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IMPLICATIONS OF CLIMATIC VARIABILITY FOR REGULATORY LOW FLOWS IN THE SOUTH PLATTE RIVER BASIN, COLORADO[1]

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ABSTRACT: The maximum concentration of a regulated substance that is allowed in a wastewater effluent usually is determined from the amount of dilution provided by the receiving water. Dilution flow is estimated from historical data by application of statistical criteria that define low flow conditions for regulatory purposes. Such use of historical data implies that the past is a good indicator of future conditions, at least for the duration of a discharge permit. Short records, however, introduce great uncertainty in the estimation of low flows because they are unlikely to capture events with recurrence frequencies of multiple years (e.g., ENSO events or droughts). We conducted an analysis of daily flows at several gages with long records in the South Platte River basin of Colorado. Low flows were calculated for successive time blocks of data (3-, 5-, 10-, and 20-years), and these were compared with low flows calculated for the entire period of record (> 70 years). In unregulated streams, time blocks of three or five years produce estimates of low flows that are highly variable and consistently greater than estimates derived from a longer period of record. Estimates of low flow from 10-year blocks, although more stable, differ from the long term estimates by as much as a factor of two because of climate variation. In addition, the hydrographs of most streams in Colorado have been influenced by dams, diversions, or water transfers. These alterations to the natural flow regime shorten the record that is useful for analysis, but also tend to increase the calculated low flows. The presence of an upward trend in low flows caused by water use represents an unanticipated risk because it fails to incorporate societal response to severe drought conditions. Thus, climate variability poses a significant risk for water quality both directly, because it may not be represented adequately in the short periods of the hydrologic record that are typically used in permits, and indirectly, through its potential to cause altered use of water during time of scarcity.
(KEY TERMS: stream discharge; climate variability; wastewater discharge; drought.)

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INTRODUCTION

The quality of surface waters in the United States and in many other countries is regulated by restrictions on the release of pollutants from point sources and nonpoint sources. For practical reasons, regulation of point sources is much better developed than regulation of nonpoint sources (Welch, 1996). Even so, the regulation of point sources involves numerous technical problems. Because the treatment of waste to a degree that would be compatible with all uses of water in the absence of any dilution is expensive and in some cases impractical or impossible, regulatory practice typically allows credit for dilution that can be anticipated at the point of discharge. Thus one of the most important problems related to the regulation of point source discharges is estimating the amount of dilution that will be available at a point of wastewater discharge.

The present analysis has two purposes. First, potential errors in the protection of water quality caused by effects of climate variability on hydrology are quantified for selected drainages in which extended gaging records are available and for which historical change in water use is not a complicating factor. Second, a similar analysis is done for drainages within which there have been large changes in water use over the historical record for flows. Attention is focused principally on the South Platte River basin of Colorado, which is located in a part of the United States where low flows are likely to be sensitive to climate change (Hurd *et al.*, 1999).

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In the United States, as required by the U.S. Clean Water Act, surface waters are classified according to their "beneficial uses." Standards then are adopted as necessary to protect these uses. Beneficial uses typically include, at a minimum, domestic water supply, agricultural water supply, recreation, and protection of aquatic life. Protection of aquatic life, which is very sensitive to water quality, has been responsible for more extensive changes in the treatment of wastewater than any of the other uses.

Protection of aquatic life is accomplished by water quality standards for specific substances, as well as some overriding requirements for absence of toxicity in the effluent as a whole. Standards typically are expressed in two forms based on duration of exposure: acute (limits on short term exposures, which may range from one hour or less to one day) and chronic (limits on concentrations averaged over intervals of a few days to as much as a month). In writing a discharge permit that will be consistent with either an acute or a chronic standard at a particular site, the regulatory authority typically restricts the concentration of each regulated substance in the effluent on the basis of: (1) the standard (environmental limit) for the substance as required for protection of aquatic life or other uses, and (2) the amount of dilution that is anticipated at the point of discharge. The dilution allowance for acute exposures or chronic exposures corresponds not to average conditions, but rather to extreme conditions. Because minimum dilution of the waste occurs when flow is low, the preparation of a discharge permit usually incorporates assumptions about anticipated low flows over both the acute and chronic averaging intervals.

The acute and chronic low flows that are incorporated into permits in the U.S. typically do not correspond to the absolute minima in the hydrologic record for a given site. Low flows for purposes of permitting are defined by statistical analysis of a hydrologic record. Low flows meeting the statistical criteria for regulatory purposes will be referred to here as "regulatory low flows."

Regulatory low flows can be defined on a hydrologic or biologic basis (USEPA, 1986). A common, hydrologically based low flow for permitting is the ${}_7Q_{10}$ (7-day, 10-year low flow) for chronic conditions and the ${}_1Q_{10}$ for acute conditions. These hydrologic thresholds have a precise statistical meaning, but are not explicitly connected to biological conditions in streams. In contrast, the calculation of a biologically based low flow is based on the capacity of aquatic communities to recover after exposure to stress (USEPA, 1986). Calculation of biologically based low flows typically is accomplished with U.S. Environmental Protection Agency (USEPA) supported software (DFLOW; Rossman, 1990).

A regulatory low flow (either biologically or hydrologically based) for a particular location is derived from analysis of historical flows at a point of discharge. Thus, the determination assumes that the historical record reflects without bias the range of hydrologic conditions that may occur over the life of the permit. Hydrologic records for specific sites often are short. Short records introduce great uncertainty in estimation of low flows and typically fail to capture extreme events with recurrence intervals of multiple years. For example, ENSO events, which may affect runoff, recur with a frequency of about four to six years and have a duration of one to two years (Hamlet and Lettenmaier, 1998), and would be poorly represented by hydrologic records of less than 25 years. Major droughts are less frequent and less regular than ENSO events, and thus can be accounted for only with even longer records. In Colorado, for example, there were five significant droughts during the 20th Century (McKee *et al.,* 1999). In addition to variation associated with climate, historical flows may exhibit secular trends associated with water development (e.g., dams, diversions, water transfers, etc.), that have important implications for use of the historical record.

