THE INFLUENCE OF CLIMATE VARIATION ON THE ESTIMATION OF LOW FLOWS USED TO PROTECT WATER QUALITY: A NATIONWIDE ASSESSMENT[1]

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ABSTRACT: Historical flow records are used to estimate the regulatory low flows that serve a key function in setting discharge permit limits through the National Pollutant Discharge Elimination System, which provides a nationwide mechanism for protecting water quality. Use of historical records creates an implicit connection between water quality protection and climate variability. The longer the record, the more likely the low flow estimate will be based on a broad set of climate conditions, and thus provides adequate water quality protection in the future. Unfortunately, a long record often is not available at a specific location. This analysis examines the connection between climate variability and the variability of biologically based and hydrologically based low flow estimates at 176 sites from the Hydro-Climatic Data Network, a collection of stream gages identified by the USGS as relatively free of anthropogenic influences. Results show that a record of 10 to 20 years is necessary for satisfactory estimates of regulatory low flows. Although it is possible to estimate a biologically based low flow from a record of less than 10 years, these estimates are highly uncertain and incorporate a bias that undermines water quality protection.
(KEY TERMS: water quality; climate variation; surface water hydrology; NPDES permits; water quality based effluent limits; design flow.)

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INTRODUCTION

Water quality in streams is affected by the addition of pollutants from point sources that are regulated through the National Pollutant Discharge Elimination System (NPDES). Most NPDES discharge permits establish water quality based effluent limits (WQBEL) for pollutant concentrations in wastewater effluent. Calculation of each WQBEL begins with the premise that the addition of effluent to the receiving water cannot cause the mixed concentration to exceed the standard set for protection of a designated use.

A mass balance equation (Equation 1) supports the calculation of each limit by setting the mixed concentration (C_m) equal to the appropriate stream standard. The controlling condition occurs when effluent flow (Q_e) is at a maximum and streamflow (Q_s) is at a minimum. By convention, maximum effluent flow is set equal to the design capacity of the treatment facility. The maximum allowable concentration in the effluent, the permit limit (C_e), also is affected by the concentration (C_s) of the pollutant in the stream, which often is small or undetectable unless there are point or nonpoint sources upstream. The minimum flow in the stream (Q_s) must be estimated according to regulatory criteria; the details of criteria for regulatory low flows are given later.

$$C_m Q_m = C_s Q_s + C_e Q_e \quad (1)$$

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The low flow estimate is arguably the most important factor determining the adequacy of water quality protection provided by a discharge permit, because it is the quantitative link between the stream standards that protect designated uses and the permit limits that regulate effluent quality. If the low flow estimate is high relative to conditions that occur in the future, then it increases the risk that aquatic life or another designated use of the water may not receive adequate protection. If the estimate is too low, it increases the probability that more money will be invested in treatment than is necessary to protect designated uses.

Bias or uncertainty in the low flow estimate can undermine the effectiveness of permit limits for ensuring protection of water quality in a stream. Climate variability has the potential to create temporal variability in annual low flows (Stahl and Demuth, 1999; Mosley, 2000). In addition, low frequency forcing functions like El Niño/Southern Oscillation and Pacific Decadal Oscillation contribute to regional patterns of climate variation (Cayan, 1996; Mantua *et al.,* 1997), and these patterns may be evident in streamflows (Redmond and Koch, 1991; Hamlet and Lettenmaier, 1999). The presence of interannual variability in low flows raises the possibility that estimates of regulatory low flow at a particular location will be sensitive to the length of the record that is examined.

Regulatory low flows are estimated using data from the historical record. Reliance on the historical record creates a connection between climate variability and water quality protection by implying that the available record is representative of conditions likely to occur in the future, at least for the term of a discharge permit. In most cases, the historical record consists of measurements taken at the nearest USGS gaging station. At any given site, the record of daily streamflow measurements could be as short as a few years, or it could span more than a century. Each flow record reflects the influence of a specific set of climate conditions. The longer the record, the more likely that it will span a broad range of climate conditions and, thus, be more likely to meet regulatory goals for protection of water quality. Even with the longest of historical flow records, the accompanying range of climate variation is small compared to variations revealed through climate reconstructions using treering data, for example (Woodhouse and Overpeck, 1998; Jain *et al.,* 2002).

Regulatory goals for protection of water quality are less likely to be met where discharge permits are based on low flows estimated from short periods of record, which are unlikely to capture a broad expression of climate variability (Saunders and Lewis, 2003). The obvious solution would be for regulatory agencies to require analysis of long records encompassing variability on the scale of decades. As a practical matter, however, such a record frequently is not available. For example, about half of the USGS gages that have been installed in Colorado have been operated for less than 10 years (Saunders and Lewis, 2003). When a short record is used, there is an increased risk that the low flow estimate will not provide adequate protection of designated uses.

The purpose of this paper is to assess, on a national scale, the influence of climate variation on two important methods defining regulatory low flows. The comparison provides an assessment of the robustness of each definition to climate variation and the risks that use of a short record may impose.

METHODS

Analysis was restricted to gaging stations selected from the Hydro-Climatic Data Network (HCDN) (Slack *et al.,* 1993). Flow at these stations is subject to little or no anthropogenic influence, a necessary condition for isolating the influence of climate variation. Selection criteria were (1) sites must be located within the conterminous U.S.; (2) the "minimum averaging time unit for acceptable values" must be daily; and (3) daily values must be available from April 1, 1930, through March 31, 2001. Also, for computational reasons, sites must have nonzero flow on all dates. The resulting data set contains 176 stations.

