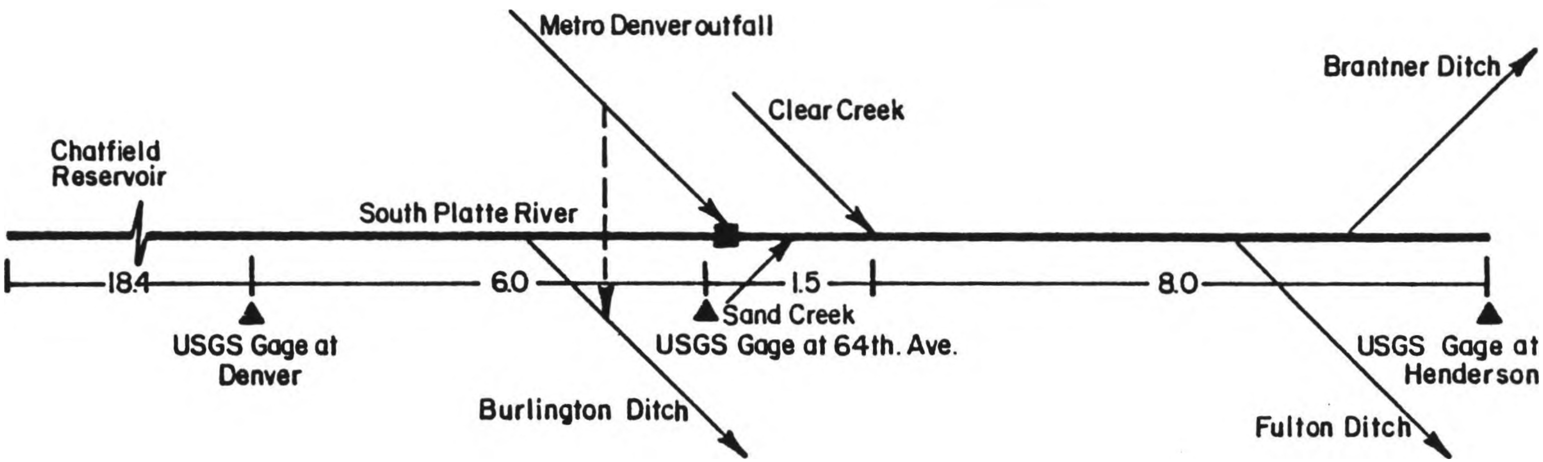
Study Sites and Flow Data

Flow data were analyzed at eight sites on four different rivers in Colorado including the South Platte River, Boulder Creek, St. Vrain Creek, and the Cache la Poudre River. Flow analysis of the South Platte River was made at three sites - Littleton and Englewood in segment 14, and Henderson in segment 15. Boulder Creek analysis was made just above the City of Boulder wastewater treatment facility near 75th Street. Flows of the Saint Vrain Creek were analyzed at Lyons, Longmont, and Platteville. The Cache la Poudre River was analyzed at Lincoln Street in Fort Collins. Analysis of theoretical effluent limits based on various design flows was made for four different wastewater treatment facilities administered by the Cities of Littleton and Englewood, the City of Boulder, the City of Longmont, and the City of Fort Collins. Specific descriptions of each of the sites have been given in a previous report (Paulson and Sanders, 1987). Straight-line diagrams are given for each of the sites in Figures 3.1-3.5.



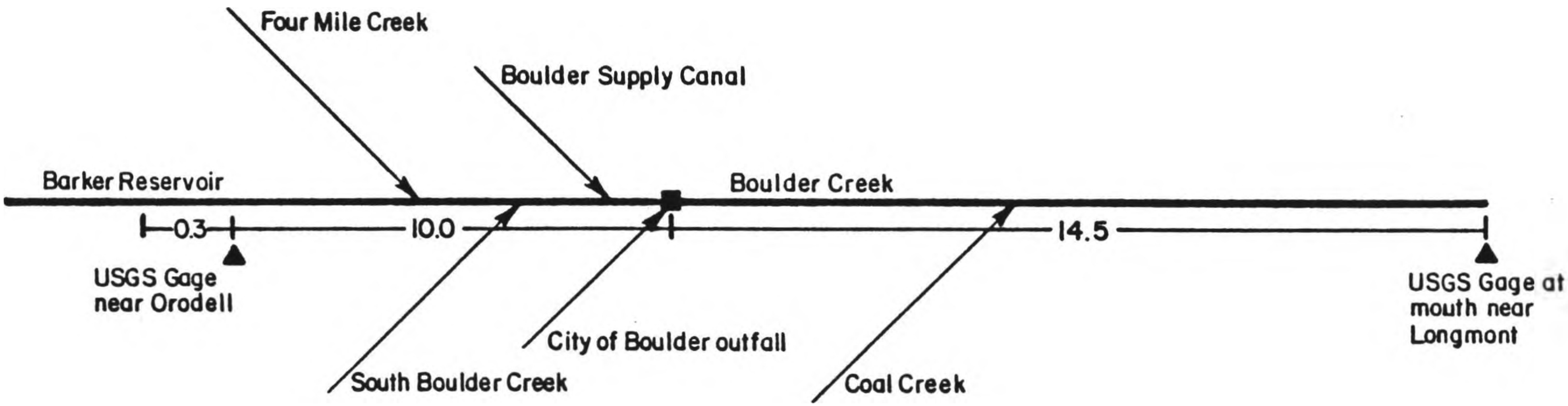
NOTE = Not to scale, distances are approximate values given in miles.

Figure 3.1 Straight-line diagram for the South Platte River (segment 14).



NOTE = Not to scale, distances are approximate values
given in miles.

Figure 3.2 Straight-line diagram for the South Platte River (segment 15).



NOTE = Not to scale, distances are approximate values given in miles.

Figure 3.3 Straight-line diagram for Boulder Creek.

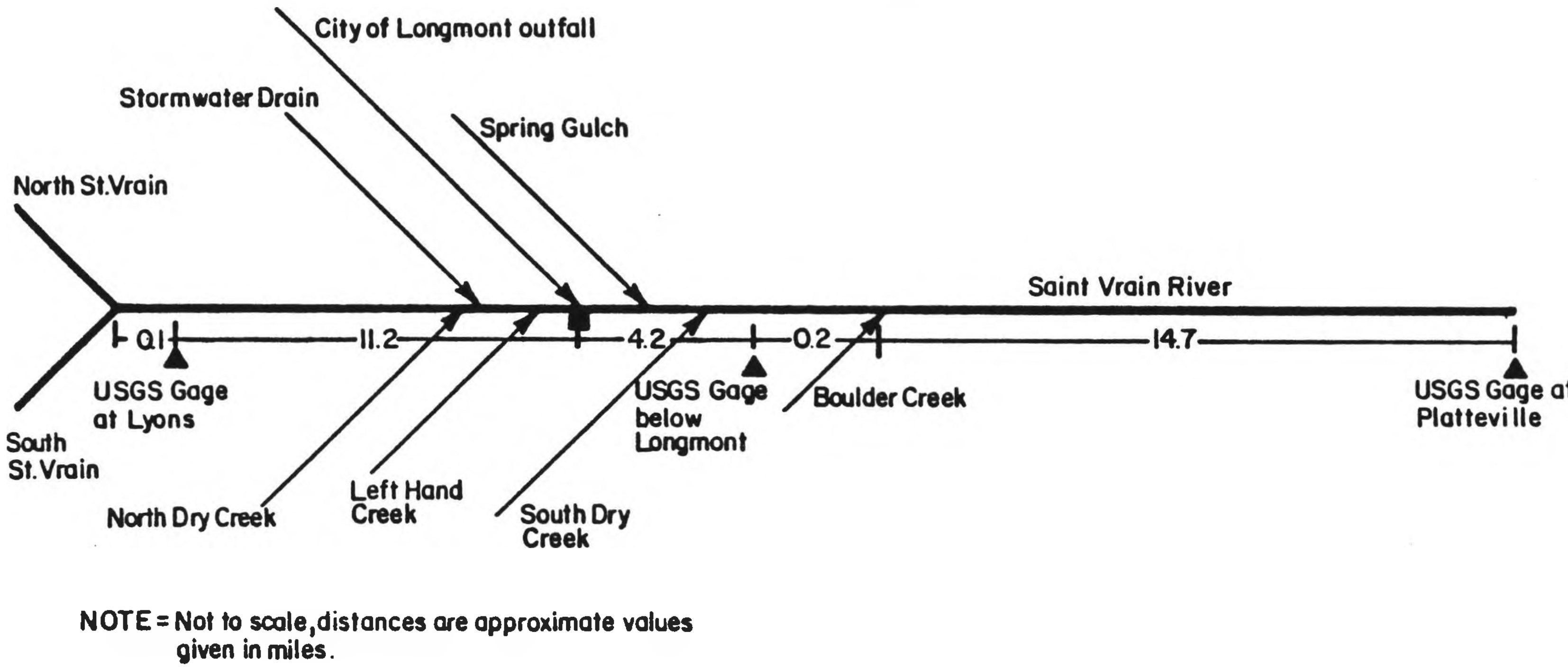
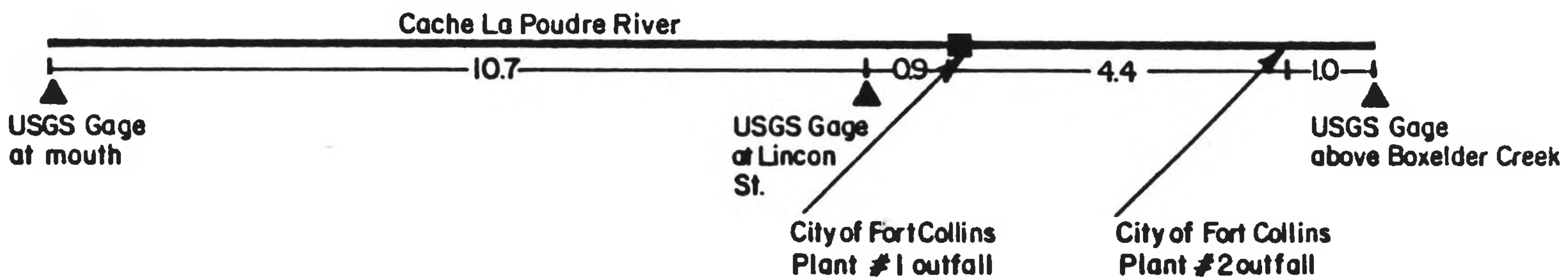


Figure 3.4 Straight-line diagram for the Saint Vrain River.



NOTE = Not to scale, distances are approximate values
given in miles.

Figure 3.5 Straight-line diagram for the Cache La Poudre River.

The data base used for flow analysis in this study consisted of USGS daily records for five of the eight sites (Littleton, Henderson, Lyons, Platteville, Fort Collins). The period of record used for Littleton, Henderson, Lyons, and Platteville was 30 years long, from 1956-1985. The record for Fort Collins was nine years, from 1977-1985. Two of the other sites (Englewood and Longmont) had very short periods of record, too short to analyze. A water balance procedure was used to produce a 30-year daily reconstructed flow record at Englewood by routing flows four miles back upstream from the USGS gage at Littleton. Flows at Longmont were estimated on the basis of multiple regression analysis using flow data at Lyons and Platteville to predict flows at Longmont for the period 1956-1985. A third site (Boulder) was ungaged. A model of daily flows and diversions for Boulder Creek was run for a 12-year period (1959-1970) to predict flows at that site. These techniques have been discussed in detail previously (Paulson and Sanders, 1987).

Flow data collected at the USGS stations used in this study consist of mean daily flows. The accuracy of streamflow data records has been rated by the USGS at each of the gages they administer. The ratings include four degrees of accuracy. "Excellent" means that about 95 percent of the daily discharges are within 5 percent of the true value; "good" means within 10 percent, "fair" means within 15 percent, and "poor" means greater than 15 percent (Duncan, 1984). Daily mean discharge is given to the nearest hundredth of a cfs for discharges less than 1.0 cfs, to the nearest tenth for discharges of 1-10 cfs and to the nearest whole for discharges of 10-1000 cfs. All of the gages used in this study were rated "good" by the USGS, except for the gage at

Littleton, which is rated "fair" during the winter period, and the gage at Fort Collins, which is rated "poor" for certain periods with no gage-height record. It should be noted that these gage ratings apply to the daily flow record as a whole. Typically, extreme low and high flows are more difficult to measure accurately than average flows. As a result, low-flow gage data probably are less accurate than gage ratings would indicate.

Homogeneity of the Flow Record

In this study, homogeneity of all flow records was analyzed first by looking at plots of annual low flow statistics versus time. For records where a distinct change in flow regime was suspected, F and t tests were conducted. Homogeneity testing using these tests was conducted at the Littleton and Englewood sites. The operation of Chatfield reservoir on the South Platte River beginning on May 29, 1975 was suspected to produce a detectable change in the flow regimes at these sites which are located just downstream. The log transformed values of annual low flows at Littleton and Englewood for the period 1956-1975 were tested against those for 1976-1985. The Statistical Package for the Social Sciences (SPSS, Nie, et al., 1975) was used on the Cyber mainframe computer at CSU to complete this analysis. Values for the two-tail probability were calculated and compared to a reference level of 0.05. Values greater than 0.05 were considered to show no significant difference in variances or means.