Uncertainty or bias in the calculation of low flows can lead to errors in preparation of permits for point-source discharges of wastewater. Overestimating regulatory low flows would lead to unacceptable impairment of water quality, and underestimating them could result in unnecessary investments in treatment. At issue is the extent to which the range of variability in stream flow can be captured by analysis of flows in a given period of record. Furthermore, a better understanding of natural variation in low flows can establish a proper context for assessing concerns about the response of low flows to climate change (Eheart *et al.,* 1999).

HYDROLOGIC CONTEXT AND METHODS

The present analysis focuses on the South Platte River basin, where hundreds of wastewater permits, each incorporating estimates of regulatory low flow at a given point in the drainage network, are in force. Moisture from the Pacific reaches the South Platte River basin primarily in the winter months when frontal systems deposit snow in the mountains (McKee *et al.,* 1999; Paulson *et al.,* 1991), but some of this moisture crosses the Continental Divide before being deposited in the South Platte River basin. The weak connection between conditions in the Pacific and the precipitation from frontal systems that cross the

Divide is evident in high variability of winter precipitation in Colorado (Changnon *et al.*, 1991) and is reflected in the absence of strong correlations between precipitation and standard indices of synoptic climate variation such as Southern Oscillation Index (SOI) and Pacific North American Index (PNA) (Redmond and Koch, 1991). Winter precipitation in the South Platte River basin is augmented by storms moving from the east; these tend to deposit maximum precipitation on the plains and in the Front Range (McKee *et al.*, 1999). Moisture from the Gulf of Mexico moves through eastern Colorado primarily in the spring (March through June), which is the wettest time of year for the Front Range (McKee *et al.*, 1999), and is followed in the summer (July through August) by convective storms that are the most important source of precipitation for the plains.

Hydrographs in the South Platte River basin are dominated by melt of snowpack, but are only weakly predictable from precipitation because the fate of snowmelt is difficult to model (Clark *et al.*, 2002). The present analysis emphasizes observed hydrographs, reflecting the work of a practicing water-quality regulatory program, rather than predictions based on synoptic climate modeling or precipitation sources.

In Colorado, the median period of continuous daily operation for extant and discontinued gages is 9 to10 years (N = 1,220) (calculated from Water Resources Data for Colorado) (USGS 2001a, b). Daily records at a few gages in Colorado span much longer periods; these provide a basis for assessing the reliability of low flows computed from shorter periods of record. Gaging stations for the present analysis (Table 1) are all for the South Platte River basin (Figure 1) except for one on the Yampa River in northwestern Colorado, which is included because the Yampa is the largest river in the state with essentially natural flows. Daily flows for all stations were obtained from the USGS National Water Information System (NWIS) web site (http:// waterdata.usgs.gov/co/nwis). For each station, the amount of storage capacity upstream was estimated from "normal capacity" of reservoirs, as listed in Ruddy and Hitt (1990). Some stations on the South Platte drainage also are affected by flows imported from watersheds west of the Continental Divide. The two largest sources of transbasin water are the Roberts Tunnel, which delivers water from Lake Dillon to the upper South Platte, and the Adams Tunnel, which delivers water from Grand Lake to the Big Thompson basin (Figure 1). Water from the Adams Tunnel is subsequently distributed from the Big Thompson to other Front Range streams, including the Cache la Poudre and the St. Vrain.

Biologically based low flows were calculated with EPA's DFLOW program (Rossman, 1990). The average number of years between flows lower than the regulatory low flow (excursions) was set to three, as is typical for regulatory purposes. The program screens not only for isolated episodes of low flow but also for clusters of low flows, as might occur in a drought year. The length of the clustering period was set to 120 days. Excursions in excess of five in one clustering period were not counted because aquatic communities are assumed by the DFLOW algorithm to experience little incremental damage from multiple excursions beyond a specific threshold (in this case five) within a clustering interval. The assumptions concerning excursions are the norm for analysis of flows that are used in preparing wastewater discharge permits in Colorado (CDPHE, 2001). Acute conditions are quantified on the basis of daily average flows. Acute conditions are of greatest interest because they are much more likely than chronic conditions to be associated with mortality of aquatic life. Thus, the present analysis deals only with the regulatory acute low flows.

Regulatory acute low flows were calculated for 10-year blocks of calendar year data beginning in 1925 (or earliest record after 1925) and advancing one year at a time up to 1998. The analysis thus includes all data through water year 1998, the latest for which data were readily available. This procedure yields a maximum of 65 values, each for a different 10-year block, for acute low flows at each station. In addition, regulatory acute low flows were calculated for the entire period of record starting with 1925 at each station. Record lengths of 3, 5, and 20 years also were used for the unregulated streams. Because there is a large range among stations in the magnitude of low flows, flow ratios were used to make comparisons among stations.

RESULTS

As indicated above, regulatory acute low flows can be computed from algorithms that are either biologically based or hydrologically-based ($_1Q_{10}$). Although they are calculated differently, the two types of estimates differ little (Figure 2). Therefore, results are given here only for biologically based low flows; conclusions will be applicable to hydrologically based low flows as well because of the close correlation between the two.

Streams Not Affected by Water Management

Few streams in the South Platte River basin are unregulated, and only two of these have long flow records: Middle Boulder Creek and Bear Creek at

TABLE 1. List of Gaging Stations Included in This Analysis.