Hydrologically based or biologically based definitions of regulatory low flows can be used in NPDES discharge permits (USEPA, 1991). In either case, the historical record is used to define a regulatory low flow (also called the "design flow") that has "a specified frequency of not being exceeded" (Rossman, 1990a). For convenience, any flow lower than the regulatory low flow is called an excursion. Under steady-state assumptions with a constant pollutant load, an excursion can cause the pollutant concentration in the stream to exceed the standard protecting a designated use. The two definitions of regulatory low flows differ in computational approach and in the rationale for excursions. Each is described below. The recurrence intervals and averaging periods used in this study are consistent with those recommended by the U.S. Environmental Protection Agency (USEPA, 1991).

The hydrologically based low flow definition takes an extreme value approach in which the low flow is the smallest x-day average (arithmetic mean) flow for which the recurrence interval is y years (${}_xQ_y$); the seven-day average, 10-year low flow (${}_7Q_{10}$) is the most common. It limits the number of years in which excursions can occur. A log Pearson Type III probability function is fitted to the annual minimum series for the available period of record and a particular averaging period. Hydrologically based low flows were calculated for a 10-year recurrence interval using averaging periods of 1, 7, and 30 days.

The biologically based low flow definition relies on the harmonic, rather than the arithmetic, mean of flow. Under the steady-state conditions given previously, pollutant concentration is inversely related to flow. The average concentration to which aquatic organisms are exposed can be calculated from the pollutant load and the harmonic mean flow for the averaging period. Therefore, from the perspective of aquatic organisms, the harmonic mean, which is the reciprocal of the arithmetic mean of reciprocals, measures exposure to concentration (Rossman, 1990b). The biologically based low flow method is empirical, searching iteratively for the harmonic mean that yields exactly the specified number of excursions for the available period of record (USEPA, 1991). Biologically based low flows were calculated for a three-year recurrence interval using averaging periods of 1, 4, and 30 days.

When the USEPA developed the biologically based low flow method, a recurrence frequency of once in three years was selected to provide roughly the same level of protection afforded by the ${}_7Q_{10}$, which was already in widespread use (USEPA, 1991). Protection was evaluated in terms of the number of excursions to which aquatic organisms might be exposed, meaning the number of excursion events rather than the number of years in which excursions occur. Because the biologically based method examines all low flow events in the period of record, rather than just one from each year, it is able to match exactly the desired frequency of exposure, albeit a frequency that has largely empirical origins.

Excursions impose stress on organisms by raising the concentration of pollutants. The assumption is that most excursions are small, leading to relatively minor stress on the organisms (USEPA, 1986). With minor stress, recovery should occur in a much shorter time than the three-year recurrence interval. A review of case studies, chiefly examining macrobenthos and fish, found that recovery from most disturbances caused by chemical stressors occurred in less than three years (Niemi *et al.,* 1990).

The biologically based low flow definition also recognizes that drought imposes severe stress on aquatic organisms, whether pollutants are present or not. Because "[d]roughts are rare events, [they] should not be allowed to unnecessarily lower design flows" (USEPA, 1986, p. 3-3). It is assumed that recovery from the stress of a drought will occur in 5 to 10 years and that an interval of 15 years without stress is desirable. It is expected that days with very low flows (potential excursions) will be clustered in a drought. The influence of a drought on the regulatory low flow is controlled by setting an upper bound on the number of excursions counted within that drought. No more than five excursions are counted within one clustering interval (120 days). Given five excursions in one drought, and an average recurrence interval of three years, a cap on the number of excursions counted will ensure 15 years, on average, between major stresses. This definition limits the frequency of excursions in the entire period of record.

Notation for biologically based low flows is analogous to that of the hydrologically based low flows in that a ${}_4B_3$ is based on a four-day harmonic mean flow and it has a three-year recurrence interval. At each station in the data set, biologically based low flows were calculated for a three-year recurrence interval using averaging periods of 1, 4, and 30 days.

All low flows were calculated with USEPA's DFLOW program (Rossman, 1990a), with modifications to facilitate efficient processing of many stations. The modifications removed interactive statements and restricted output to a specific set of low flow measures. Output from the modified program was checked against the original program to verify that calculations had not been altered inadvertently.

All regulatory low flow measures were calculated at each station for the full period of record (70 years for this study), and for subsets thereof. Subsets were established with record lengths of 3 to 10 years in one-year increments (biologically based low flows only), and 10 to 65 years in five-year increments (all low flow measures). The minimum record length corresponds to the recurrence interval for each low flow measure. For each subset of n years, the analyses were performed with the first n years, beginning with April 1930, and repeated 70-n additional times by advancing the record in one-year steps. Each subset provides one estimate of a particular low flow measure, the "true" value of which is taken to be the value derived from the entire period of record (70 years). Thus, the number of estimates available ranges from 68 when the record length is three years, to six when record length is set to 65 years. DFLOW operates on increments of climate years, which begin on April 1 and are offset six months from the start of the water year (Gordon *et al.,* 1992).

Much of the information presented in this paper is summarized with box-and-whisker plots created with a statistical program (WINSTAT®). On each graph, the vertical bar displays the 95th, 75th, 50th (median), 25th, and 5th percentiles, as well as the maximum and minimum for each set of values. The central 50 percent of values is enclosed by a box, within which the median is located with a dash. The "whiskers" span the central 90 percent of the values. The maximum and minimum of each distribution is marked with a "plus" symbol. It is an efficient mechanism for comparing shifts in the shape and position of distributions as the record length is increased for all stations, for example. Variance is estimated with the interquartile range (IQR), which is the difference in magnitude between flows at the 75th and 25th percentiles. Skewness is determined with a resistant measure based on the 90th and 10th percentiles (Helsel and Hirsch, 2002). The frequency with which low flow estimates for a particular record length exceed the true value by at least a factor of two is used to assess the practical importance of bias and uncertainty.