FLOW ANALYSIS

Low flows were analyzed to learn more about the patterns of drought events and to help define appropriate alternatives to the 7Q10 design flow. The two techniques used to calculate design flows in this study were: distribution-based frequency/duration statistics and the U.S. EPA biologically-based method. Low-flow periods were also analyzed for run length below a range of design flow values.

Frequency/Duration Analysis

Frequency/duration analysis was used to determine the magnitudes of flows that would be expected to occur at a given frequency for a given length of time. A mathematical procedure was used to generate the frequency distribution statistics in this study. As described in chapter one, this procedure requires that a theoretical statistical distribution be fitted to a sample of daily flow data to determine flow magnitudes corresponding to given recurrence intervals. The graphical method was also tested for use, but was dropped in favor of the mathematical approach because of the relative consistency and wide use of that approach.

The selection of an appropriate distribution function to describe the pattern of low flows is critical. For the purposes of this sutdy, the log-Pearson Type III distribution was chosen, primarily to maintain consistency with current prevailing practices. The log-Pearson Type III distribution has been used extensively for flood flow analysis, and also for low-flow analysis by various agencies, including the USGS and U.S. EPA (U.S. EPA, 1986; Petsch, 1979). Distributions other than the log-Pearson Type III may prove to be more appropriate for low-flow analysis. Although extensive research in this area was beyond the scope of this project, four distribution functions were evaluated. They included the normal, lognormal, Pearson Type III and log-Pearson Type III. Flows were transformed and were evaluated for goodness of fit to each of the distributions using Chi-square and Shapiro-Wilk tests as described in a previous report (Paulson and Sanders, 1987).

The log-Pearson Type III distribution is based on three statistical parameters - mean, standard deviation, and skewness coefficient. The distribution has a limited range in the left direction (zero) and unlimited in the right direction and is fitted to the logs of flow values to normalize the data. The most common way to fit this distribution is to calculate frequency factors for given recurrence intervals and then to use the following equation.

$$\log x = \bar{x}_{log} + K(S_{log})$$

where x = flow for a given recurrence interval T

$\bar{x}_{log}$ = the mean of the logarithms of low flows

S_{log} = the standard deviation of the logarithms of low flows

K = a frequency factor, which is a function of the coefficient of skewness of the logarithms of low flows and the probability level and can commonly be found in tables (U. S. Interagency Advisory Committee, 1982).

One difficulty with low-flow analysis by the log-Pearson type III distribution or any other distribution which uses the skewness as a parameter is the choice of a skew value to use. Generally, in flood flow analysis the skew used in the log-Pearson type III distribution is a combination of the regionalized skew and the station skew. Regionalized skews have not yet been developed for low flows in the state of Colorado. Consequently, station skews based on the historical record were used in the analysis. An alternative approach that has been recommended is to use zero for a skew value. The choice of a skew value could have a significant effect on the outcome of analysis and should be considered further.

Low flows were analyzed on an annual, monthly, and seasonal basis to define frequency/duration statistics. Annual low flows were analyzed by separating the period of record into climatic years (April 1 - March 31) and evaluating the lowest flows for each year. Monthly flows were analyzed in a similar way except that an overlapping procedure was developed to reduce the bias toward the middle of the month. This procedure involved using flows from the end of the previous month and the beginning of the following one to calculate moving averages for a given month. For example, to calculate monthly 7-day moving average flows for the month of September, flows occurring on August 29-31 and October 1-3 were used to calculate 30 values for the month of September. To calculate 4-day moving average flows, two days from the end and beginning of other months were used.

Months were grouped into seasons using flow as the criterion. Although seasonal water and effluent quality may also be significant criteria, the major focus of this study was on flows. Statistics (mean, median, standard deviation) for monthly 7-day flows and monthly 7Q3 statistics were used to separate the months into high, low, and transition flow seasons. The transition designation was given to months that exhibited inconsistent flows from year to year and could not be grouped conclusively. The process used to defne low-flow seasons consisted of two or three steps. First, the months were given initial seasonal designations based on flow statistics. Second, low flows were calculated for each season and compared to verify that the seasons were appropriate. In some cases, a third step was required to adjust the seasons to ensure that months were grouped correctly.

Biologically-Based Analysis

The general approach of the biologically-based technique is to look at the number of low-flow excursions (low flows below a lower limit or design flow) that have occurred in the past to gain an understanding of how many excursions are likely to occur in the future. A daily flow record is split into low-flow periods and low-flow excursions are counted for various low-flow limits. The flow that is chosen for the design flow is the maximum flow that results in no more than the allowed number of excursions for the entire period of record, or no more than one excursion every three years.

Low-flow periods used for analysis by the U.S. EPA biologically-based method are 120-day periods, rather than the more traditional annual period. According to the U.S. EPA, low flows are expected to occur in a certain pattern grouped within a 120-day low-flow period followed by a 120-day period of few, if any, low flows (U.S. EPA, 1986). Each low-flow period begins with a low-flow excursion and lasts exactly 120 days. Depending on the pattern of low-flow excursions, the number of days between low-flow periods may vary.

Within each 120 day low-flow period, there may be one or more low-flow excursion events. An excursion event is defined as a sequence of consecutive days where each day belongs to an x-day average flow that is below the design flow (U.S. EPA, 1986). For example, if three 4-day moving averages of a consecutive six day period are less than the design flow, then those six days belong to a low-flow excursion event. The number of excursions in a low-flow event is calculated as the total number of days in the event divided by the duration (e.g. one day for the acute and four days for the chronic flow). The maximum number of excursions to be counted for any given low-flow period is five. Given an allowable frequency of one excursion every three years, this provides for no more than 15 years, on the average, for ecosystems to recover from severe stress caused by a drought.

The biologically-based design flow calculations is an iterative convergence procedure that consists of five basic parts (U.S. EPA, 1986). The parts are:

1. Determination of the allowed number of excursions, the number that will produce an average of no more than one excursion every three years, given by the equation:

   (allowed excursions) = (number of years of record)/(3)
2. Calculation of x-day (1-day for CMC, 4-day for CCC) running averages from the record of daily flows.
3. Calculation of the total number of excursions of a specified flow for a given flow record.
4. Determination of initial lower and upper limits on the design flow with the corresponding number of excursions from Part III, and an initial trial flow.
5. Calculation of the design flow by successive iterations using the method of false position.

In certain cases, values other than the standard ones given for durations (1-day or 4-day) or frequency (once in three years) may be used to calculate special user-defined flows. The criteria currently used to justify a chronic duration longer than four days is a relatively stable flow regime, represented by a coefficient of variation of daily flows that is less than or equal to one (U.S. EPA, 1986).

The above procedure is carried out by computer program (U.S. EPA programs DFLOW or DESCON) used in conjunction with direct access to STORET daily flow record files. For the purposes of this study, the U.S. EPA computer program DFLOW (U.S.EPA, 1986) was used to calculate biologically-based design flows. An IBM PC version of the program was converted for use on the Cyber 205 and was used in conjunction with data files of USGS daily flow records.

Biologically-based flows were calculated for acute (1-day duration) and chronic (4-day and 30-day durations) conditions at each site. The criterion used to calculate the flows was an allowable frequency of occurrence of once in every three years, as recommended by the U.S. EPA. Other frequencies may also be used with the program.

Analysis of Low-Flow Events

Low-flow events were also analyzed with a simplified version of the U.S. EPA biologically-based method, referred to here as excursion analysis. The excursion analysis involved the same basic principles as the biologically-based approach - analysis of the patterns and durations of low-flow excursions (low flows below a lower limit). With this simplified approach, excursions were analyzed over the entire data record as a whole rather than over 120-day low-flow periods as in the U.S. EPA method. The purpose of this simplified excursion analysis was to quantify the number of days within each year with flows below a given threshold level and to help define the timing and lengths of low-flow events.

Two kinds of information were developed with the excursion analysis. First, low-flow excursions below various frequency statistic design flows were tallied over the period of record. The number of excursions was set equal to the number of single days below the cutoff level (1-day duration excursions). Excursions of 4-day and 30-day durations were also tallied for comparison purposes. Second, run lengths were calculated for each of the low-flow events. A run length was defined as the number of consecutive days with flows below a given level. The number of excursions occurring within a given low-flow event was calculated as the run length of the event divided by the duration of the excursion. For example, the number of 30-day excursions occurring in a run length of 35 days would be 35/30 or 1.17 excursions.

Chapter 4 - Results and Discussion

The daily flow records for each of the sites in this study were analyzed for homogeneity and for an appropriate distribution function. Low-flow analysis was made for flows of 1-,4-,7-, and 30-day durations to correspond to instream aquatic life criteria based on acute and chronic concentrations. Design flows were calculated with two different methods - distribution-based frequency/duration statistics, and the U.S. EPA biologically-based method. Annual, seasonal, and monthly design flows were calculated and compared. Low-flow events were analyzed for 1-day excursions and for run lengths. The results of each type of analysis follow, with specific illustrations given throughout the chapter for various sites (primarily Englewood). Complete low-flow analysis results for each of the sites are given in the form of tables and figures in the final report - Evaluation of Design Flow Criteria for Effluent Discharge Permits in Colorado (Paulson and Sanders, 1987).

HOMOGENEITY

Many of the streams along the Front Range have been heavily influenced by man's activities and may exhibit changes in the low-flow regime or non-homogeneities, as a result. Two approaches were used in this study to identify changes in low-flow characteristics - plots of annual 7-day low flows versus time, (see Figure 4.1 for Littleton) and F and t-testing for changes in variance and mean. The plots show a variety of patterns in annual low flows. Some sites seem to exhibit a

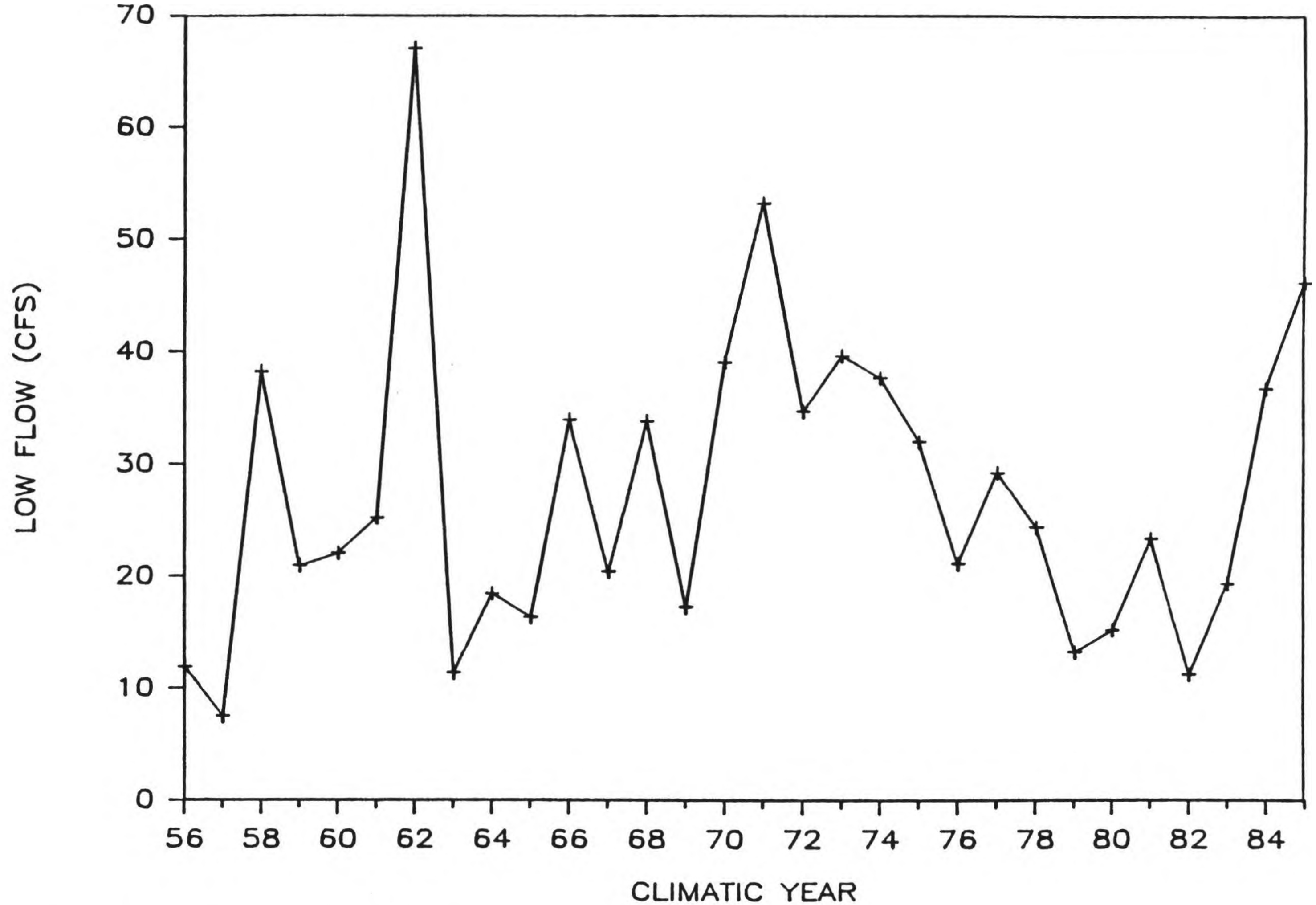


Figure 4.1 . Annual 7-day low flows versus time at Littleton.

trend, while others appear to have cycles in low flows. The causes for these patterns are unknown. They may be due to natural historical weather patterns, or may indicate non-homogeneities in the data record, although this has not been confirmed statistically.