Location	Gage No.	Area (mi²)	Median Flow (cfs)	Upstream Storage (10^3 af)	Transbasin Flow Source
South Platte Below Cheesman	06701500	1,752	97	322	–
South Platte at Denver	06714000	3,861	191	396	Roberts
South Platte at Henderson	06720500	4,713	340	446	Roberts
South Platte Near Kersey	06754000	9,598	772	1,220	Roberts, Adams
South Platte at Julesburg	06764000	23,193	232	1,584	Roberts, Adams
Poudre at Canyon Mouth	06752000	1,056	90	38	–
Poudre Near Greeley	06752500	1,877	77	307	Adams
Bear Near Morrison	06710500	164	26	0	–
Bear at Sheridan	06711500	260	17	2	–
Middle Boulder	06725500	36	16	0	–
South Boulder	06729500	109	17	41	–
Boulder at Orodell	06727000	102	42	12	–
St Vrain at Lyons	06724000	212	34	0	–
St Vrain at Mouth	06731000	976	135	122	Adams
Yampa	09251000	3,410	402	57	–

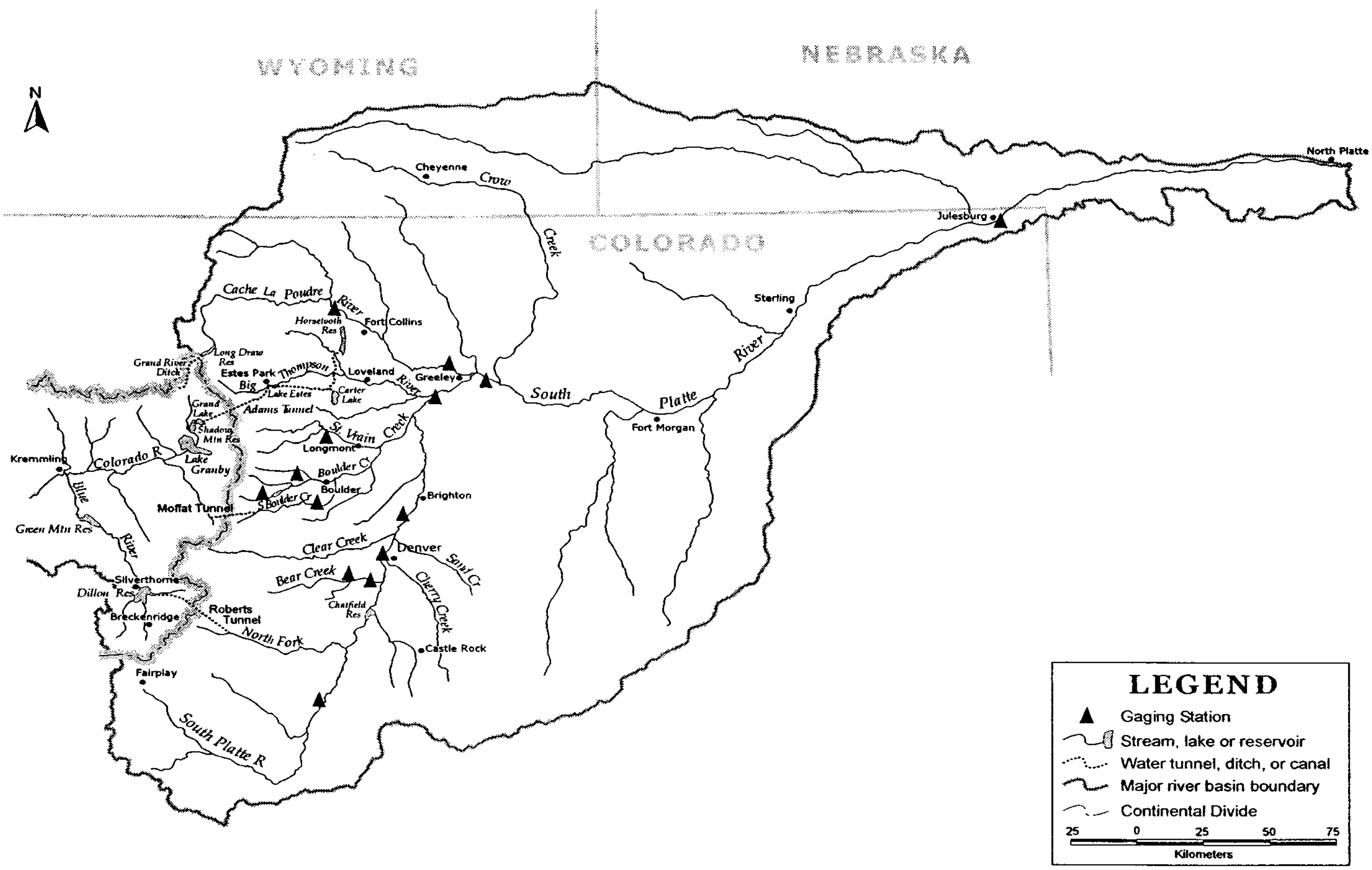

Figure 1. Map of the South Platte Basin Showing Locations of Gaging Stations Included in This Study.

Morrison. Bear Creek, although unregulated above Morrison, shows evidence of incremental growth in low flow due to wastewater discharge, and therefore was eliminated from the analysis of unregulated streams. The hydrographs of Middle Boulder Creek and the Yampa River, which has little regulation relative to basin size but lies outside the South Platte drainage, show the expected domination of the hydrograph by spring snow melt and an extended period of base flow (Figure 3). Seasonality in flows is strong; it appears in the hydrologic record even in years of extreme low flows.