TABLE 1. Mean Annual Flow (MAF) and Drainage Area of the HCDN Sites Selected for Analysis.

Hydrologic Region	**No. of Sites**	**Range of MAF (m^3/s)**	**Range of Drainage Area (km^2)**
Northeast (NE)	41	1.6 to 335.6	76 to 29,940
Southeast (SE)	16	3.1 to 670.7	173 to 44,548
Ohio (OH)	22	4.0 to 796.6	269 to 74,165
North Central (NC)	22	10.0 to 1,936.9	1,355 to 308,210
Upper Mississippi (UM)	11	1.4 to 200.1	425 to 30,549
Lower Mississippi (LM)	9	0.4 to 77.8	168 to 5,278
Southwest (SW)	8	1.6 to 41.9	218 to 13,183
California (CA)	15	0.2 to 219.1	23 to 13,088
Columbia (CB)	32	5.5 to 319.6	148 to 35,095
All Regions	176	0.2 to 1,936.9	23 to 308,210

RESULTS

The data set consists of 176 sites in the conterminous U.S. (Figure 1). The sites have been assigned to hydrologic regions based on Lettenmaier *et al.* (1994). Regional characteristics of the sites are given in Table 1. The sites cover a very wide range of flow conditions and represent drainage basins of varying size.

The effect of climate variability on estimates of regulatory low flows is examined at each station as a function of the period of record analyzed. Two stations have been selected to illustrate the analysis that is applied to all stations. The St. John River at Fort Kent, Maine (USGS Station 01014000), and the Virgin River at Littlefield, Arizona (USGS Station 09415000), drain basins that are similar in area, but are located in vastly different physiographic and climatic regions of the country. Variability in estimates

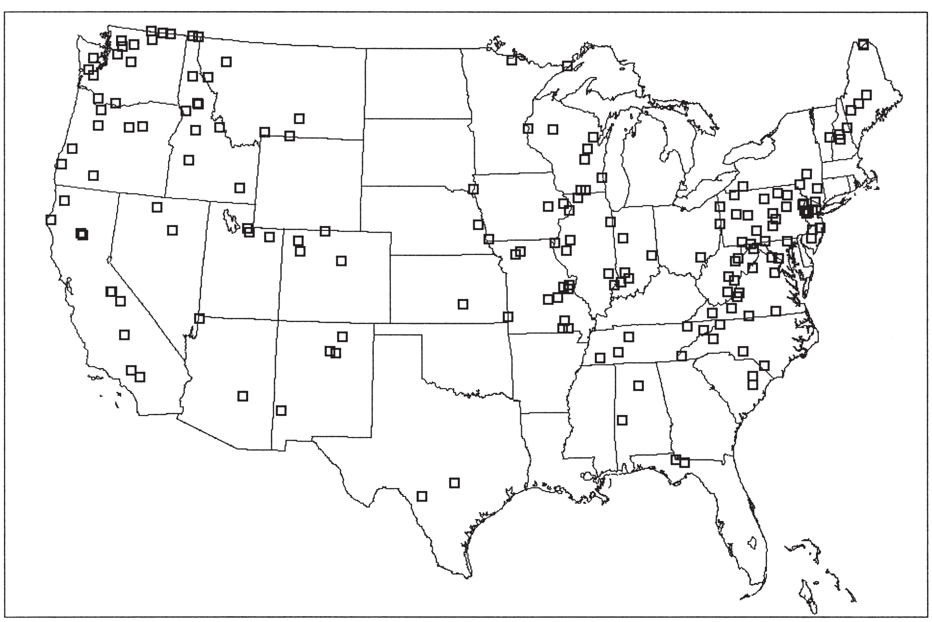


Figure 1. Geographical Distribution of Stream Gaging Sites Selected From the HCDN Set.

of four low flow measures is shown for each of the two stations in Figure 2. A record length of 10 years was used to show results of the incremental calculations for each measure. The "true" values are shown for perspective. In general, the ${}_1B_3$ is the most conservative measure, and the ${}_7Q_{10}$ is the least conservative at both locations. It is surprising that the two acute measures of low flow (${}_1B_3$ and ${}_1Q_{10}$) are not always closer in value than the two biologically based measures (${}_1B_3$ and ${}_4B_3$). In fact, the long term values for the St. John River show that the ${}_4B_3$ is less than the ${}_1Q_{10}$. The data from the St. John River and the Virgin River also demonstrate the implications of climate variation over the period of record. The biologically based low flow measures show the legacy of each drought more consistently by preserving the signal for up to 10 years, whereas the hydrologically based low flows show a smoother pattern of variation associated, presumably, with having fit a distribution to the estimates.