For most of the sites there seems to be a distinct period of lower than average flows from 1956-1965. A ranking of the annual 7-day low flows by year at all of the sites indicates that 50-90 percent of the 10 driest years at each site occurred from 1956-1965. This could well be indicative of a dry low-flow period throughout the state of Colorado during that decade. The results of the low-flow analysis show that the classic 7Q10 was hardly ever experienced during the wet years of the record indicating that this particular statistic may be too stringent at times, while during the dry period it was experienced quite a number of times indicating that this may not be stringent enough.

Tests for the homogeneity of flow records at Littleton and Englewood showed no significant difference in variances or means of low flows at either site before and after the construction of Chatfield Dam. Causative agents for step changes in the low flow regimes at the other sites in this study were lacking. As a result, the data were assumed to be homogeneous at each of the sites and a 30 year period of record was utilized where available. More work could be done to improve detection of non-homogeneities and methods to deal with non-homogeneous records.

The treatment of cycles and trends is an important issue in the generation of low-flow statistics. For analysis of data that exhibits a trend, it is reasonable to select a subset of the total data set from the most current data for analysis. This subset should be sufficiently large to provide a reasonable basis for low-flow statistical analysis (i.e. at least 10 years long). For data that appears to be cyclic, it is more reasonable to use a longer data set (i.e. 30 years) with the assumption that the longer period of record is homogeneous and more accurately reflects the flow regime of the site.

At some sites, it is difficult to determine whether an apparent change in the flow regime is indicative of a trend or cycle. This dilemma makes the choice of an appropriate period of record for analysis very difficult. As mentioned, a number of the sites in this study seem to exhibit a "dry" period for the first ten years of analysis (1956-1965). On the one hand, it would be easy to eliminate the earlier data, since it appears to be dissimilar to the more recent data (non-homogeneous), and determine the low flow statistics with the more recent "wet" years. On the other hand, for the "dry" period since the low flow period could occur again, calculating the low flow statistics using the dry year data will provide a margin of safety for the environment.

DISTRIBUTION OF ANNUAL AND MONTHLY LOW FLOWS

The results of distribution testing for annual 7-day low flows are given in Table 4.1. these results indicate that, with the exception of Henderson, annual 7-day low flows were normally distributed at all sites using the Chi-square and Shapiro-Wilk test. Henderson flows failed the Shapiro-wilk test at 5 percent level of significance when no data transformations were utilized. Annual 7-day low flows at Henderson appeared to have had a lognormal distribution.

Results of distribution testing on monthly 7-day low flows are shown in Table 4.2. Low flows at Littleton, Englewood, Henderson, and Fort Collins were normalized with the Log-Wilson-Hilferty

Table 4.1. Relative scores of normality testing using the Chi-square Goodness-of-Fit and the Shapiro-Wilk Test on annual 7-day low flows for the period of record at each site.

Site	No transformation A	No transformation B	Logarithmic A	Logarithmic B	Wilson-Hilferty A	Wilson-Hilferty B	Log-Wilson-Hilferty A	Log-Wilson-Hilferty B
Littleton								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0
Englewood								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0
Henderson								
Passed	1	0	1	1	1	1	1	1
Failed	0	1	0	0	0	0	0	0
Boulder								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0
Lyons								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0
Longmont								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0
Platteville								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0
Fort Collins								
Passed	1	1	1	1	1	1	1	1
Failed	0	0	0	0	0	0	0	0

A = Chi-square goodness-of-fit test.
B = Shapiro-Wilk test for normality.
Passed = 5% significance level.

Table 4.2. Relative scores of normality testing using the Chi-square Goodness-of-Fit and the Shapiro-Wilk Test on monthly 7-day low flows for the period of record at each site.

Site	No transformation A	No transformation B	Logarithmic A	Logarithmic B	Wilson-Hilferty A	Wilson-Hilferty B	Log-Wilson-Hilferty A	Log-Wilson-Hilferty B
Littleton								
Passed	4	0	12	11	9	8	12	12
Failed	8	12	0	1	3	4	0	0
Englewood								
Passed	3	1	12	11	10	9	12	12
Failed	9	11	0	1	2	3	0	0
Henderson								
Passed	7	2	11	11	9	10	11	12
Failed	5	10	1	1	3	2	1	0
Boulder								
Passed	9	10	11	12	12	11	11	12
Failed	3	2	1	0	0	1	1	0
Lyons								
Passed	10	7	12	10	12	12	12	12
Failed	2	5	0	2	0	0	0	0
Longmont								
Passed	9	7	12	12	12	12	12	12
Failed	3	5	0	0	0	0	0	0
Platteville								
Passed	9	7	12	12	12	11	12	12
Failed	3	5	0	0	0	1	0	0
Fort Collins								
Passed	0	0	12	10	2	4	12	12
Failed	12	12	0	2	10	8	0	0

A = Chi-square goodness-of-fit test.
B = Shapiro-Wilk test for normality.
Passed = 5% significance level.

transformation, while a Wilson-Hilferty transformation normalized low flows at Lyons. Hence, monthly low flows at the former sites may approximate a Log-Pearson Type III distribution, while at Lyons, low flows may approximate a Pearson Type III distribution. Monthly low flow data at Boulder, Longmont, and Platteville appear to fit a lognormal distribution.

FREQUENCY STATISTIC DESIGN FLOWS

The results of the annual low-flow frequency analyses are presented in two formats - as tables and frequency curves for each site (see Table 4.3 and Figure 4.2 for Englewood). Low-flow frequency statistics are given for durations of 1-, 4-, 7- and 30-days and recurrence intervals of 2, 3, 5, 7, 10 and 15 years. As an example, the 7-day moving average low flow occurring once every 10 years on the average (7Q10) from Table 3.5 for Englewood is 28 cfs. Below the annual frequency statistic table is a table of the annual low flows (Table 4.4). An annual low flow may be defined as the lowest moving average of a given duration for any given year. The values in Table 4.4 were fit to a log-Pearson Type III distribution to produce the frequency statistic flows given in Table 4.3.

Frequency curves, which are plots of flow magnitudes versus recurrence intervals for 1-, 4-, 7- and 30-day durations, were prepared for each site (see Figure 4.2 for Englewood). As the recurrence interval increases, the slopes of the curves flatten out in every case. This is an indication that the difference in magnitude between a 7Q2 and a 7Q3 flow is much greater than the difference between a 7Q10 and 7Q15. The frequency curve may be used with interpolation to approximate

Table 4.3. Annual low flow frequency statistics at Englewood.

Recurrence interval (years)	Low flow (cfs) Duration 1-day	4-day	7-day	30-day
2	43	48	52	61
3	35	40	43	53
5	30	33	35	44
7	27	30	32	41
10	24	26	28	36
15	22	25	26	34

Table 4.4. Annual low flows for each year of record at Englewood.

Climatic year (4/1-3/31)	Low flow (cfs) Duration 1-day	4-day	7-day	30-day
1956	27	33	35	38
1957	14	14	15	18
1958	54	68	71	78
1959	38	42	44	51
1960	27	31	33	49
1961	29	34	36	46
1962	92	114	119	133
1963	28	30	32	41
1964	19	22	26	44
1965	29	35	36	41
1966	60	65	67	85
1967	40	43	48	50
1968	48	54	60	87
1969	40	43	46	57
1970	66	69	73	99
1971	85	92	95	112
1972	47	65	66	72
1973	60	63	65	73
1974	44	55	64	104
1975	37	45	53	70
1976	38	40	44	51
1977	45	50	60	75
1978	45	47	50	58
1979	38	40	41	54
1980	43	47	51	64
1981	46	46	48	54
1982	38	40	43	54
1983	35	35	37	53
1984	73	75	76	87
1985	79	94	98	136

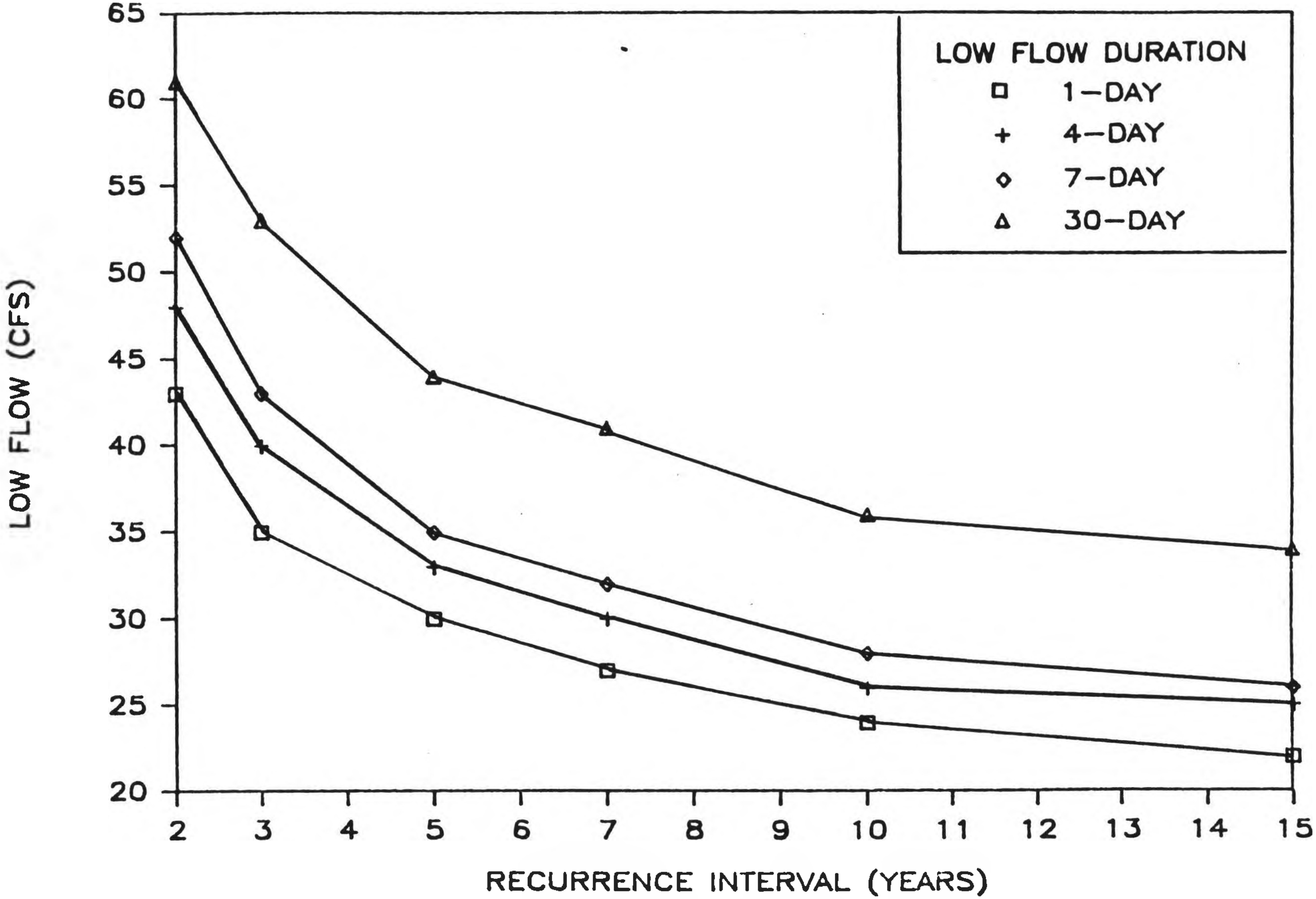


Figure 4.2. Annual frequency curves for 1, 4, 7 and 30-day moving average low flows at Englewood.

frequency statistic flows of different recurrence intervals than those previously calculated. For example, a 30Q4 for Englewood may be approximated as 48 cfs (Figure 4.2). In addition, frequency curves may be used to define comparable annual frequency statistics, by drawing a horizontal line through the graph at a given flow value. For example, a line drawn through 40 cfs at Englewood shows that the same flow is approximated by a 1Q2.4, a 4Q3, a 7Q3.8, and a 30Q8.

The annual frequency statistic flows for 1-, 4-, 7- and 30-day durations and 2, 3, 5 and 10 year recurrence intervals were ranked from low to high for each site (Table 4.5). The 1Q10 flow statistic is consistently the lowest, followed by the 4Q10 or 1Q5. The 30Q2 and 30Q3 flow statistics are consistently the highest and second highest flows. In general, the order of the ranked flows varies with the pattern of low-flow events. At some sites, duration is a more critical factor in determining flow magnitude and at other sites the recurrence interval is the critical factor.

A second comparison of annual frequency statistic low flows is given in Table 4.6. Percent increases in flow magnitudes varied from site to site. For acute 1Q10 and 1Q3 flows the average increase over all the sites was 81 percent and ranged from 36 percent to 175 percent. The increase in magnitude from chronic 7Q10 to 30Q10 flows average 59 percent and ranged from 0 percent to 177 percent. Increases from chronic 7Q10 to 30Q3 flows averaged 160 percent and ranged from 89 percent to 362 percent.

The period of record chosen for low-flow analysis had a significant effect on the annual frequency statistic flows. This was well-evidenced at Englewood and Longmont. At these sites, analysis was conducted for

Table 4.5. Ranking of annual low flow frequency statistics.