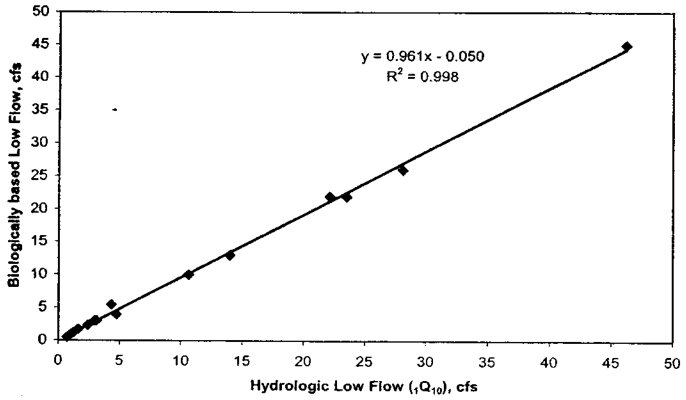

Figure 2. Relationship Between Biologically Based and Hydrologically Based ($_1Q_{10}$) Low Flows for All Stations Shown in Table 1. Each point is based on the full record at each site.

Colorado experienced four major droughts (1931 to 1941, 1951 to 1957, 1963 to 1965, and 1975 to 1978) (McKee *et al.*, 1999) over the period of record for Middle Boulder Creek and the Yampa River. The severity of each drought, and thus its effect on stream flows, varied among drainage basins. Annual flows in Middle Boulder Creek and the Yampa River illustrate local variation in the effects of major droughts (Figure 4).

Record length has a large effect on estimates of regulatory low flows, as shown by Figure 5, which gives the low flow value from the DFLOW algorithm for Middle Boulder Creek over 3-, 5-, and 10-year periods of record (see methods section for details). Annual minima and regulatory low flows estimated from short records (3- and 5-years) show a wide range of values and the medians differ significantly from the acute low flow based on the entire record (Wilcoxon signed ranks test; $p < 0.01$). About 75 percent of the regulatory low flows from three-year blocks are larger than the regulatory low flow based on the entire record. As record length increases, the range of values decreases and the median converges on the regulatory low flow for the entire record. Convergence occurs when record length reaches about 10 years. Thus, Figure 5 illustrates the consequences of standard permitting practice, which often is limited to consideration periods of record below 10 years. Even with a record length of 10 years, there is considerable variation

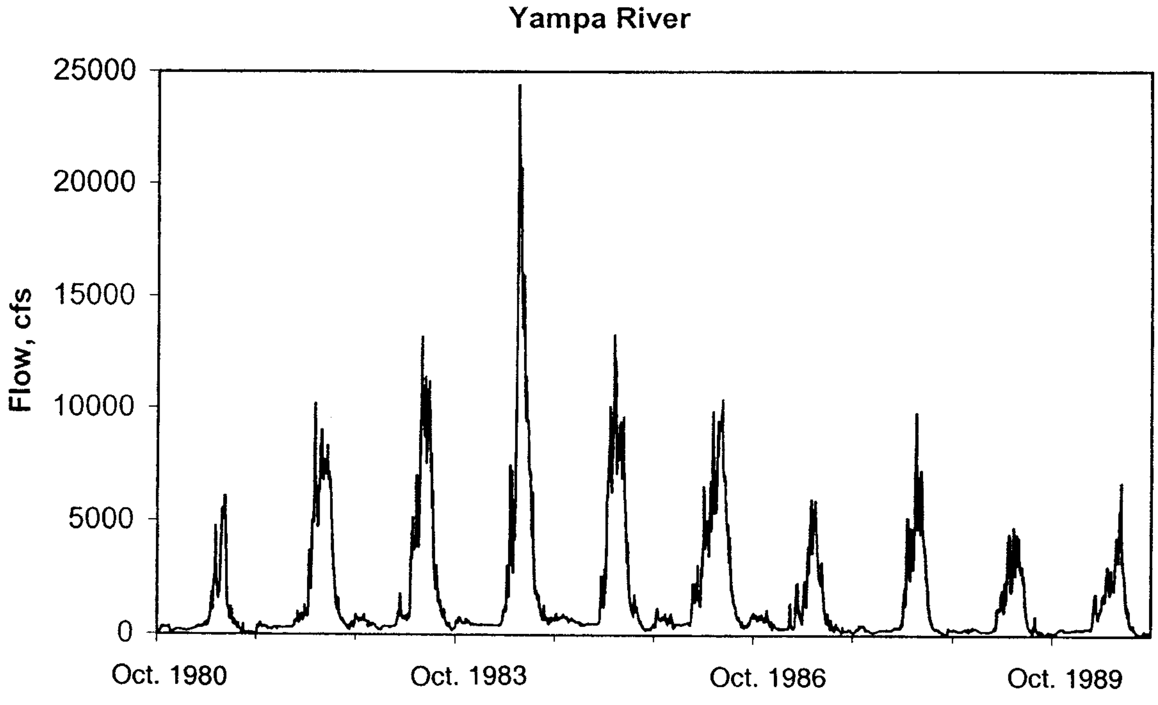

Figure 3. Daily Flows in the Yampa River for a Period Beginning January 1, 1979. Annual peaks are produced by snowmelt for the decade beginning October 1, 1980.