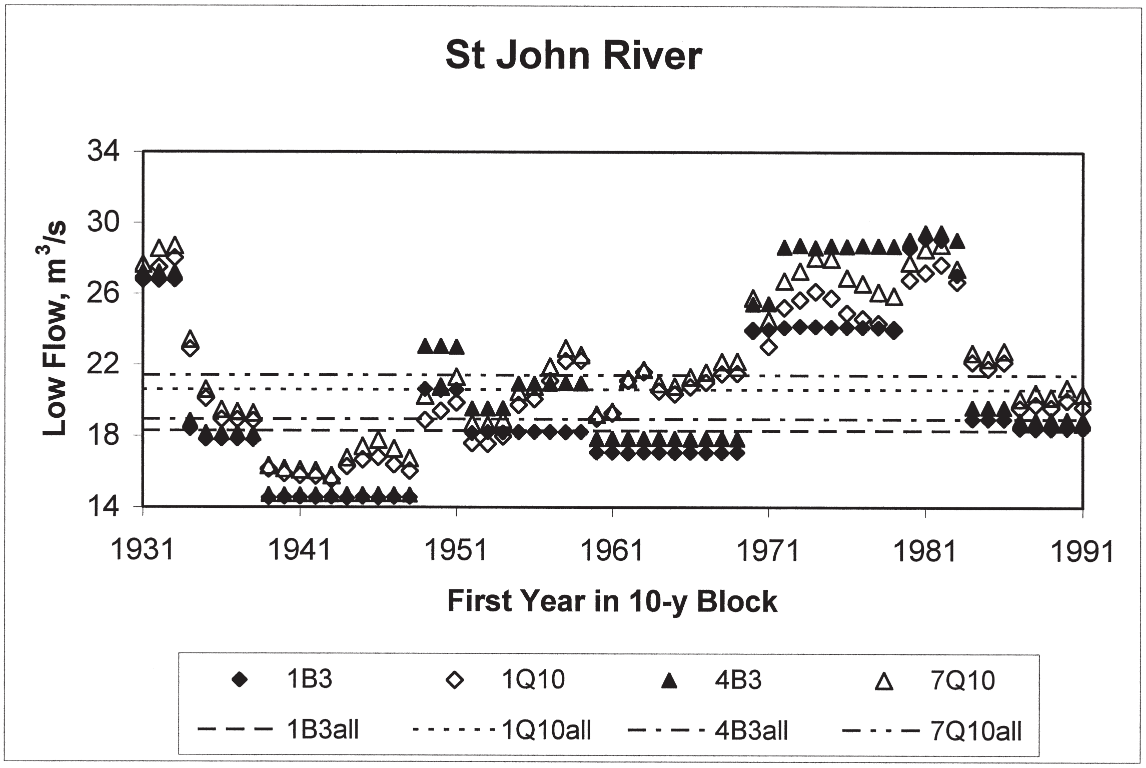
The 10-year record is just one of several record lengths used in the study, and it is the shortest for which measures can be compared between the two definitions. A broader perspective on the role of record lengths is presented for the biologically based low flows (Figures 3 and 4). Although flows differ greatly at the two example stations, some common features emerge from the analysis. Extending the length of the record decreases the median and the variance of each set of low flow estimates, and increasing the averaging interval increases the low flow estimate. In addition, the distributions of the estimates tend to become more symmetrical about the median as the averaging interval (1, 4, or 30 days) is increased. These trends are evaluated in greater detail with the entire data set.

Comparing all stations is challenging because flows vary over several orders of magnitude. Low flow estimates could be scaled to a common basis (e.g., divide by the long term low flow), but an attractive alternative is to use flow percentiles drawn from the distributions appropriate for each averaging interval (1, 4, or 30 days for biologically-based low flows). Each low flow estimate at each station has been translated to a percentile based on the complete record of flows at that station.

When all sites are examined together, the influence of record length on low flow estimates (as percentiles) is apparent (Figure 5). Each box-and-whisker element of the figure characterizes the distribution of medians from the 176 sites. The set of low flow estimates from which each median is calculated will vary in number according to record length (e.g., for a record length of three years, the 70-year period of record yields 68 low flow estimates). The box-and-whisker plots demonstrate that, as record length is increased, low flow estimates calculated from a subsample of the data record will converge on the "true" value, defined here as the low flow calculated for the entire 70-year record. This is not surprising insofar as the longer records are likely to include a greater range of climate variation. The same convergence occurs for low flows of different averaging intervals, although the disparity between the true value and the medians for short record lengths is diminished as the averaging interval is increased (Figure 5). For the same record length, percentiles are larger when averaging period is increased because the DFLOW program seeks "non-overlapping" excursions (see Rossman, 1990a). Most of the hydrologic regions show the same general pattern displayed in Figure 5. Of those that differ, the Lower Mississippi (LM) region shows substantially higher percentiles until the record length exceeds 15 years, and the California/Great Basin region has median percentiles that are consistently about twice that observed for all stations.

Increasing record length also decreases the variance (IQR) of low flow estimates. The IQR for ${}_1B_3$ low flow estimates is shown as m^3/s in the dimensions of the quartile boxes for individual stations (Figures 3 and 4) and as flow percentiles at all stations (Figure 6). As record length increases, the central tendency of the set of low flow estimates approaches the true value asymptotically, and there is greater certainty that any estimate will be close to the true value.

The relationship between record length and biologically based low flow estimates shows that a short record is likely to overestimate the true low flow (i.e., there is a bias in the estimate of central tendency). Bias and skewness are evident in the distributions of estimates based on short records, but it would be useful to have a quantitative perspective on the risk of inadequate protection when a short record must be used. The frequency with which low flow estimates are twice as large as the true value can serve that purpose. If a discharge limit were set on the basis of a low flow estimate that is twice as large as the true value, an effluent discharging at the permit limit could result in a mixed concentration downstream that is twice the standard. If the probability of such an event is high, it presents a serious risk that efforts to protect water quality will be undermined. The bias introduced by short records is important for estimates of the ${}_1B_3$, as indicated by the proportion that are at least twice as large as the true value (Figure 7). Results are similar for the ${}_4B_3$, and somewhat less problematic for the ${}_{30}B_3$. The same pattern of convergence is seen in most of the regions. The Columbia basin sites are unusual in that the same degree of convergence is achieved in four or five years, instead of ten. Sites in the upper and lower regions of the Mississippi basin show greater bias than is typical of