Rank	Littleton		Englewood		Henderson		Boulder		Lyons		Longmont*		Longmont**		Platteville		Fort Collins	
(1=low)	cfs	stat	cfs	stat	cfs	stat	cfs	stat	cfs	stat	cfs	stat	cfs	stat	cfs	stat	cfs	stat
1	10	1Q10	24	1Q10	17	1Q10	5.1	1Q10	0.8	1Q10	10	1Q10	12	1Q10	27	1Q10	0.9	1Q10
2	12	1Q5	26	4Q10	22	4Q10	6.9	4Q10	1.2	4Q10	12	4Q10	13	4Q10	29	4Q10	1.2	1Q5
3	12	4Q10	28	7Q10	26	7Q10	7.2	1Q5	1.3	7Q10	12	7Q10	14	7Q10	31	7Q10	1.3	4Q10
4	12	7Q10	30	1Q5	27	1Q5	8.4	7Q10	1.4	1Q5	12	1Q5	14	1Q5	35	1Q5	1.4	7Q10
5	13	4Q5	33	4Q5	36	4Q5	9.0	4Q5	2.1	4Q5	15	1Q3	17	1Q3	38	4Q5	1.4	30Q10
6	14	1Q3	35	1Q3	40	1Q3	9.6	1Q3	2.2	1Q3	15	4Q5	17	4Q5	40	7Q5	1.5	1Q3
7	15	7Q5	35	7Q5	41	7Q5	10.4	7Q5	2.4	7Q5	16	7Q5	18	7Q5	42	1Q3	1.5	4Q5
8	16	30Q10	36	30Q10	46	30Q10	11.5	4Q3	3.3	4Q3	18	30Q10	19	30Q10	43	30Q10	1.6	7Q3
9	17	1Q2	40	4Q3	51	4Q3	11.7	1Q2	3.6	1Q2	19	1Q2	20	4Q3	47	4Q3	1.8	4Q3
10	18	4Q3	43	1Q2	60	1Q2	12.7	7Q3	3.6	30Q10	19	4Q3	21	7Q3	50	7Q3	1.9	1Q2
11	19	7Q3	43	7Q3	61	7Q3	14.3	30Q10	3.8	7Q3	20	7Q3	21	1Q2	53	1Q2	2.0	7Q3
12	22	4Q2	44	30Q5	67	30Q5	14.7	4Q2	4.7	30Q5	22	30Q5	22	30Q5	55	30Q5	2.0	30Q5
13	22	30Q5	48	4Q2	76	4Q2	16.1	7Q2	5.2	4Q2	23	4Q2	24	4Q2	59	4Q2	2.2	4Q2
14	25	7Q2	52	7Q2	89	7Q2	17.1	30Q5	5.9	7Q2	25	7Q2	26	30Q3	64	7Q2	2.4	7Q2
15	27	30Q3	53	30Q3	89	30Q3	20.1	30Q3	6.0	30Q3	26	30Q3	26	7Q2	67	30Q3	2.9	30Q3
16	34	30Q2	61	30Q2	126	30Q2	24.1	30Q2	7.8	30Q2	30	30Q2	31	30Q2	83	30Q2	4.8	30Q2

* values based on regression of daily flows.
** values based on regression of log-transformed daily flows.

Table 4.6. Comparison of annual frequency statistic low flows.

Site	1Q10 to 1Q3	7Q10 to 7Q3	30Q10 to 30Q3	7Q10 to 30Q10	7Q3 to 30Q3	7Q10 to 30Q3
	Percent increase in flow magnitude*					
Littleton	50	58	59	42	42	125
Englewood	46	54	47	28	23	89
Henderson	135	135	93	77	46	242
Boulder	88	51	40	70	58	139
Lyons	175	192	67	177	58	362
Longmont	50	67	44	50	30	117
Platteville	36	61	56	26	34	116
Fort Collins	67	43	107	0	45	107

* Percent increase = (larger flow - smaller flow) / smaller flow

two different periods of record - a 30-year period from 1956-1985 and a 10-year period from 1976-1985. The results of the analysis are compared in Table 4.7. The flows calculated with the shorter, more recent period of record are consistently higher than the flows calculated with the longer record. This difference averages about 30 percent and generally increases with increasing recurrence interval. The cause for this significant difference in flow records can be related to either natural dry and wet cycles (dry years occurring in the first 10 years of record), or to a trend in the flow data. Careful analysis of these factors should be incorporated into the choice of a length of record for low-flow analysis, as was discussed in the section on homogeneity of the flow record.

Monthly frequency statistic low flows are summarized in Table 4.8 for Englewood. The table includes design flows for each month of the year for 1-, 4-, and 7-day durations at 2, 3, 5 and 10 year recurrence intervals. As an example, the monthly 7Q5 for August at Englewood is equal to 79 cfs. On the average, percent increases from one monthly design flow to another (i.e. from 1Q10 to 1Q3) are comparable to percent increases for annual flows given in Table 4.6. However, percent increases are greater for high flow months (e.g. June) than for annual flows and less for low flow months (e.g. January).

Monthly 7-day low flows for each water year of record at Englewood are presented in Table 4.9. The values in this table are the low flows that were fit to a log-Pearson Type III distribution to define the frequency statistics given in Table 4.8. Examination of Table 4.9 and similar tables in the previous report for other sites (Paulson and Sanders, 1987) shows how flows may vary from one month to another on a

Table 4.7. Comparison of annual low flow frequency statistics using two different periods of record at Englewood and Longmont.

a. Englewood

Recurrence Interval (years)	1-day A	1-day B	4-day A	4-day B	7-day A	7-day B	30-day A	30-day B
2	43	44	48	46	52	49	61	60
3	35	40	40	41	43	45	53	54
5	30	36	33	38	35	41	44	51
10	24	34	26	36	28	38	36	49

b. Longmont (based on a regression of daily flows)

Recurrence Interval (years)	1-day A	1-day B	4-day A	4-day B	7-day A	7-day B	30-day A	30-day B
2	21	26	24	28	26	30	31	34
3	17	22	20	26	21	27	26	30
5	14	20	17	23	18	24	22	27
10	12	18	13	21	14	22	19	23

A period of record 1956-1985
B period of record 1976-1985

Table 4.8. Monthly low flow frequency statistics at Englewood.

Month	7-day low flow (cfs) Recurrence interval (years)				4-day low flow (cfs) Recurrence interval (years)				1-day low flow (cfs) Recurrence interval (years)			
	2	3	5	10	2	3	5	10	2	3	5	10
Jan	67	56	48	41	65	55	47	40	62	53	46	39
Feb	69	58	50	42	66	56	48	41	63	53	46	40
Mar	74	61	52	44	71	58	50	42	67	55	47	40
Apr	107	78	58	43	101	74	56	41	93	67	50	37
May	246	159	110	77	230	148	102	70	204	130	89	60
Jun	234	144	94	60	212	130	85	52	188	113	73	45
Jul	186	137	95	63	162	120	84	55	133	98	69	47
Aug	159	112	79	54	150	101	71	47	130	89	63	43
Sep	76	56	43	32	69	52	40	30	64	48	37	28
Oct	67	50	40	32	63	48	38	31	62	47	37	28
Nov	73	62	52	46	70	60	51	45	66	55	48	43
Dec	70	62	52	46	69	59	51	45	66	56	49	43

Table 4.9. Monthly 7-day low flows for each year of record at Englewood.

Water year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1955	24	45	38	37	38	34	34	110	62	40	261	130
1956	38	59	50	37	37	43	42	215	153	65	39	15
1957	18	41	37	33	37	41	62	270	1190	753	535	73
1958	86	158	95	74	78	71	217	585	307	123	53	44
1959	58	53	51	46	60	61	121	263	232	131	82	33
1960	82	75	65	61	71	94	483	485	245	222	43	36
1961	50	75	83	77	74	102	132	324	130	196	432	274
1962	278	338	150	119	180	155	286	229	282	195	72	35
1963	32	44	60	52	55	50	35	39	34	26	34	107
1964	46	61	68	50	50	58	105	196	118	145	72	40
1965	36	60	51	43	44	60	87	284	402	520	670	335
1966	190	117	80	76	85	66	99	109	85	72	84	49
1967	56	81	68	75	53	47	50	86	135	125	206	96
1968	72	96	86	81	83	83	97	198	154	165	213	108
1969	105	79	70	46	50	68	73	158	722	488	341	103
1970	137	308	219	169	119	126	314	2129	1461	597	220	143
1971	142	129	109	95	120	113	114	427	368	309	230	78
1972	66	75	78	84	82	70	68	117	239	153	139	65
1973	65	78	75	79	93	111	164	1143	981	461	268	64
1974	120	117	97	109	123	222	322	280	153	165	80	53
1975	88	75	75	76	78	79	82	186	352	531	236	119
1976	44	48	64	78	74	74	78	121	100	247	220	113
1977	89	87	88	78	60	64	102	153	60	72	122	58
1978	50	55	58	58	60	56	47	78	53	121	104	48
1979	55	49	41	46	61	63	151	253	493	226	105	51
1980	54	67	84	85	112	100	175	2155	1203	407	166	53
1981	48	71	64	54	62	64	59	115	48	69	74	89
1982	77	54	57	56	46	43	37	79	94	138	305	248
1983	141	59	59	53	48	136	405	1887	2259	845	556	92
1984	76	93	115	107	140	154	292	1393	758	312	664	265
1985	529	281	208	112	98	110	182	1214	572	393	277	64

fairly consistent basis. For example, at Englewood, the average of monthly 7-day low flows for January is 72 cfs and for June is 398 cfs. Although flows vary from month to month there may be even more significant differences from year to year. The month of June at Englewood is a good example, with 7-day low flows ranging from 34 to 2259 cfs. Figure 4.3 provides a graphical illustration of the differences in frequency statistic flows from one month to another at Englewood. The figure includes four bars for each month of the year which give monthly 7-day low flows at 2, 3, 5 and 10 year recurrence intervals.

Monthly low flows for this study were calculated using an overlapping procedure as described in the methods chapter This procedure produced values that differ from values calculated without overlapping. The differences in monthly 7-day low flow frequency statistics at Littleton with and without overlapping are illustrated in Table 4.10. In general, with the overlapping procedure, monthly low flows for each year had lower means, smaller standard deviations and varying skews when compared to low flows calculated without overlapping. The frequency statistic flows in Table 4.10 are similar, with values occasionally higher with overlapping but more often lower, particularly for high flow months.

In most cases, monthly frequency statistic flows are higher than annual frequency statistic flows. Percent increases of monthly 7Q10 flows over annual 7Q10 flows are given for each month at five sites in Table 4.11. The increases range from 0 percent for several months at Fort Collins to 1914 percent for the month of June at Fort Collins.

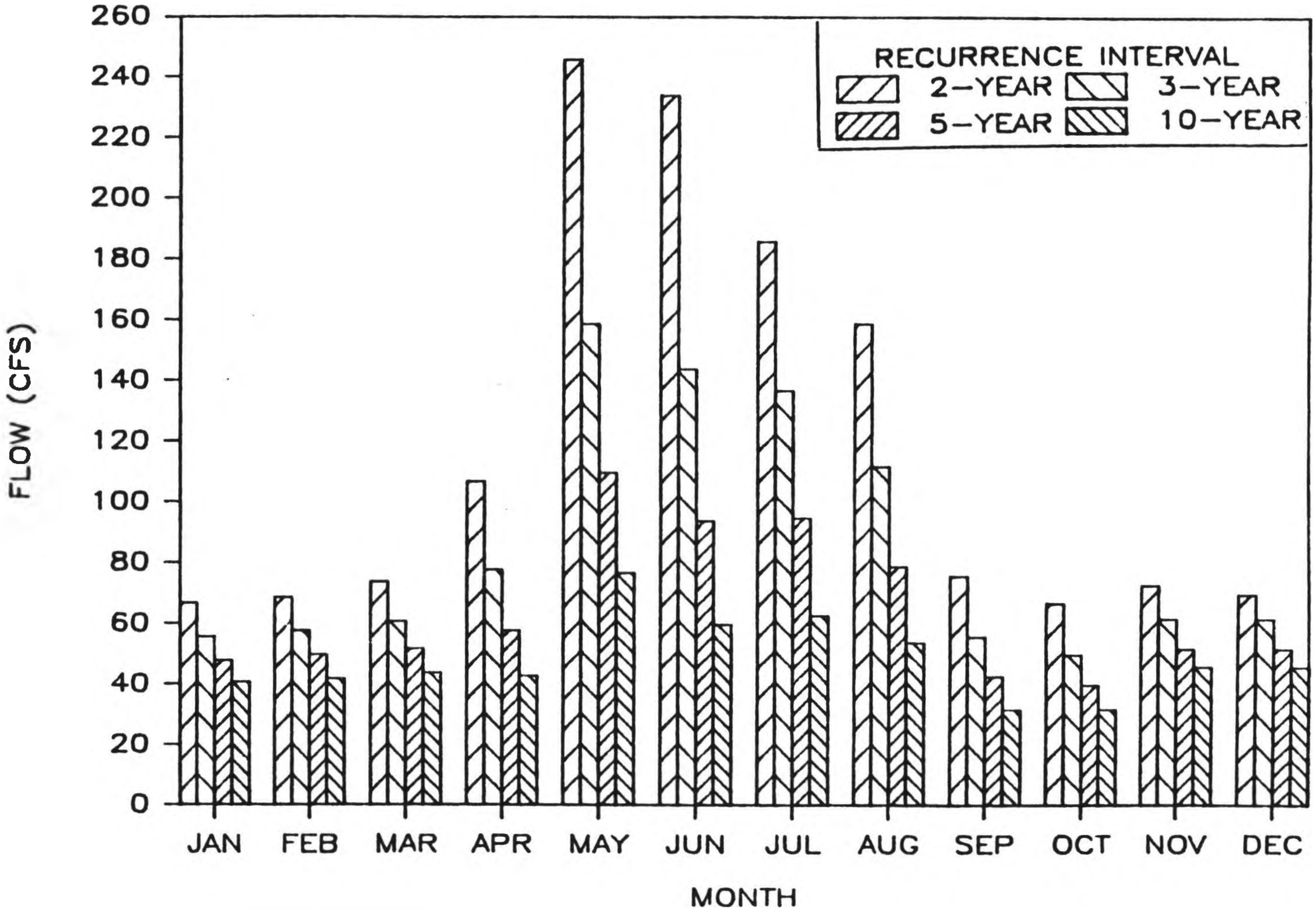


Figure 4.3. Graph of monthly 7-day moving average low flows for 2, 3, 5 and 10 year recurrence intervals at Englewood.