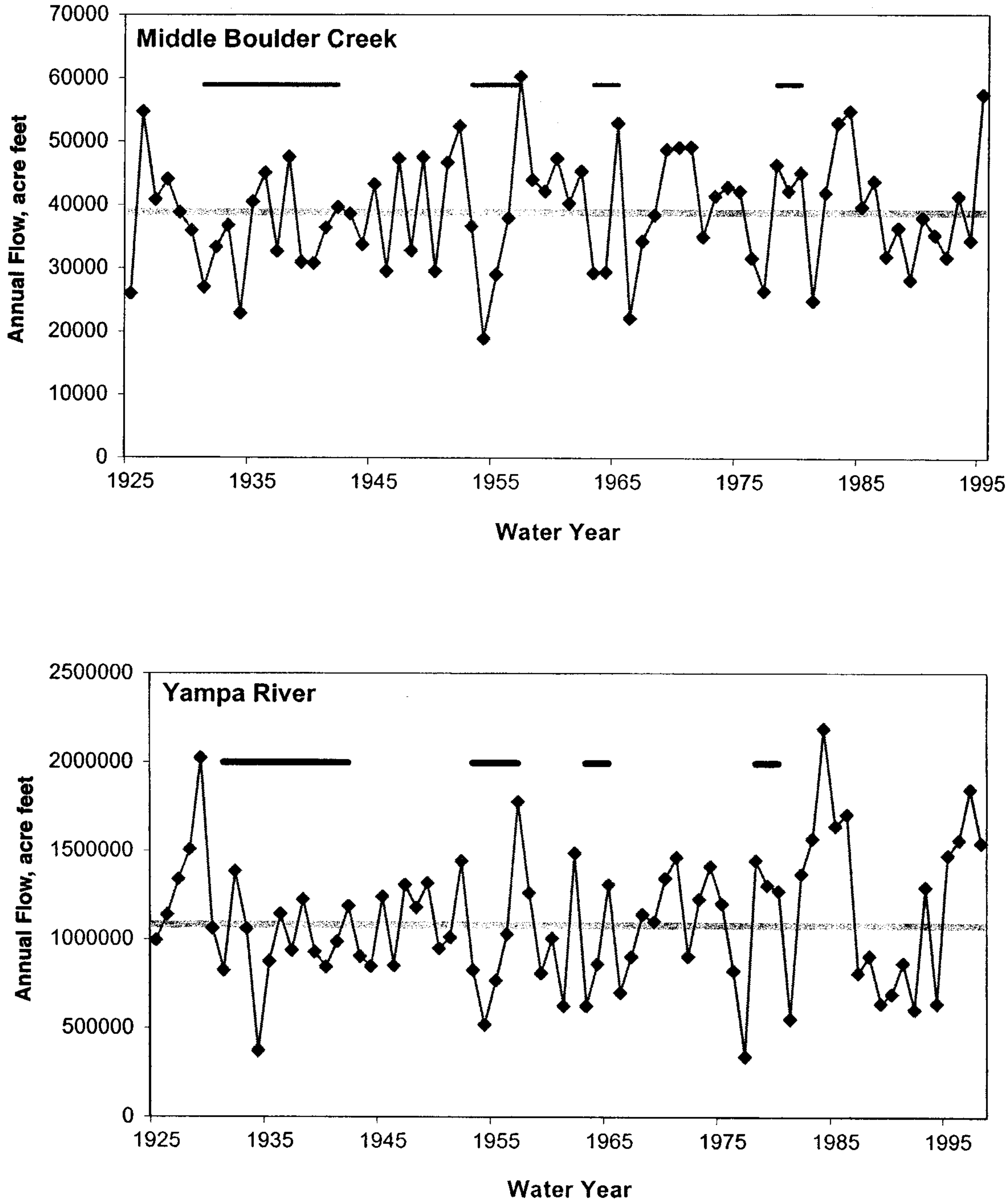

Figure 4. Annual Flows in the Middle Boulder Creek for Water Years 1925 to 1995 (upper panel), and Yampa River for Water Years 1925 to 1998 (lower panel). The median for the period of record is indicated with a solid horizontal line. The duration of each statewide drought is indicated by short horizontal bars.

around the median, as shown in Figure 6 for both Middle Boulder Creek and the Yampa (the ratio of the 10-year regulatory low flow to the long term regulatory low flow usually falls between 0.5 and 2.0).

For unregulated streams, calculations based on successive 10-year blocks often yield the same regulatory low flows for as much as a decade (e.g., Figure 6). Persistence of regulatory low flows from one 10-year block to the next is explained by the strong influence of specific episodes of low flow. For example, extreme low flow in the Yampa River during August 1934 affected the calculation of biologically based low flows for 10 successive 10-year blocks (those ending in years 1934 to 1943).

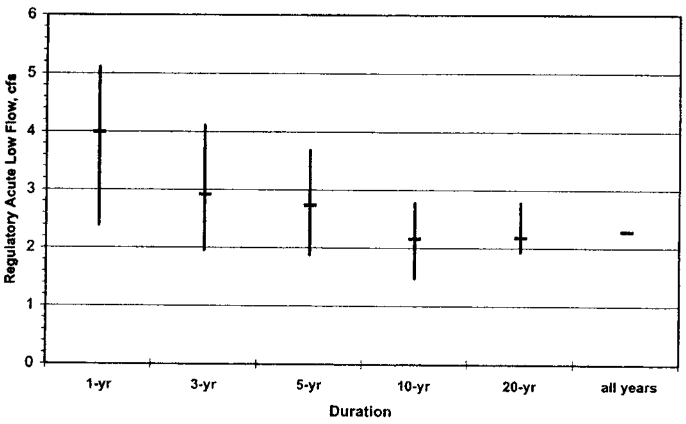

Figure 5. Influence of Record Length on Regulatory Low Flow Estimates for Middle Boulder Creek. Each vertical bar spans a range encompassing the central 80 percent of values. Each horizontal dash represents the median of regulatory low flows, as computed from the DFLOW algorithm.

Subsampling of long records quantifies the level of protection associated with estimates of low flow derived from short records (3, 5, or 10 years). Because the period of record is almost 74 years for the Yampa River, low flows can be calculated for each of 65 successive 10-year blocks, 70 successive 5-year blocks, and 72 successive 3-year blocks. The record for Middle Boulder Creek is shorter by three years, and therefore yields three fewer estimates in each category. Table 2 summarizes the results of subsampling; results are expressed as percent of trials showing higher estimates of low flow than the full record. The expected value of all percentages in Table 2 is 50 percent (i.e., if a short record is representative of the full record, about half of the estimates of low flow from the short record should be higher than for the full record, and about half should be lower). Strong deviation from 50 percent is evidence of bias caused by use of short records. For records of 3- and 5-year length, there is substantial positive bias (i.e., the long term regulatory low flow is most often overestimated. For 10-year records, the opposite is true.