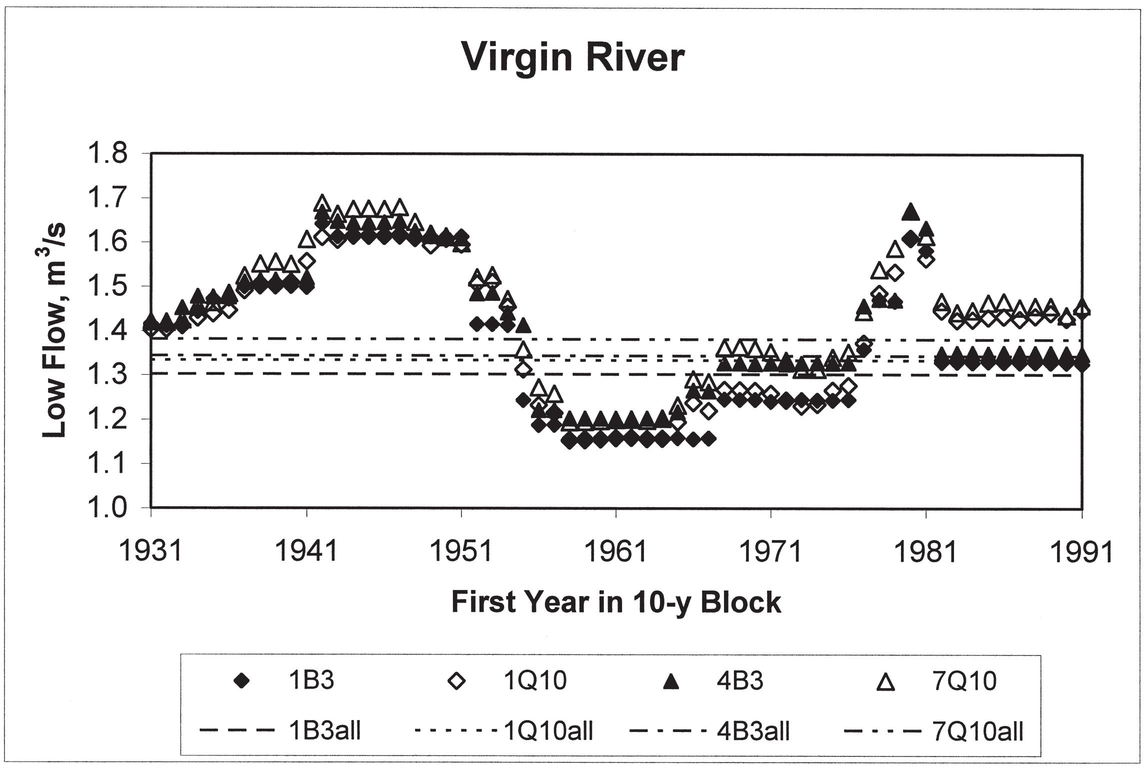


Figure 2. Selected Low Flow Measures for the St. John River, Maine, and the Virgin River, Arizona. Symbols represent low flow estimates for consecutive 10-year blocks. Lines show low flows calculated for the full period of record (shown with suffix "all").

all sites; 10 to 15 years may not be enough in those regions to reduce bias adequately.

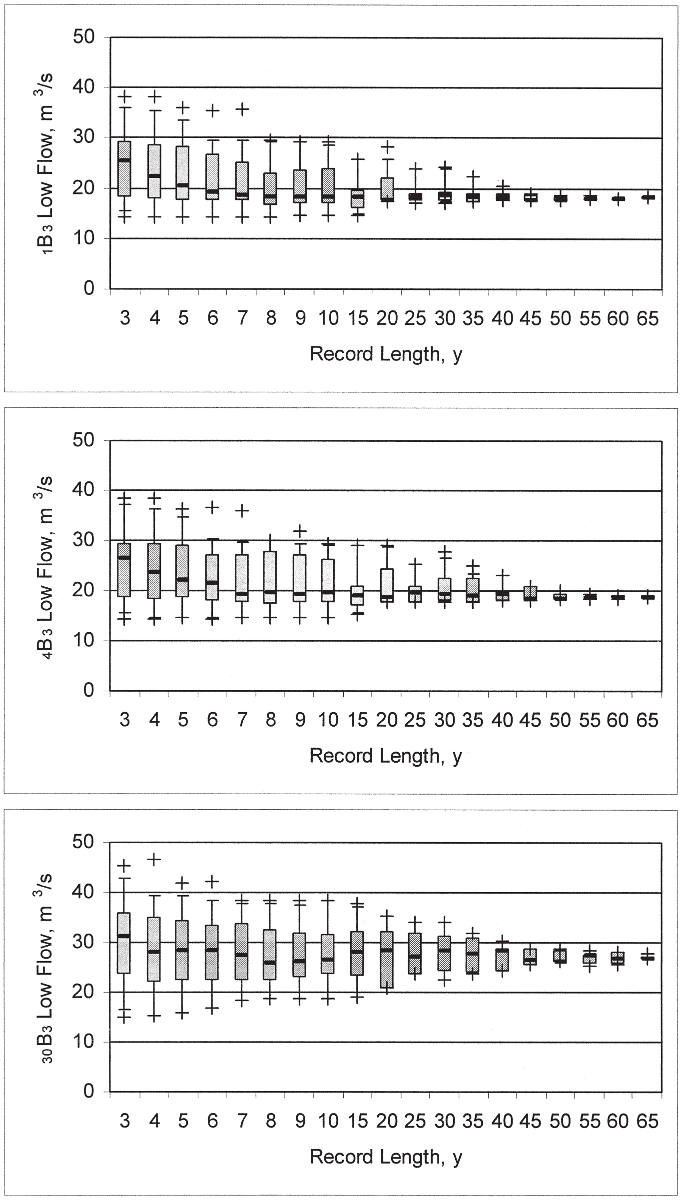


Figure 3. Effect of Record Length on Distributions of Biologically Based Low Flow Estimates for the St. John River at Fort Kent, Maine. For each record length, a box and whisker plot characterizes the distribution of low flow estimates.