Table 4.10. Comparison of monthly 7-day low flow frequency statistics (with and without overlapping) at Littleton.

Month	7-day low flow (cfs) Recurrence interval (years)							
	2		3		5		10	
	A	B	A	B	A	B	A	B
Jan	32	32	25	25	20	20	15	16
Feb	34	36	27	29	21	23	16	18
Mar	39	43	30	34	24	25	18	19
Apr	65	76	44	51	31	35	21	24
May	162	198	97	114	62	70	39	42
Jun	154	168	94	102	62	66	40	42
Jul	157	164	107	112	75	79	50	53
Aug	130	145	87	103	61	70	40	47
Sep	52	54	38	40	28	29	20	21
Oct	40	39	28	27	21	20	15	15
Nov	38	38	31	30	24	25	21	21
Dec	34	35	26	27	21	21	17	17

A calculated with overlapping.
B calculated without overlapping.

Table 4.11. Comparison of monthly to annual 7Q10 flows.

Month	% Increase of monthly over annual 7Q10's*			
	Englewood	Boulder	Longmont	Fort Collins
Jan	46	31	42	0
Feb	50	90	58	0
Mar	57	114	42	21
Apr	54	126	42	0
May	175	233	67	29
Jun	114	590	358	1914
Jul	125	662	358	1507
Aug	93	328	275	429
Sep	14	221	175	50
Oct	14	67	67	7
Nov	64	55	75	0
Dec	64	126	75	0

*Percent Increase = ((monthly) - (annual)) X 100 / (annual)

Months were grouped into seasons to calculate seasonal design flows at four sites - Englewood, Boulder, Longmont and Fort Collins. The year was separated into two to four seasons of low, transition or high flow months, depending on the specific flow characteristics of each site. The statistical criteria used to group the months into seasons at Englewood are summarized in Table 4.12. The selection of flow seasons using these criteria is a relatively subjective trial and error process. Once an initial selection was made, seasonal flows were calculated and compared to check the appropriateness of the seasons. Where necessary, months were regrouped into more appropriate seasons.

For the sites analyzed, the grouping of months into seasons varied. Low season months consistently included December, January, February, and March. At some sites, September, October, November, April and/or May were also grouped with the low season. High season months included May, June, July and August. The only month that was consistently high at each of the four sites was June. Transition months included March, April, May, August, September, October and November. The definition of low-flow seasons is a site-specific process and should be based on characteristics at a given site. In this study, the grouping of months was based on flow alone. Other factors that should be considered in the definition of seasons for discharge permitting include variation from month to month in effluent quantity and quality and instream water quality.

Seasonal 7-day low-flow frequency statistics at 2, 3, 5 and 10 year recurrence intervals at Englewood are given in Table 4.13 with seasonal low flows for each year given below in Table 4.14. The critical importance of how months are grouped is illustrated in Tables 4.13 and

Table 4.12. Monthly 7-day low flow statistics used to group months into seasons at Englewood.

Month	Season	Flow (cfs) Mean	Median	SD*	Monthly 7Q3	Seasonal 7Q3
Jan	Low	72	75	29	56	45
Feb	Low	76	71	34	58	45
Mar	Low	84	70	41	61	45
Apr	Transition	146	102	116	78	78
May	High	493	229	619	159	80
Jun	High	434	239	511	144	80
Jul	High	268	195	213	137	80
Aug	High	223	206	181	112	80
Sep	Low	99	73	78	56	45
Oct	Low	95	66	97	50	45
Nov	Low	98	75	75	62	45
Dec	Low	82	70	42	62	45

* Standard deviation

Table 4.13. Seasonal 7-day low flow frequency statistics at Englewood.

Recurrence Interval (years)	Low flow (cfs) Low (Sep-Mar)	Transition (Apr)	High (May-Aug)	High* (Apr-Aug)
2	54	107	111	78
3	45	78	80	60
5	37	58	60	49
10	30	43	44	40

*Based on two seasons only, low and high.

Table 4.14. Seasonal 7-day low flows for each year of record at Englewood.

Year (ending)	Low flow (cfs) Low (Sep-Mar)	Transition (Apr)	High (May-Aug)	High* (Apr-Aug)
1956	37	42	39	39
1957	15	62	270	62
1958	71	217	53	53
1959	44	121	82	82
1960	33	483	43	43
1961	36	132	130	130
1962	119	286	72	72
1963	32	35	26	26
1964	46	105	72	72
1965	36	87	284	87
1966	66	99	72	72
1967	47	50	86	50
1968	72	97	154	97
1969	46	73	158	73
1970	103	314	220	220
1971	95	114	230	114
1972	66	68	117	68
1973	65	164	268	164
1974	64	321	80	80
1975	53	82	186	82
1976	44	78	100	78
1977	60	102	60	60
1978	50	47	53	47
1979	41	151	105	105
1980	51	175	166	166
1981	48	59	48	48
1982	43	37	79	37
1983	48	405	556	405
1984	76	292	312	292
1985	98	182	277	182

*Based on two seasons only, low and high.

4.14. Seasonal flows for two different sets of seasons were calculated with the first set including low (September-March) and high (April-August) seasons and the second set adding a transition season (April). When April is grouped in the high flow season, the high season flows are much lower than when April is not included in that season (e.g. 7Q2 of 78 cfs compared to 111 cfs). The reason for this significant difference is illustrated in Table 4.14. The lowest flows for the high flow seasons (April-August) may occur in either April or May-August, depending on the year. When April is grouped with May-August, the lowest flow in either season is chosen. Comparison of the last three columns of Table 4.14 illustrates this point.

A comparison of monthly, seasonal, and annual frequency statistic low flows shows that annual flows are consistently less than or equal to seasonal flows which are consistently less than or equal to monthly flows (Figure 4.4). This pattern is due to the variation of flows from one month to another and to the occurrence of minimum flows in different months, for various years. The reasoning for this is similar to that given above for seasonal flows. The lowest values occurring in a year-long period are used to calculate annual statistics and will almost always be lower than any single monthly low-flow statistic which is based on the lowest flows occurring within a much shorter period.

BIOLOGICALLY-BASED DESIGN FLOWS

Design flows were calculated with the U.S. biologically-based method for acute (1-day duration) and chronic (4- and 30-day durations) concentrations at all the sites. The values are given in Tables 4.15-4.17 along with comparable frequency statistic flows and percent

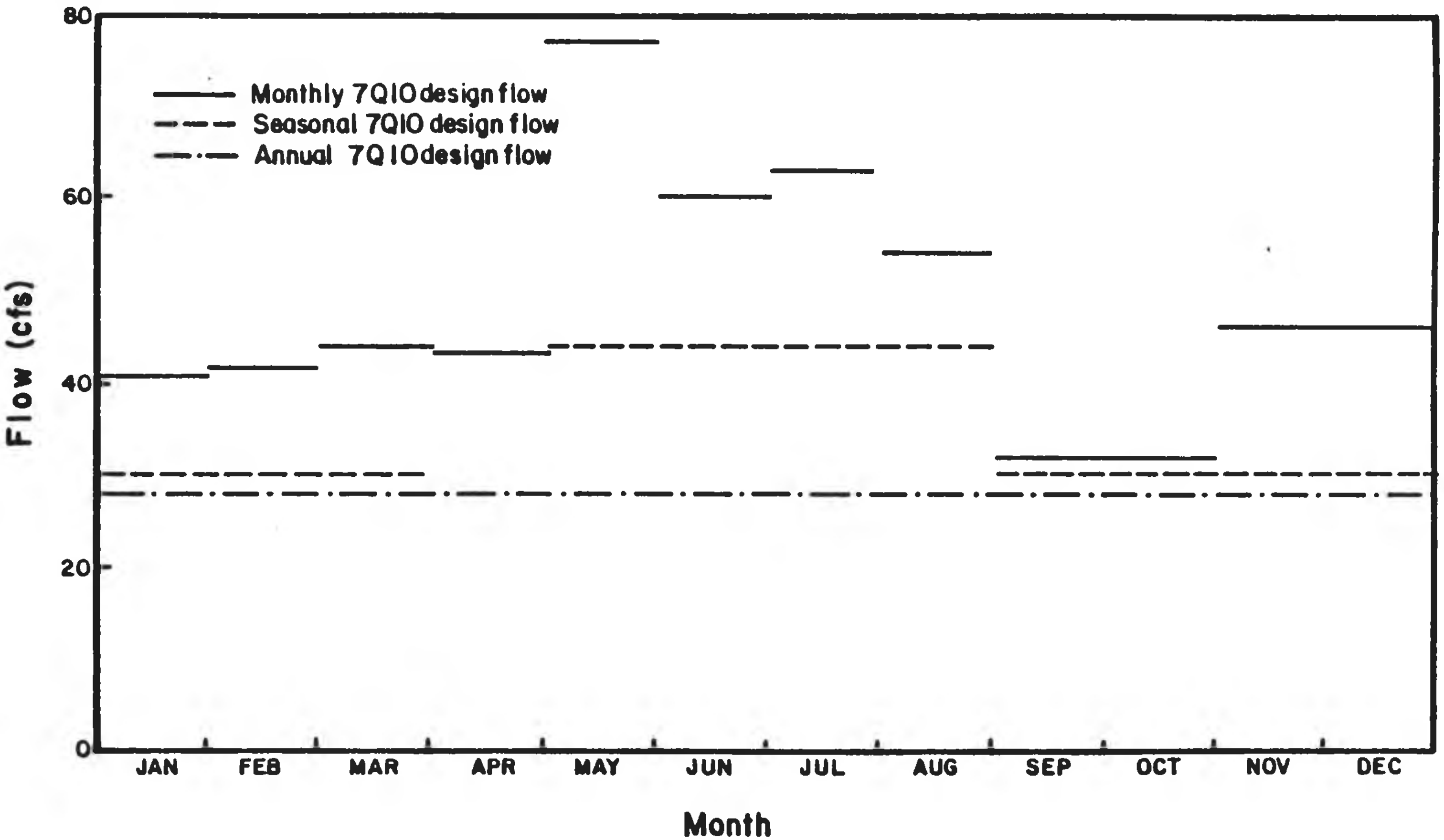


Figure 4.4. Comparison of monthly, seasonal, and annual 7Q10 flows for Englewood.

Table 4.15. Biologically-based acute design flows and comparison to 1Q10 flows.

Site (acceptable no of excs)	1Q10 flow (cfs)	Number of 1-day excursions	Bio-based 1-day 3-yr flow (cfs)	Number of 1-day excursions	% Difference in flows*
Littleton (10.17)	10	9	10.0	9	0.0
Englewood (10.17)	24	10	26.0	10	7.7
Henderson (10.17)	17	16	12.0	9	-41.7
Boulder (3.49)	5	1	6.0	3	16.7
Lyons (10.17)	0.8	19	0.5	5	-60.0
Longmont (10.17)	10	15	9	10	-11.1
Platteville (10.17)	27	11	26.0	8	-3.8
Fort Collins (3.17)	0.9	3	1.3	3	30.8

* % Difference = ((1-day 3-yr flow) - (1Q10)) * 100 / (1-day 3-yr flow)

Table 4.16. Biologically-based chronic design flows and comparison to 7Q10 flows.

Site (acceptable no of excs)	7Q10 flow (cfs)	Number of 4-day excursions	Bio-based 4-day 3-yr flow (cfs)	Number of 4-day excursions	% Difference in flows*
Littleton (10.17)	12	16.25	10.7	8.50	-12.1
Englewood (10.17)	28	10.00	29.9	10.00	6.4
Henderson (10.17)	26	17.25	15.9	10.00	-63.5
Boulder (3.49)	8	5.00	6.9	2.75	-15.9
Lyons (10.17)	1.3	21.00	0.8	9.50	-62.5
Longmont (10.17)	12	20.00	10.8	10.00	-11.1
Platteville (10.17)	31	15.50	27.9	9.50	-11.1
Fort Collins (3.17)	1.4	1.50	1.5	3.00	6.7

* % Difference = ((4-day 3-yr flow) - (7Q10)) * 100 / (4-day 3-yr flow)

Table 4.17 . Biologically-based chronic design flows based on a 30-day moving average and comparison to 30Q10 flows.