The 5-year duration of a discharge permit is the focus of an additional analysis. Daily flows for random 5-year blocks were compared with regulatory low flows from the full data set. Every 5-year record would have one or two excursions if expected excursions (one per three years) were evenly distributed over time. Excursions (flows below the regulatory low flow) tend to be clustered, however (Table 2). In each of the unregulated streams, two or more excursions would have occurred in about 40 percent of the randomly chosen 5-year blocks tested with the regulatory low flow for the full data set (Table 3). The same kind

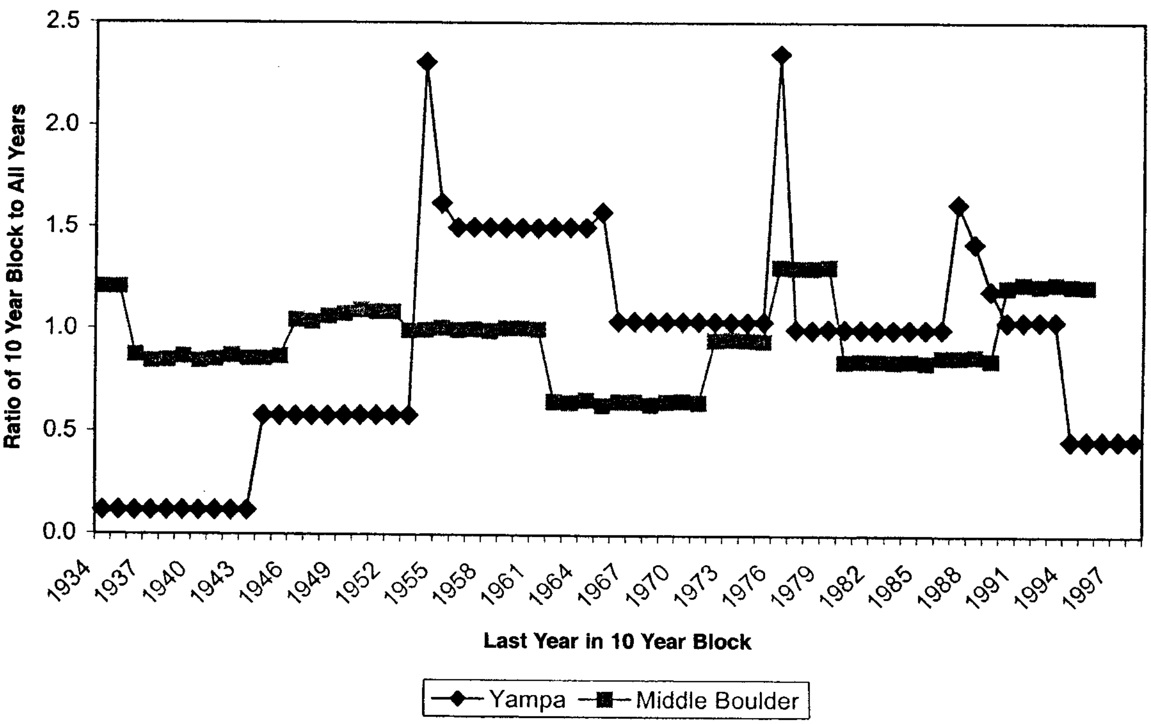

Figure 6. Regulatory Low Flows for the Yampa River and Middle Boulder Creek. Each point represents a calculation based on the previous 10 years of daily flow data. Flows are expressed as the ratio of the regulatory low flow for 10-year records to the regulatory low flow for the full period of record (1925 to1998).

TABLE 2. Number (N) and Frequency of Excursions (flows below the acute biologically based low flow) Expected When Acute Low Flows Are Derived From the Full Data Record or From All Possible Records of 3-, 5-, or 10-Year Length.

	Yampa	Middle Boulder Creek
Record Length (years)	74	71
Analysis of the Full Record		
Observed Excursions (N)	104	64
Excursions in Clusters (N)	96	55
Years With Clusters (N)	3	3
Excursions Not in Clusters (N)	8	9
Excursions Counted (N)*	23	24
Allowable Excursions (N)**	25	24
Analysis of Short Records: Percent of Trials With More Daily Excursions than for the Full Record***		
Three-Year Records	74	77
Five-Year Records	57	64
Ten-Year Records	46	31
Analysis of Short Records: Percent of Trials With More Clustered Excursions Than for the Full Record***		
Three-Year Records	74	70
Five-Year Records	57	58
Ten-Year Records	25	27

*Excursions exceeding five within clusters are not counted (see text for explanation).
**Number of excursions allowed by regulatory convention for protection of aquatic life.
***The expected value is 50 percent if short records are representative of the full record.

of evaluation was performed systematically for the regulatory acute low flow calculated from the 3-, 5-, or 10-years immediately prior to the start of a five-year permit interval. The frequency of five-year permit intervals with excursions was similar for the full record and for 10-year records, but not when acute low flows were calculated from 5- or 3-year records. In other words, standards are substantially more likely to be violated if regulatory low flows are calculated from a 3- or 5-year record than for a 10-year record.