The robustness of biologically based low flows to the effects of climate variation can be compared to that of a commonly used hydrologically based low flow, the $_7Q_{10}$. Typical measures of acute ($_1B_3$ and $_1Q_{10}$) and chronic ($_4B_3$ and $_7Q_{10}$) low flow are considered. When a long data record is available, the two chronic measures of low flow are strongly correlated (Figure 8). Acute low flows show the same pattern. This is not to say that the two chronic measures yield the same low flow values, however. The $_4B_3$ tends to be more conservative than the $_7Q_{10}$: at 156 of 176 stations, the $_4B_3$ was less than the $_7Q_{10}$ when the full period of record was analyzed. Even with a record of only 10 years, the $_4B_3$ remains more conservative than the $_7Q_{10}$ (140 of 176 stations). Variance (IQR) shows a very close correspondence between the two chronic low flow measures, and the same is true of the two acute measures. There is probably no advantage to either definition in terms of the variability of estimates when records are at least 10 years in length.

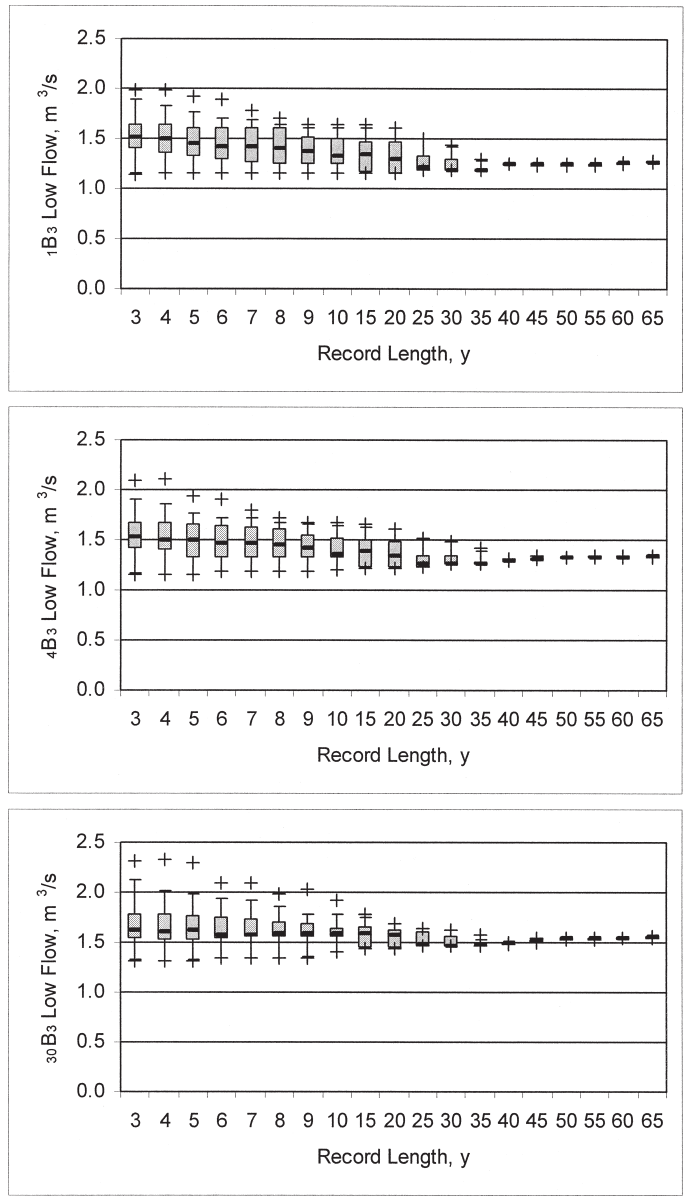


Figure 4. Effect of Record Length on Distributions of Biologically Based Low Flow Estimates for the Virgin River at Littlefield, Arizona.