Site (acceptable no of excs)	Coefficient of variation	30Q10 flow (cfs)	Number of 30-day excursions	Bio-based 30-day 3-yr flow (cfs)	Number of 30-day excursions	% Difference in flows*
Littleton (10.17)	1.84	17	11.07	16.5	10.17	-3.1
Englewood (10.17)	1.77	36	4.17	38.3	10.17	6.0
Henderson (10.17)	1.52	46	13.03	43.0	8.67	-7.0
Boulder (3.49)	1.38	14	3.30	14.8	3.47	5.7
Lyons (10.17)	1.61	3.6	15.83	2.5	9.80	-44.0
Longmont 10.17	1.51	18	17.93	15.7	9.63	-86.2
Platteville (10.17)	1.51	43	8.57	44.5	10.17	3.4
Fort Collins (3.17)	2.82	1.4	0.00	1.9	3.17	-27.3

* % Difference = ((30-day 3-yr flow) - (30Q10)) * 100 / (30-day 3-yr flow)

differences. The flow statistic used to compare to the acute 1-day, 3-year flow was the 1Q10. The chronic 4-day, 3-year and 30-day, 3-year flows were compared to the 7Q10 and 30Q10, respectively. The number of acceptable and actual excursions are also listed for each flow. Excursions are defined differently for each type of calculation (acute and chronic) as described in the methods section.

Acute 1-day 3-year design flows were similar in magnitude to the 1Q10 or 1Q15 frequency statistic flows. Chronic 30-day 3-year flows were approximated by 30Q10 or 30Q15 flows. These findings correspond closely to the results of an EPA study which analyzed 60 streams across the nation, including a number in this region (U.S. EPA, 1986). In four out of eight cases, or 50 percent, the 1Q10 flow was higher than the 1-day, 3-year flow. This compares to 65 percent of 60 streams tested in a recent EPA study (U.S. EPA, 1986). The 7Q10 flow was higher than the 4-day, 3-year flow at six out of eight sites or 75 percent, as compared to 77 percent in the EPA study. The 30Q10 flow was higher than the 30-day, 3-year flow in five out of eight cases or 62 percent, as compared to 0 percent in the EPA study.

Coefficients of variation based on the complete daily flow record were calculated at each site and are listed in the first column of Table 4.17. The values range from 1.51 to 2.82 and are within the range of values for the 60 rivers in the EPA study (U.S. EPA, 1986). Coefficients of variation as mentioned previously have been used as criteria for determining whether or not 30-day flows may be used in place of shorter duration flows for chronic flow calculations. A low coefficient of variation is considered indicative of a relatively stable flow regime. In the EPA report, a coefficient of variation of approximately 1.0 or below was used to define sets of flow data appropriate for a 30-day averaging period instead of the four day averaging period. According to this criterion, none of the sites in this study had a flow regime appropriate for a 30-day averaging period.

EXCURSION AND RUN LENGTH ANALYSIS

The analysis of low-flow events based on 1-day flows below a given annual or monthly flow (1-day excursions) was used to help define the patterns and durations of such events for various low-flow statistics. Four- and thirty-day excursions were also calculated for comparison at one site. The analysis of one-day excursions may be used to help select an apprpriate acute design flow (1-day duration). The one-day excursions are not as useful for selecting a chronic design flow, which is of a longer duration (e.g. 4-, 7-, or 30-days). Four- or thirty-day excursions may be used to help select an appropriate chronic design flow, but run lengths, which are discussed in the next section, provide more information and are thus more useful for that purpose.

The results of the 1-day low-flow excursion analysis are summarized for Englewood in Table 4.18. The number of excursions for each year of record is given for six different annual flows, two acute and four chronic. Total numbers of years and days with excursions are listed at the bottom of the table. With reference to Table 4.18, it can be seen that the flow of the South Platte at Englewood did not go lower than any of the various design annual flows in the years 1984 and 1985. However, in 1964 there were seven excursions below the 1Q10 of 24 cfs, and 100 excursions the 30Q3 of 53 cfs, almost one in every three days.

Table 4.18. One-day low-flow excursions at Englewood.

Climatic Year (4/1-3/31)	Number of excursions for a given annual flow* Acute flows 1Q10 (24 cfs)	1Q3 (35 cfs)	7Q10 (28 cfs)	Chronic flows 30Q10 (36 cfs)	7Q3 (43 cfs)	30Q3 (53 cfs)
1956	0	12	2	16	74	145
1957	41	63	47	69	169	232
1958	0	0	0	0	0	0
1959	0	0	0	0	4	40
1960	0	9	1	9	15	22
1961	0	5	0	6	19	33
1962	0	0	0	0	0	0
1963	0	18	0	18	36	79
1964	7	26	17	28	41	100
1965	0	4	0	8	46	96
1966	0	0	0	0	0	0
1967	0	0	0	0	3	38
1968	0	0	0	0	0	2
1969	0	0	0	0	2	11
1970	0	0	0	0	0	0
1971	0	0	0	0	0	0
1972	0	0	0	0	0	1
1973	0	0	0	0	0	0
1974	0	0	0	0	0	2
1975	0	0	0	0	4	9
1976	0	0	0	0	5	29
1977	0	0	0	0	0	3
1978	0	0	0	0	0	11
1979	0	0	0	0	9	76
1980	0	0	0	0	0	11
1981	0	0	0	0	0	24
1982	0	0	0	0	8	48
1983	0	1	0	4	6	24
1984	0	0	0	0	0	0
1985	0	0	0	0	0	0
Years with excursions (30 total)	2	8	4	8	15	22
Days with excursions (10958 total)	48	138	67	158	441	1036

*Excursion = single 1-day flow below a given level.

Summaries for one-day excursions for all the sites are given in Tables 4.19 and 4.20 as percent of total years and total days with excursions, respectively. The number of years with excursions ranges from 3 to 82 percent. The average number of years with excursions over all the sites are: acute flows - 1Q10 average 11 percent, 1Q3 average 31 percent; chronic flows - 7Q10 average 20 percent, 30Q10 average 47 percent, 7Q3 average 49 percent, and 30Q3 average 74 percent. The number of days with excursions varies from 0.1 to 13.4 percent with the following averages: acute flows- 1Q10 average 0.25 percent, 1Q3 average 1.1 percent; chronic flows - 0.5 percent, 30Q10 average 1.9 percent, 7Q3 average 3.2 percent, and 30Q3 average 9.0 percent.

An analysis of excursions below monthly frequency statistic flows for each month of the year showed many more excursions below monthly flows than below annual flows (Tables 4.21 and 4.22). The increase in the number of excursions ranged from 500 percent to 850 percent. The reason for the increase is that the cumulative probabilities of low flows occurring within each of 12 months are much greater than the single probability of a low flow occurring within a given year. The implication of this analysis is that a more restrictive monthly flow statistic is required to provide a comparable level of protection to that provided by a given annual statistic. A comparable level of risk for excursions below an annual 7Q10 frequency statistic would be provided by a monthly 7Q115 statistic. A monthly 7Q115 flow may be higher or lower than an annual 7Q10, depending on the month.

The use of a monthly flow statistic for dilution purposes may be quite effective in using the natural assimilative capacity of a river during higher flows. During high flows less treatment would be required

Table 4.19. Percent of years with one-day low flow excursions for the period of record.

Site	Percent of years with one-day excursions* Acute flows 1Q10	1Q3	Chronic flows 7Q10	30Q10	7Q3	30Q3
Littleton	3	33	17	73	57	73
Englewood	7	27	13	73	50	73
Henderson	10	30	27	30	50	70
Boulder	18	27	27	54	36	82
Lyons	17	27	20	43	43	70
Longmont	13	27	20	47	50	77
Platteville	10	30	13	33	47	67
Fort Collins	11	44	22	22	56	78

*Excursion = single 1-day flow below a given level.

Table 4.20. Percent of days with one-day low flow excursions for the period of record.

Site	Percent of days with one-day excursions* Acute flows 1Q10	1Q3	Chronic flows 7Q10	30Q10	7Q3	30Q3
Littleton	0.3	1.7	0.6	2.5	3.5	8.8
Englewood	0.4	1.2	0.6	1.4	4.0	9.4
Henderson	0.3	1.1	0.6	1.6	4.2	12.9
Boulder	0.1	0.6	0.3	2.9	1.6	6.3
Lyons	0.3	0.9	0.7	1.7	1.8	5.0
Longmont	0.2	1.5	0.5	2.9	4.0	8.5
Platteville	0.3	1.7	0.5	1.8	3.4	8.0
Fort Collins	0.1	0.3	0.2	0.2	3.5	13.4

*Excursion = single 1-day flow below a given level.

Table 4.21. One-day low flow excursions below monthly 7Q10 flows.

Month	Total number of excursions* Site Englewood (30 Years)	Boulder (11 Years)	Longmont (30 Years)	Platteville (30 Years)	Fort Collins (9 Years)
Jan	46	11	54	53	0
Feb	31	14	39	35	0
Mar	27	28	54	60	0
Apr	30	13	41	22	0
May	29	4	23	31	0
Jun	30	17	47	20	9
Jul	47	8	26	35	22
Aug	26	2	32	36	14
Sep	41	16	43	66	10
Oct	30	12	50	38	7
Nov	15	10	25	37	0
Dec	47	13	36	48	1

*Excursion = single 1-day flow below a given level.

Table 4.22. Comparison of one-day low flow excursions below monthly and annual 7Q10 flows.

Site	Flow record (years)	Total number of excursions* Monthly 7Q10's	Annual 7Q10	Percent of days Monthly 7Q10's	Annual 7Q10
Englewood	30	397	67	3.6	0.6
Boulder	11	148	25	3.7	0.3
Longmont	30	470	52	4.3	0.5
Platteville	30	481	58	4.4	0.5
Fort Collins	9	63	6	1.9	0.2

*Excursion = single 1-day flow below a given level.

at the point of discharge while still maintaining mainstream uses. However, in order for the use of a monthly design flow to be acceptable it must allow protection of the aquatic system and stream uses at a level of, at least, the conventional 7Q10 using annual values.

Using the concept of equality of risk, the recurrence interval for the monthly flow can be determined. The assumptions made are:

1) 10 years of daily flow;

2) Monthly data are independent; and

3) Equality of the risk of one or more excursions in a 10 year period.

The risk for one or more excursions of the 7Q10 is found using the equation given below:

$$R = 1 - (1 - \frac{1}{T_R})^N$$

where: R = risk of one or more excursions in N outcomes

N = number of outcomes, 10 when analyzing annual data and 120 when analyzing monthly data

T_R = recurrence interval of the flow.

For the risk of one or more excursions of the 7Q10:

$$R = 1 - (1 - \frac{1}{10})^{10} = 0.65.$$

This means there is a 65 percent chance in the next ten years that there will be one or more flows less than the 7Q10. Equating the level of risk to monthly flows and solving for the monthly recurrence interval

$$0.65 = 1 - (1 - \frac{1}{T_R})^{120}$$

$$T_R = 114.81 \text{ years}$$

As a result of this analysis, the 7Q115 flow should be calculated for each month to maintain equal risk of excursions. This would then be used as the design flow available for dilution. It should be noted that estimation of an 115 year recurrence interval flow from only 30 years of data or less will require extrapolation of the data increasing more uncertainty in the results as compared to estimating a 10 year recurrence interval flow which requires interpolation of the data and less uncertainty in the results.

The monthly recurrence interval could also be determined by assuming equal risk with the annual flow that one or less excursions occur in a ten year period. This risk is equal to the probability of no excursion of the 10 year flow in 10 years (0.35) plus the probability of only one excursion in 10 years (0.39). The monthly recurrence interval which will theoretically have the identical risk is approximately 120 years. It would appear that the difference of the recurrence intervals are sufficiently small when considering the problem of uncertainty in the data analysis that the 115 year recurrence interval should suffice.

Run lengths of low-flow events, or the number of consecutive days with flows below a given level, were calculated at each of the sites for two acute flows (1Q10 and 1Q3) and four chronic flows (7Q10, 7Q3, 30Q10, and 30Q3). The results for Platteville are given in Table 4.23. For comparison purposes, run lengths below the annual 30Q3 flow for all the sites are given in Table 4.24. Median run lengths below the 30Q3 in Table 4.24 range from two to four days at each of the sites as follows: two days - Boulder and Lyons; three days - Littleton, Englewood, Henderson and Fort Collins; four days - Longmont and Platteville.

The run length analysis may be used to evaluate the appropriateness of various chronic or acute design flows for use in discharge permitting. Given specific criteria for the allowable duration of the

Table 4.23 . Run lengths of low-flow events for the period of record at Platteville (1956-1985).

1Q10 (27 cfs)		1Q3 (42 cfs)		7Q10 (32 cfs)		7Q3 (50 cfs)		30Q10 (43 cfs)		30Q3 (67 cfs)	
Run length (days)	Number of runs	Run length (days)	Number of runs	Run length (days)	Number of runs	Run length (days)	Number of runs	Run length (days)	Number of runs	Run length (days)	Number of runs
1	2	1	5	1	2	1	9	1	7	1	23
2	2	2	7	3	1	2	10	2	4	2	14
5	1	3	3	4	1	3	4	3	4	3	7
17	1	4	8	5	2	4	4	4	6	4	6
19	1	5	3	7	1	5	4	5	3	5	5
		6	1	13	1	6	1	6	2	6	4
		7	1	19	1	7	3	7	1	7	4
		8	1			8	1	8	2	8	1
		9	1			9	2	9	2	9	3
		13	1			10	2	13	1	10	2
		15	1			11	1	19	1	11	3
		25	1			12	2	25	1	12	3
		26	1			13	2	26	1	13	2
						17	1			15	1
						18	1			16	1
						20	1			17	1
						27	1			23	1
						29	1			26	1
						47	1			30	1
										31	1
										33	1
										34	1
										40	1
										42	1
										50	1
										52	1
										53	1
										81	1

Table 4.24. Run lengths of low flow events for flows below the annual 30Q3 for the period of record.