Streams Affected by Water Management

The flows recorded at sites other than Middle Boulder Creek and the Yampa River are affected to varying degrees by hydrologic regulation in the form of dams, diversions, importation of transbasin water, and conversion of water rights to municipal use. Furthermore, the amount of regulation has changed over time in most cases. The flow of Bear Creek at Sheridan is an example of the effect of a dam on low flows (Figure 7). In 1979, Bear Creek Reservoir began regulating flows for flood control and recreation (Ruddy and Hitt, 1990). After closure of the dam, regulatory acute low flows downstream increased from 0.4 cfs to 4.8 cfs. Impoundment did not show its full effect on regulatory low flows calculated with 10-year blocks until 1989, which was the first year in which no pre-impoundment flows influenced calculations. A period of transition (1979 to 1988), during which low flow calculations were based on a mix of pre- and post-impoundment flows, is evident in Figure 7.

TABLE 3. Frequency of Excursions (flows less than the regulatory low flow) During a Five-Year Permit Interval When the Acute Regulatory Low Flow is Calculated From the Full Record and From the Preceding 10-, 5-, or 3-Year Record.

	Yampa	Middle Boulder Creek
Full Record		
Permit Interval With at Least Two Excursions (percent)	44	38
Permit Interval With at Least 15 Excursions (percent)	22	9
Ten-Year Record (immediately preceding)		
Permit Interval With at Least Two Excursions (percent)	37	30
Permit Interval With at Least 15 Excursions (percent)	23	11
Five-Year Record (immediately preceding)		
Permit Interval With at Least Two Excursions (percent)	59	39
Permit Interval With at Least 15 Excursions (percent)	57	34
Three-Year Record (immediately preceding)		
Permit Interval With at Least Two Excursions (percent)	70	53
Permit Interval With at Least 15 Excursions (percent)	67	47

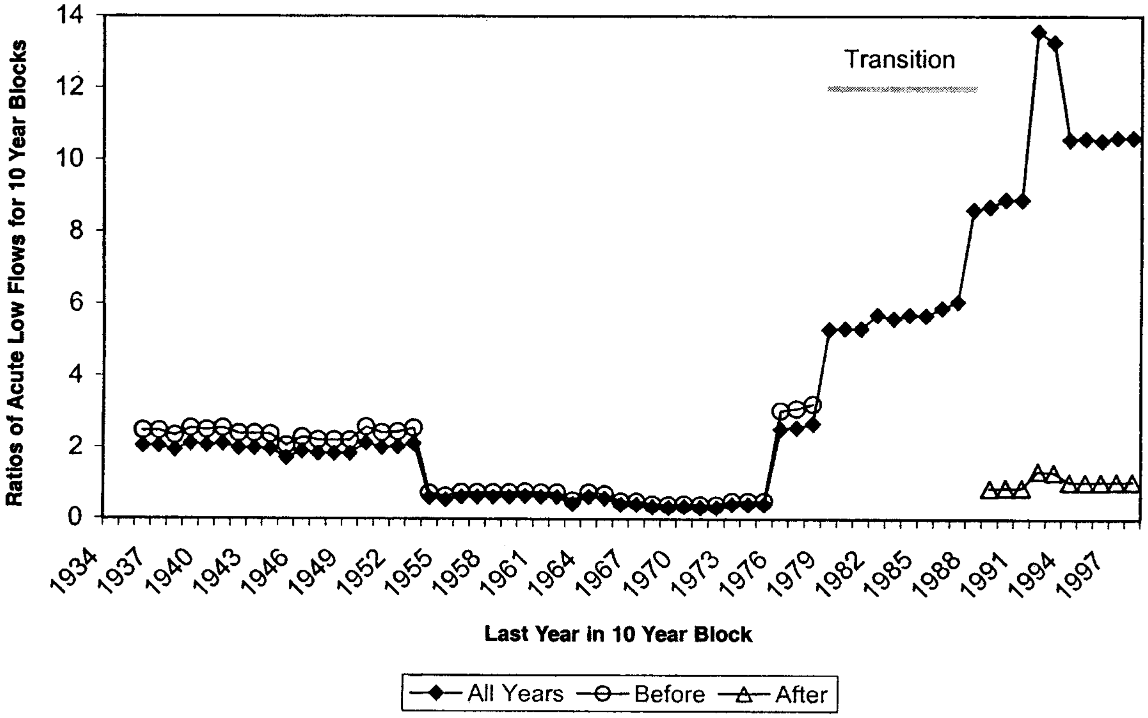

Figure 7. Regulatory Low Flows for Bear Creek Expressed as the Ratio of the Low Flow for Successive 10-Year Records to the Regulatory Low Flow for the Full Period of Record (1925 to 1998) and for 10-Year Records Not Including the Influence of the Dam ("before") and Restricted to Post-Dam Conditions ("after"). The record for the Sheridan gage is influenced by construction of a reservoir upstream of the gage that was completed in 1979. Separate lines indicate ratios calculated on the basis of flows observed before and after completion of the reservoir.

Importation of transbasin water has been a part of the water economy of the South Platte River basin for more than a century. The amount of imported water increased greatly, however, in the mid-1950s after completion of the Colorado-Big Thompson (CBT) project, which brings water from storage in the upper Colorado River basin, through the Adams Tunnel, to Marys Lake in the Big Thompson River drainage (Figure 1). About half of the water is allocated to the Cache la Poudre basin, but flows in the Big Thompson and St. Vrain drainages are also augmented with CBT water (Tyler, 1992). The effect of adding CBT water to the Cache la Poudre basin is evident at the Greeley gage, where acute biologically based low flows have increased to two to three times the long term mean (Figure 8). The transition period for calculating low flows extends from 1954 to 1963 (S. Gerlek, 1977, Water Supplies of the South Platte River Basin, unpublished M.S. Thesis, Colorado State University, Fort Collins, Colorado). Although water began to flow with dedication of the Adams Tunnel in 1947, deliveries were small until Horsetooth Reservoir was completed in 1951. Deliveries expanded rapidly as additional storage was added to the South Platte River basin through 1953; 1954 was the first year in which the full effects of the CBT project were registered at the Greeley gage.