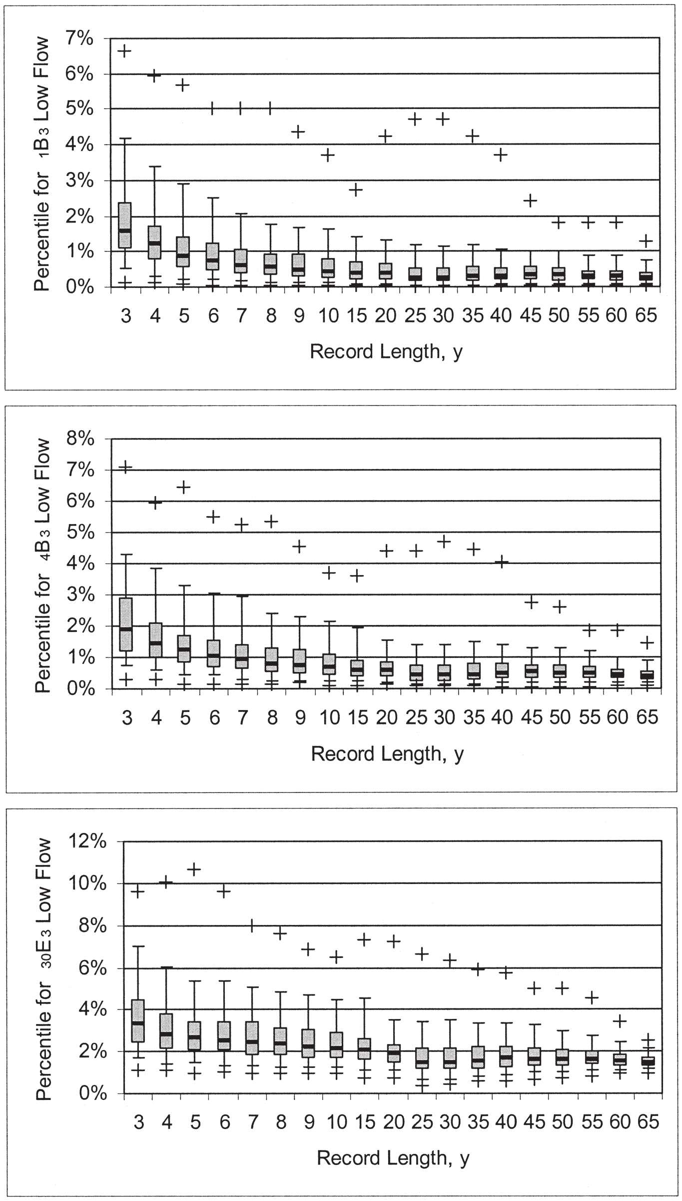


Figure 5. Effect of Record Length on Distributions of Low Flows, Expressed as Flow Percentiles, for the 176 Stations Included in the Study. Each distribution is composed of median flow percentiles from all of the stations. At each station, the median is determined from the set of percentiles corresponding to the low flow estimates.

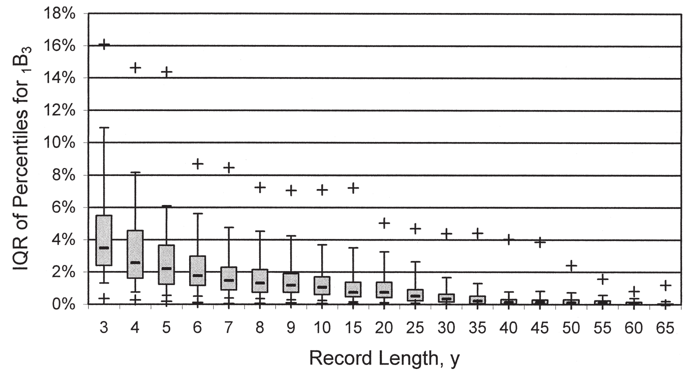


Figure 6. Effect of Record Length on the Variance (IQR) of $_1B_3$ Low Flow Estimates. Each distribution is based on the set of 176 stations. The IQR is calculated from flow percentiles.

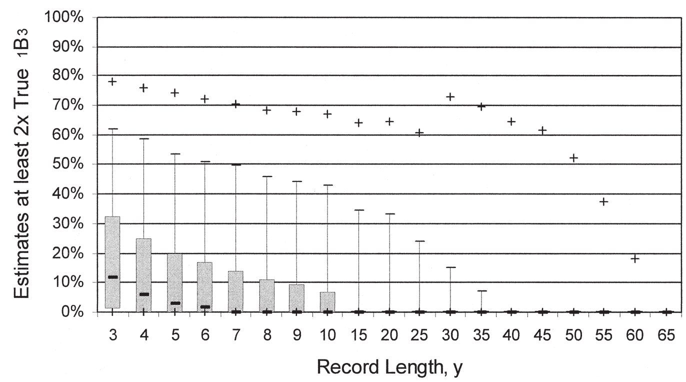


Figure 7. The Practical Importance of Bias and Uncertainty as a Function of Record Length. Each distribution, based on the set of 176 stations, shows the frequency with which $_1B_3$ estimates exceeds the true value by at least a factor of two.

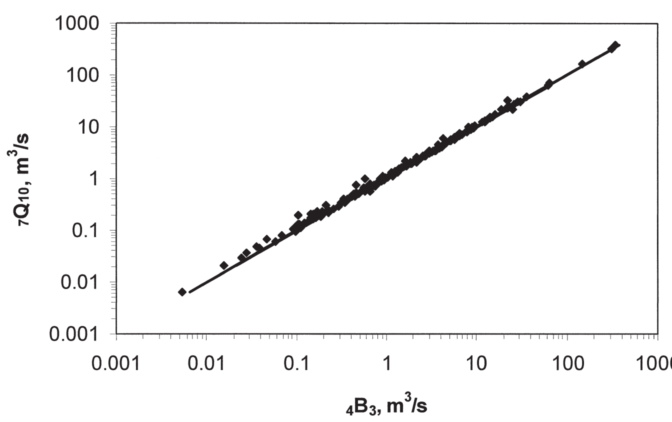


Figure 8. Comparison of Two Measures of Chronic Low Flows at the 176 Stations Used in the Study. Low flows were calculated from the full period of record. The line of equivalence is included for perspective.

The importance of bias and uncertainty remains a consideration even with record length set to 10 years. At about 40 percent of the stations, one or more of the low flow estimates derived from the 10-year records is more than twice the true value for that station. For the chronic low flows, when either measure shows an important bias, it is likely to be larger in the $_4B_3$ than in the $_7Q_{10}$ (52 of 70 stations). For the acute low flows, the importance of bias and uncertainty is about the same in the two measures.