Littleton (1956-1985) Run length (days)	Littleton Number of runs	Englewood (1956-1985) Run length (days)	Englewood Number of runs	Henderson (1956-1985) Run length (days)	Henderson Number of runs	Boulder (1961-1970) Run length (days)	Boulder Number of runs	Lyons (1956-1985) Run length (days)	Lyons Number of runs	Longmont (1956-1985) Run length (days)	Longmont Number of runs	Platteville (1956-1985) Run length (days)	Platteville Number of runs	Fort Collins (1977-1985) Run length (days)	Fort Collins Number of runs
1	43	1	41	1	26	1	16	1	51	1	30	1	23	1	17
2	21	2	18	2	18	2	7	2	23	2	11	2	14	2	8
3	17	3	15	3	12	3	3	3	14	3	7	3	7	3	3
4	8	4	7	4	7	4	2	4	8	4	11	4	6	4	4
5	6	5	12	5	5	5	3	5	2	5	5	5	5	5	2
6	7	6	8	6	3	6	2	6	4	6	5	6	4	6	2
7	6	7	5	7	2	8	1	7	2	7	3	7	4	7	2
8	5	8	2	8	4	9	1	8	1	8	3	8	1	8	2
9	3	9	4	9	4	10	1	9	2	9	3	9	3	10	2
10	3	10	1	10	2	11	3	10	3	10	3	10	2	12	3
1	1	11	4	11	5	13	1	11	2	11	1	11	3	13	1
13	2	12	3	12	1	17	1	12	1	12	5	12	3	17	1
14	1	13	6	13	2	43	1	15	1	13	1	13	2	23	1
15	1	14	3	14	2			16	2	16	1	15	1	24	1
16	3	15	2	15	3			18	1	18	2	16	1	40	1
17	3	16	1	16	4			21	2	21	1	17	1	70	1
18	1	17	1	20	1			23	1	22	1	23	1	93	1
19	1	18	1	21	1			24	1	27	1	26	1		
20	1	19	2	25	1			29	1	30	1	30	1		
22	1	22	1	29	1			50	1	32	2	31	1		
28	1	34	1	33	1					38	1	33	1		
35	1	55	1	37	1					43	1	34	1		
46	1	71	1	78	1					45	1	40	1		
50	1	137	1	87	1					111	1	42	1		
51	1	51	1	108	1					116	1	50	1		
129	1	129	1	138	1							52	1		
				203	1							53	1		
												81	1		

design flow and frequency of excursions below the design flow, one can select a flow that will meet these requirements. For example, at Platteville, the number of 30-day excursions below the 30Q3 is equal to 14.87 (81/30 + 53/30 + 52/30 + 50/30 + 42/30 + 40/30 + 34/30 + 33/30 + 31/30 + 30/30). If the criteria were for a chronic design flow duration of 30 days and a frequency of occurrence of once every three years, then for a 30-year period, 30/3 or 10 excursions would be allowed. In this case, the 30Q3 flow would not be acceptable. If the criteria were once every two years, however, 15 excursions would be allowed over a 30-year and the 30Q3 would be sufficient. This kind of analysis can be applied to other sites with various duration and frequency criteria to define appropriate chronic design flows.

Chapter 5 - Proposed Guidelines for Computing Design Flows

The calculation of design flows should follow a standard set of procedures to ensure consistency and fairness in the development of NPDES permits. This chapter includes an evaluation of existing analytical methods and selection procedures for design flows, followed by a set of recommended guidelines.

DISCUSSION OF ANALYTICAL METHODS

The methods used to calculate design flows are still in the process of development. Flood flow analytical methods have been applied to low-flow analysis with only limited success. The development of analytical methods specifically suited to low flows and the determination of design flows is an area where further research is required. The analysis of low flows in this study reviews some of the existing low-flow methods, defines a few new approaches and points out a number of problems and areas requiring further research.

Selection of an adequate data set is an important prerequisite to valid analysis. The period of record recommended for low-flow frequency analysis in the literature is 30 years of daily flows. Periods of record shorter than 30 years may be sufficient for biologically-based analysis. The homogeneity, or consistency, of the data set over time is an important consideration. Non-homogeneous data sets can produce results that are not representative of existing flow conditions.

Unfortunately, it is often difficult to separate trends due to man-induced changes in the environment from natural cycles that are inherent in the flow regime. Further research is needed to define specific tests and criteria to identify non-homogeneities more conclusively. Where data are non-homogeneous or where long periods of record are not available, ten years of data may be used to produce valid results.

A major problem in securing an adequate data set for the analysis of design flows is that flow gages are not often located just upstream of the point of discharge where the calculations must be made. The adjustment of data records by regression analysis or water balance procedures to transfer information to a point of interest is an uncertain science at best. Additional research is required to develop models capable of transfering data to locations that are ungaged or have short periods of record. The work in this study at the three sites with insufficient data records has shown the critical importance of selecting an appropriate model to transfer data accurately. Data from the nearest gage may not represent flow conditions at the point of interest and the resulting errors in the analysis should be considered. In some cases, it has been shown that the range of values for the design flows analyzed was within the range of differences between the data sets alone. It is highly recommended that dischargers begin to collect flow data upstream from the point of discharge where gaging stations are missing. This information will enable more accurate estimates of actual flows and may reduce the margins of safety that are factored into a regression or water balance analysis.

Errors in the data record due to measurement and rating curve inaccuracies at gaging stations should be recognized in the analysis.

At very low flows, where design flows are calculated, errors may be significant. To account for these errors, design flows should be given as estimates only as accurate as allowed by the errors. With more research, it may be possible to attach error bounds to estimates of design flows. Permit limits could be made more flexible to reflect these potential ranges of error as well.

Once an adequate data set has been secured, there are a variety of methods that can be used to analyze the data. In this study, three types of analysis were applied: frequency/duration, biologically-based, and excursion analysis.

There are a number of drawbacks to the use of mathematically defined frequency/duration statistics to calculate design flows. First, the estimate of a distribution function that fits low-flow data is difficult. The log-Pearson Type III distribution has been applied widely in both flood and low-flow frequency analysis. However, the results of this study have shown that the log-Pearson Type III distribution did not fit annual low-flow data at any of the sites tested and fit monthly data at only a few of the sites. Normal or log-normal distributions were more appropriate in a number of cases. No one distribution was adequate to cover all the sites for both annual and monthly flows. The use of an incorrect distribution function to analyze the flow data can introduce significant errors, but it may require extensive statistical analysis to avoid such problems.

Another source of error in frequency analysis is the violation of necessary statistical assumptions of randomness and independence of events. These assumptions are often violated by serially correlated annual or monthly low flows. Errors in parameter estimates may also affect the analysis. As an example, the frequency factor used in the log-Pearson Type III equation should be based on a combination of the regionalized and stations skews of low-flow data. However, regionalized skews have not been defined for low flows in the state of Colorado. This potential source of error has not been addressed previously, but could have a significant effect on the outcome of low-flow analysis. Estimates of sample means and variances may also introduce additional errors due to lack of data.

The graphical method of frequency analysis may be a viable alternative to the mathematical method because it eliminates some of the problems just described. No assumption as to a theoretical distribution function and no parameter estimates are required for the graphical method. However, there remain two major drawbacks to frequency statistic design flows. The first is that frequency/duration flows do not provide equal levels of protection from one site to another. As illustrated in this and other studies, the number of excursions below a given flow statistic, like the 7Q10, may vary by a factor of two to three from stream to stream, even along the Front Range in Colorado. In addition, frequency statistics do not relate directly to aquatic life criteria because they are based on the extreme low flow event for each year and do not account for any other low flows occurring during that same year.

The other two types of analysis, biologically-based and excursion, are more appropriate for the evaluation of design flows than frequency/duration statistics because they include the consideration of all flows that fall below a given threshold value defined by the design flow. A more complete evaluation of the potential effects on aquatic life uses is provided by either of these methods than by frequency analysis. The advantages of the biologically-based method over excursion analysis are that it accounts for low-flow patterns and extended drought periods, and is relatively easy to implement with existing programs developed by the U.S. EPA and STORET data files. One drawback of the biologically-based method is that it provides less information than excursion analysis, which can be used to evaluate the lengths and patterns of low-flow events at a specific site.

Monthly or seasonal design flows have been applied in a number of states to more fully utilize stream assimilative capacities. A major issue that has received little attention thus far is the significant increase in the number of excursions that occur below monthly or seasonal frequency statistic flows than below annual flows. This increase was well evidenced by the results of this study. The implication of this analysis is that a more restrictive monthly flow statistic is required to provide a comparable level of protection to that provided by a given annual statistic. As an example, it was shown that a comparable level of risk for an annual 7Q10 is defined statistically by a monthly 7Q115. However, a comparable level of risk may not be appropriate. It makes more sense to define an allowable frequency of excursions occurring in each month or season and choose monthly or seasonal flows to achieve those criteria. The allowable number of excursions could vary over the year to provide a high level of protection during critical seasons for aquatic life in the same way that seasonal standards have been applied. Greater use of assimilative capacity and more excursions could be allowed during non-critical periods. Neither the biologically-based method nor excursion analysis have been applied on a monthly or seasonal basis in this study. Nonetheless, either one could be modified to define monthly or seasonal design flows. More research, however, may be required to define appropriate criteria.

A new technique was developed in this study to deal with the calculation of moving averages for monthly design flows. The technique, termed an overlapping procedure, is used to eliminate bias of the analysis toward the middle values of the month. In this study overlapping was used only to calculate monthly frequency statistic flows, but could also be applied to biologically-based or excursion analysis. Use of the overlapping procedure complicates the analysis, but it should be recognized that without overlapping a bias is introduced. This bias becomes more important as the duration of the moving averages increases. The results of this study showed that the bias tended to produce higher monthly frequency statistic flows without the overlapping procedure.

SELECTION OF APPROPRIATE DESIGN FLOWS

The criteria for the selection of appropriate design flows in the state of Colorado are based on the requirements of the most sensitive water use, which is aquatic life in most cases. Economic implications of various design flows may temper the selection, but current water quality regulations require that priority be given to the maintenance of existing instream uses. To protect aquatic life, the U.S. EPA has recommended that dual design flows be used to reflect acute and chronic conditions, and has recommended 1-day for acute and 4-day or 30-day for chronic. The recommended allowable frequency of occurrence is once in every three years. Alternative duration and frequency criteria may be justified as long as instream uses are protected.

Given a set of duration and frequency criteria, the selection of annual design flows is a relatively straightforward process. Historical low-flow data can be evaluated by either the biologically-based method or by excursion analysis to define flows that meet the criteria. Frequency/duration statistics can be used to approximate the flow values defined by this analysis at a given site, but do not provide consistent levels of protection from one stream to another.

In this study, it was found that the design flows meeting the criteria recommended by the U.S. EPA were the 1Q10 for acute flows and 7Q10 or 7Q15 for chronic flows. These design flows are very restrictive and provide no relief for dischargers from current limits. However, based on the criteria, these flows maintain the required levels of protection for aquatic life. If the economic implications of such stringent design flows warrant a change, then the first factor to adjust must be the criteria. If the allowable frequency were switched to once every two years or if the chronic duration were switched from 4-day to 30-day , the effect on the design flow could be significant.

Monthly and seasonal design flows can be used effectively to increase the use of assimilative capacity and still maintain existing instream uses. The application of monthly or seasonal design flows will require further research in a number of areas, including the adaptation of biologically-based analysis and the definition of allowable excursions on a monthly or seasonal basis. It is recommended that seasonal variations in water quality and effluent quality also be reflected in the calculation of seasonal effluent limits. The choice of whether to use monthly or seasonal design flows may be a compromise between increased complexity and greater utilization of assimilative capacity. The results of this study have shown that the differences between annual and monthly design flows are much greater than between annual and seasonal design flows. The use of monthly design flows could result in substantially higher permit limits than seasonal flows, depending on the number of flow excursions allowed. The ability of dischargers to adjust their treatment processes on a monthly basis and the increased complexity of implementation, however, may restrict the use of monthly limits.

RECOMMENDED GUIDELINES TO COMPUTE DESIGN FLOWS

1) Select data set.

Use 10 years of the most recent daily flow data available, and update design flow values every five years with the permit renewal. This approach should reduce problems with non-homogeneity and short data records. If data are not available upstream of the point of discharge, use regression analysis or a water balance analysis to transfer flows to the correct location.

2) Define selection criteria.