DISCUSSION

Low flow conditions are determined by a suite of natural and anthropogenic factors (Smakhtin, 2001). Where anthropogenic factors play little or no role, variations in low flows are likely to be associated with variations in climate. By regulatory convention, WQBELs in NPDES permits are established by estimating regulatory low flows from the historical record of streamflow. The basis for estimating low flows is, therefore, of crucial importance for protection of water quality throughout the U.S.

Reliance on the historical record embeds a role for climate variability in the regulatory process. Longer periods of record are more likely to encompass a broad range of climate conditions in any region, but a long record may not be available. Consequently, it is important to understand, at least in a relative sense, how water quality protection can be compromised by inadequate representation of climate variability.

Water quality protection also might be undermined by trends in climate, such as global warming. Jacoby (1990) points out that climate change presents special problems for the present system of determining regulatory low flows because of the lag between the initiation of a trend and its appearance in the historical record that is used to estimate low flows. For the duration of a discharge permit (usually five years), however, the effect of a climate trend on streamflows is likely to be overshadowed by interannual variations in flow. In other words, the existing protocol avoids a reckoning with climate trends because it does not project far into the future. The same may not be true of capital improvements where the design and construction process may extend over a much longer period of time.

Each NPDES permit limit incorporates an implicit assumption that low flows estimated from the available record will provide adequate protection of designated uses in the future. When stations from across the U.S. are examined, it appears that a record length of 10 to 20 years is desirable if estimates of low flow are to provide a suitable approximation of the "true" value, which would be obtained if a record of sufficient length were examined. Shorter records capture too little of the range of climate variability.

Regional differences were noted concerning the relationship between bias and record length. Observations from other studies may provide helpful insights, although regional boundaries may differ some from those used in this study. Sites in the Columbia Basin region, for which bias was less than was typical for all sites together, tend to represent large drainages with relatively high runoff. The short term persistence (lag one serial correlation) of annual flows tends to be low for sites in this region (Vogel *et al.,* 1998), and base flows tend to correlate well with low flows (Reilly and Kroll, 2003). On the other hand, the two regions in the Mississippi Basin, which include a relatively small number of sites in a large and geographically diverse area, tend to have relatively high coefficients of variation for annual flows, and base flow correlations tend to perform poorly. The authors hesitate, however, to draw strong conclusions because the number of sites is small for several regions in this study. Clearly, there is room for additional work.

The problem with short records is not just the higher variance of the low flow estimates, which might be expected, but also a strong bias that increases the likelihood of overestimates. The practical effect of a higher value for a regulatory low flow is to increase the chance that the stream standard will be exceeded. The observed bias is more likely to threaten a designated use than it is to result in excessive treatment costs.

When at least 10 years of flow data are available, either low flow definition (biologically based or hydrologically based) can be used. The chronic low flows (${}_4B_3$ and ${}_7Q_{10}$) (Figure 8) are similar and the acute low flows (${}_1B_3$ and ${}_1Q_{10}$) are similar when medians are compared across all stations, and variances are comparable, too. The importance of bias and uncertainty (based on the frequency of estimates that are twice as large as the true value), on the other hand, tends to be higher for the chronic biologically based low flows.

When a record shorter than 10 years must be used, only the biologically based low flows are available. Flexibility in the definition of biologically based low flows makes it possible to estimate a low flow from a record as short as three years, but there is good reason to be cautious about producing such an estimate. When the available record is too short, and there is concern that analysis of the existing record would yield a low flow estimate with an unacceptable level of uncertainty or bias, alternative approaches could be applied. A number of options exist (see review by Smakhtin, 2001), the selection of which depends heavily on regional or local conditions. Most of these techniques were developed for ungaged streams, and virtually all effort has been devoted to the estimation of ${}_7Q_{10}$ (but see Martin and Ruhl, 1993).

The most common approach involves the prediction of a specific low flow measure, typically the ${}_7Q_{10}$, with regional regression equations. This approach has been used widely in the U.S. (e.g., Vogel and Kroll, 1992; Ries and Friesz, 2000). The predictive relationships use watershed characteristics, such as drainage area, and climate variables, such as annual precipitation, to explain variation in low flows calculated for sites in a particular geographic region. Careful selection of variables can improve performance of regional equations (Kroll *et al.,* 2004), but there is no general equation that can be applied throughout the U.S.

Base flow correlation may offer an improvement over regional regression where a suitable reference station is available (Reilly and Kroll, 2003). Base flow is a measure of low flow conditions, albeit not conditions of specific regulatory significance. Base flow can be estimated with a smaller data set than that necessary for calculating a regulatory low flow, however. If a correlation can be established with base flow at a nearby site, one at which regulatory low flows also can be calculated, it may provide an option for estimating regulatory low flows at the site with a short record. The approach assumes that the correlation between base flows is transferable to regulatory low flows (Reilly and Kroll, 2003).

An alternative to estimating low flow by regression or correlation relies on creation of a synthetic flow record. Where a time series of daily flows can be synthesized, any type of regulatory low flow, whether biologically based or hydrologically based, can be estimated. The daily flows can be generated with a rainfall/runoff model, provided that adequate attention is paid to performance under low flow conditions (Smakhtin *et al.,* 1998), or techniques of stochastic hydrology may be applied where a suitable reference gage exists (e.g., Holtschlag and Salehi, 1992; Xu *et al.,* 2002).

The connection between climate variability and water quality protection is not unexpected, but little effort has been made previously to characterize the risks incurred when climate variability is not considered adequately in the calculation of limits for pollutants regulated through NPDES discharge permits. It is not uncommon for the historical record of streamflows to be relatively brief. When only a short record is available, uncertainty and bias in low flow estimates increase the likelihood that designated uses will not be protected adequately. An understanding of the risks makes it possible to consider alternative measures for setting low flows.

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