First, determine whether the design flows are to be calculated on an annual, monthly, or seasonal basis. Then define duration and frequency criteria to protect the most sensitive stream use, which is usually aquatic life.

a. duration

Use two durations, 1-day for acute conditions and 4-day for chronic conditions as recommended by the U.S. EPA. A longer chronic duration may be justified if the flow and water quality conditions are relatively stable. Check coefficients of variation for low flows (flows less than the mean annual flow) and for major water quality variables to see if a longer duration is warranted. Relatively low C_v values, from 0.8 to 1.0 can be used to justify longer durations.

b. frequency

Select an allowable frequency of excursions that will protect indigenous aquatic populations on a site-specific basis. The U.S. EPA has recommended once in three years to allow populations to recover fully after periods of stress. However, once in two years may be sufficient, depending ont the characteristics of the species present. Scientific rationale for the selection of a frequency other than once in three years should be provided. If monthly or seasonal flows are to be used, choose seasonally varying frequencies that reflect critical or non-critical conditions for aquatic life. During critical periods, use once in three years or a more restrictive frequency, and during non-critical periods use less restrictive frequencies. Account for cumulative effects of excursions during the course of several seasons within a year. The use of seasonal frequencies will require further research into acceptable levels of protection for particular uses.

3) Calculate design flows with the biologically-based method.

Use the program developed by the U.S. EPA for personal computers, or a similar version, along with STORET data files to calculate biologically-based design flows. Calculate flows on an annual, monthly, and seasonal basis initially to see which is the most effective. Monthly flows will provide for the greatest use of assimilative capacity, but may be difficult to implement on such a short-term basis. Seasonal flows are recommended as a practical compromise between annual and monthly values. Seasonal variations in water quality and aquatic life requirements should also be incorporated into the analysis.

a. <u>annual flows</u>

Use existing programs and annual frequency criteria.

b. <u>monthly flows</u>

Adapt programs to a monthly basis and use monthly frequency criteria. If a moving average is used in the analysis, use the overlapping procedure to calculate averages for longer duration flows (i.e. 7-day or longer). Overlapping is not required for 1-day or 4-day durations.

c. <u>seasonal flows</u>

Group months into low, high, and transition discharge seasons based on flow, water quality and effluent quality. First, make the initial selection of seasons based on flows. Use basic statistics (mean, median, and standard deviation) on moving averages of acute or chronic durations for each month to separate the seasons. Next, look at seasonal variations in the controlling water quality variables (e.g. pH and temperature for un-ionized ammonia levels). Group critical water quality months with the low discharge season, if they have not already been grouped there by the flow analysis. At this stage, also incorporate consideration fo critical seasons (e.g. spawning periods) for aquatic life. Finally, check for large variations in effluent quality or quantity and adjust the selection of seasons if necessary. These last two steps may help to group transition flow months with high or low discharge seasons, or may actually change the designations of high or low given in the first stage of flow analysis. If water and effluent quality data are limited, base the selection of seasons on flows alone. Calculate seasonal design flows with programs adapted to a seasonal basis and with seasonal frequency criteria. Apply overlapping to longer duration flows, especially within short, one or two month long, seasons.

4) Evaluate potential sources of error.

Consider potential errors based on the quality of the data set and the analysis. Factors to consider in the quality of data include: accuracy and completeness of the flow record, specifically during low-flow periods; the proximity of the gage to the point of interest; and the homogeneity of the data. Further research may be required to evaluate data errors quantitatively, but errors should be accounted for qualitatively at the least. Errors stemming from the analysis should be less when applying the biologically-based approach versus the frequency/duration methodology.

Chapter 6 - Summary, Conclusions, and Recommendations

This study addressed two major aspects of design flows: methods used to compute design flows, and alternative design flows for use in NPDES permitting. Traditional frequency/duration statistics were calculated on an annual, monthly, and seasonal basis and were compared to design flows calculated with the U.S. EPA biologically-based method. The appropriateness of various design flows computed with these methods was measured by duration and frequency criteria recommended by the U.S. EPA for the protection of aquatic life.

The results of this study have shown that frequency/duration analysis is not an appropriate method to calculate design flows for NPDES permits. An empirical, distribution-free approach like the biologically-based method ,which relates directly to frequency and duration criteria, is a better alternative. A standard set of analytical methods should be used for design flow calculations to maintain consistency in NPDES permitting. Recommended guidelines have been proposed based on the results of this study. Further research is required to better define these methods, particularly with respect to seasonal design flows.

Recommendations

1) Follow the proposed guidelines given here for the calculation of design flows.

2) Conduct further research on seasonal water quality and aquatic life requirements to define seasonally varying frequency criteria.

3) Improve techniques to quantify potential sources of error and define error bounds for design flows.

4) Collect flow data at locations just upstream of dischargers to enable better estimates of appropriate design flows.

5) For sites where data are not available, improve techniques to transfer flow data from distant gages to the point of discharge.

6) Develop a data base of instream and effluent water quality to verify that instream uses are protected.

REFERENCES

ASCE Task Committee on Low Flow Evaluation, Methods and needs of the Committee on Surface Water Hydrology of the Hydraulics Division (1980). Characteristics of Low Flows, ASCE, HY5:717-747.

Boner, M.C. and L.P. Furland (1982). Seasonal Treatment and Variable Effluent Quality Based on Assimilative Capacity. Journal WPCF, 54(10)1408-1416.

Colorado Water Quality Control Act (1973). CRS 25-8, as amended in 1981, 1983, 1985.

Colorado Water Quality Control Commission (1979). Regulations for Effluent Limitations, 5 CCR 1002-3.

Colorado Water Quality Control Commission (1984a). The Basic Standards and Methodologies, 5 CCR 1002-8.

Colorado Water Quality Control Commission (1984b). Regulations for the Colorado State Discharge Permit System, 5 CCR 1002-2.

Colorado Water Quality Control Division (1984). Colorado Water Quality Compliance Strategy Report. State of Colorado Department of Public Health, Denver, Colorado.

David, M.H. and E.L. David (1983). Cost-effective Regulatory Options for Water Quality Limited Streams. Water Resources Bulletin 19(3):421-428.

Downing, D. and S. Sessions (1985). Innovative Water Quality-based Permitting: a Policy Perspective. Journal WPCF, 57(5):358-365.

Duncan, A.C., R.C. Ugland, R.D. Steger, and S.L. Blattner (1984). Water Resources Data, Colorado, Water Year 1984. Volume 1. USGS Water Data Report CO-84-1.

Epp, D.J. and C.E. Young (1981). Cost Reductions due to Seasonal Variations in Municipal Waste Water Treatment Levels. Water Resources Bulletin 17(2):215-224.

Federal Water Pollution Control Act (1972). P.L. 92-500, as amended by the Clean Water Act of 1977, P.L. 95-217, and subsequent amendments.

Ferrara, R.A. and M.A. Domino (1985). A Case Study Analysis for Seasonal Nitrification: Economic Efficiency and Water Quality Preservation. Journal WPCF, 57(7):763-769.

Foster, T. (1983). Water Quality Standards in Colorado. Proceedings of the 1983 ASCE Conference on Environmental Engineering, ASCE, pp. 158-164.

Hargett, D. and J.A. Seagraves (1980). Benefits and Cost of Seasonal Effluent Permits in North Carolina. North Carolina Department of Natural Resources, UNC-WRRI-79-135.

Herbay, J.P. and Y. Smeers (1983). Water Quality Management With Time Varying River Flow and Discharger Control. Water Resources Research, 19(6):1481-1487.

Jennings, M.E. and M.A. Benson (1969). Frequency Curves for Annual Flood Series with Some Zero Events or Incomplete Data. Water Resources Research, 5:1:276-280.

Kuchenrither, R.D. C.P. Houck, C.W. Ingrahm, M.M. Grimes, and G.K. Elmund (1983). Variable Effluent Nitrification Requirements Based on Instream Water Quality. Journal WPCF, 55(12):1489-1496.

Lamb, J.C. (1980). Conflict Between Energy Conservation and Water Pollution Control Standards. Journal WPCF, 52(4)L655-660.

Lamb. J.C. and D.B. Hull (1985). Current Status in Use of Flexible Effluent Standards. Journal WPCF, 57(10):993-998.

Low Flow Project Team (1986). Interim Report - Evaluation of Design Flow Criteria for Effluent Discharge Permits in Colorado. Environmental Engineering Program, Department of Civil Engineering, Colorado State University, Fort Collins, CO.

Matalas, N.C. (1963). PRobability Distribution of Low Flows. USGS Professional Paper 434-A.

Matalas, N.C. (1967). Mathematical Assessment of Synthetic Hydrology. Water Resources Research, 3:937-945.

McGinnis, D.F. Jr., and W.H. Sammons (1970). Discussion of "Daily Streamflow Simulation" by K. Payne, W.R. Newman, and K.D. Kerri. Journal Hydraulic Division ASCE, 96:1201-1206.

McMahon, T.A. and A. Diaz Arenas, editors (1986). Methods of Computation of Low Streamflow. UNESCO.

Nie, N.H., C.H. Hull, J.G. Jenkins, K. Steinbrenner, and D.H. Bent (1975). Statistical Package for the Social Sciences. McGraw-Hill.

Northwest Colorado Council of Governments (1984). Point Sources - Nonpoint Sources Trading in the Lake Dillon Watershed.

Paulson, C.L. and T.G. Sanders (1987). Final Report - Evaluation of Design Flow Criteria for Effluent Discharge Permits in Colorado. Environmental Engineering Program, Department of Civil Engineering, Colorado State University, Fort Collins, CO.

Petsch, H.E. (1979). Streamflow Statistical Summaries for Colorado Streams Through September 30, 1975. Volume 1. USGS Open File Report 79-681.

Pitman, W.V. (1978). Trends In Streamflow Due to Upstream Land-use Changes. Journal of Hydrology. 39:227-237.

Rehels, H.F., J.C. Dozier, D.M. Word, and J.R. Holland (1982). Treatment Cost Savings Through Monthly Variable Effluent Limits. Journal WPCF, 54(12):1224-1230.

Riggs, H.C. (1968). Frequency Curves, from Techniques of Water-Resources Investigations of the USGS, 1968-0-275-362.

Riggs, H.C. (1972). Low Flow Investigations, from Techniques of Water-Resources Investigations of the USGS, 1972-0-477-434.

Riggs, H.C. (1976). Effects of Man on Low Flows. Environmental Aspects of Irrigation and Drainage, ASCE, pp. 306-314.

Riggs, H.C. (1977). Some Statistical Tools in Hydrology, from Techniques of Water-Resources Investigations of the USGS. 1977-240-961/123.

Schaughnessy, W., D. Foster, R. Freed, and N. Beach (1984). Potential Impact of Trading and Seasonal Permitting on the Delaware Estuary. Presented at the 57th Annual Conference of the WPCF, New Orleans, Louisiana, October 1-4.

Searcy, J.K. (1959). Flow Durations Curves. USGS Water Supply Paper 1542-A.

Singh, P, and J.B. Stall (1965). Hydrology of 7-Day 10-Year Low Flows. Journal of the Hydraulics Division, ASCE, pp. 1753-1771.

Tasker, G.D. (1972). Estimating Low Flow Characteristics of Streams in Southeastern Massachusetts from Maps of Ground-Water Availability. USGS Professional Paper 800-D, D217-D220.

U.S. EPA (1983a). National Pollutant Discharge Elimination System Regulations, 40 CFR Part 122.

U.S. EPA (1983b). Stream Design Flow, Technical Guidance Manual for Critical Design Conditions. H. Biswas, GKY and Associates.

U.S. EPA (1983c). Water Quality Standards Regulation, 40 CFR Part 131.

U.S. EPA (1983d). Water Quality Standards Handbook. Office of Water Regulations and Standards.

U.S. EPA (1983e). An Analysis of Industry and Pollutant Suitability for Innovative Permit Designs. JRB Associates, for the U.S. EPA Office of Policy, Planning, and Evaluation, Washington, D.C.

U.S. EPA (1983f). Implementing Innovative Water Quality Permitting: Georgia's Monthly 7Q10 NPDES System. The Skylonda Group, for the U.S. EPA Office of Policy, Planning, and Evaluation, Washington, D.C.

U.S. EPA (1983g). Water Quality Comparison of Alternative Permit Designs. GKY and Associates, Inc. for the U.S. EPA Office of Policy, Planning, and Evaluation, Washington, D.C.

U.S. EPA (1984a). Ambient Aquatic Life Water Quality Criteria for Ammonia. Office of Research and Development, Duluth, Minnesota.

U.S. EPA (1984b). Innovative NPDES Permitting in North Carolina. The Skylonda Group, Inc. for the U.S. EPA Office of Policy, Planning, and Evaluation, Washington, D.C.

U.S. EPA (1985). Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. by Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, and W.A. Brungs.

U.S. EPA (1986). Technical Guidance Manual for Performing Waste Load Allocation, Book VI - Design Conditions, Chapter 1 - Stream Design Flow for Steady-State Modeling. Office of Water Regulations and Standards and Office of Research and Development, Duluth, Minnesota.

U.S. Interagency Advisory Committee on Water Data (1982). Guidelines for Determining Flood Flow Frequency (2nd Edition, revised). USGS Office of Water Data Coordination, Hydrology Subcommittee Bulletin 17B, Reston, VA.

Willey, B.R. and H.H. Benjes, Jr. (1985). Innovative Water Management Plan Reduces Treatment Costs. Journal WPCF, 57(5):378-383.

Zar, J.H. (1974). Biostatistical Analysis. Prentice Hall, Englewood, NJ.

Zitta, V.L. (1979). Statistical Analysis of Stream Events as Applied to Controlled Release of Lagoon Effluents.