One more example of conspicuous trends for low flows in the South Platte basin involves the South Platte at Henderson. The gage at this location is about 17 miles downstream of the gage at Denver, but between the gages little has changed with respect to water management except for relocation of the outfall for a major wastewater treatment plant. The change in location placed the outfall downstream of the Burlington Canal, which is one of the largest diversions along the South Platte. Following the relocation of the outfall, and the addition of capacity at the wastewater treatment plant, acute low flows in the South Platte at Henderson increased to more than five times the long term mean (Figure 9).

Stations at the downstream end of the system (i.e., Kersey and Julesburg on the South Platte) reflect the aggregate effects of the various water management practices upstream. At the Kersey gage, there has been a trend toward increasing low flows (Figure 9), but the trend is muted in comparison to those of Bear Creek and the Cache la Poudre. Further downstream, at the Julesburg gage, there has been no trend (Figure 9).

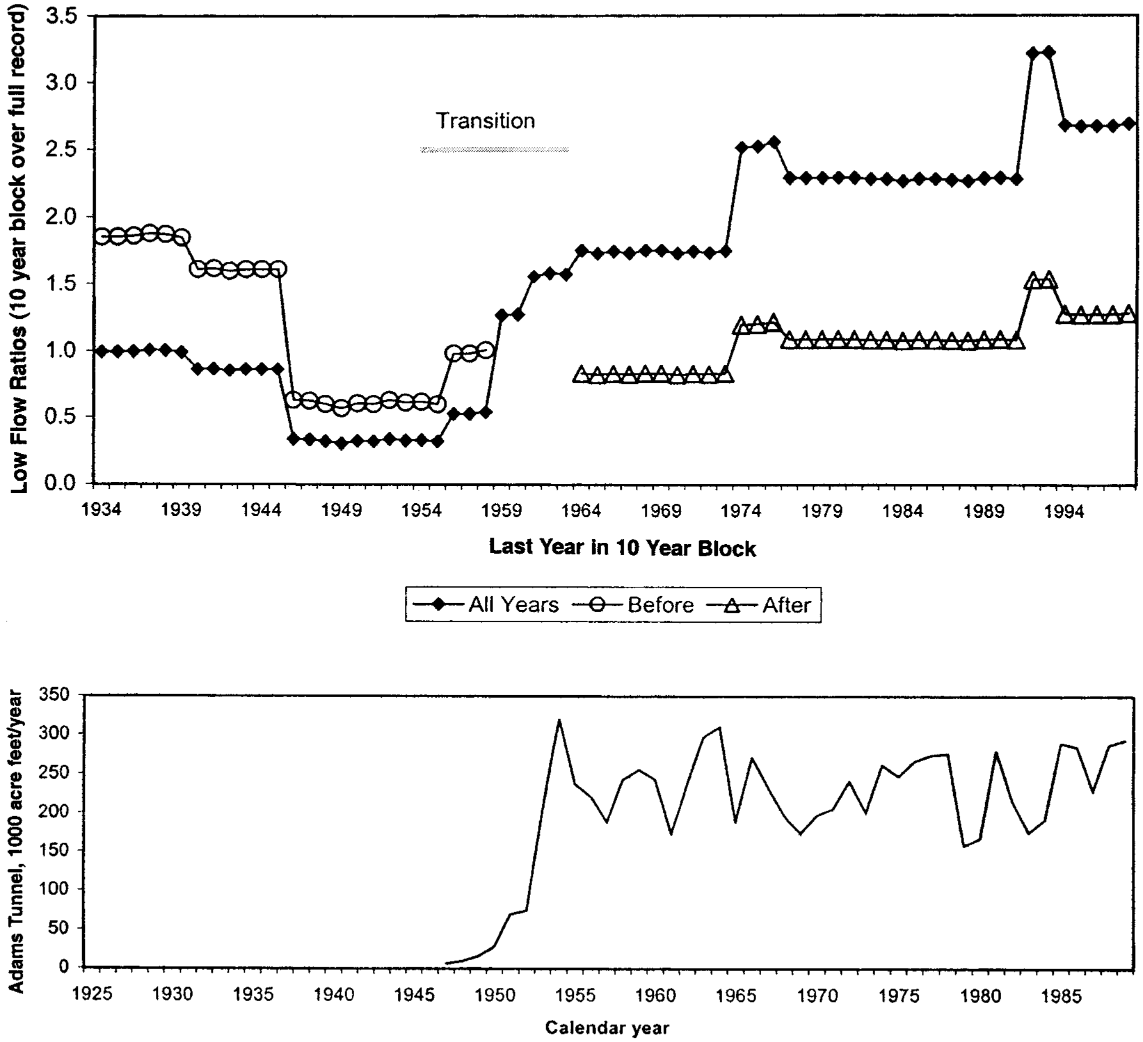

Figure 8. The Upper Panel Shows Regulatory Low Flows for the Cache La Poudre River at the Canyon Gage and at Greeley Expressed as the Ratio of the Regulatory Low Flow for Successive 10-Year Records to the Regulatory Low Flow for the Full Period of Record (1925 to 1998) and for 10-Year Records not Including the Influence of the Dam ("before") and Restricted to Post-Dam Conditions ("after"). The lower panel shows calendar year deliveries of CBT water through the Adams Tunnel. Years shown on the lower panel correspond to first year of each 10-year block shown in the upper panel.

Comparative Variability of Low Flow Estimates From 10-Year Records

Table 4 gives an overview of low flows and their variability; the stations are sorted on the basis of variance in the ratio of regulatory acute low flows for 10-year records to the regulatory acute low flow for the entire period of record. Variance was calculated against a mean of 1, which would be the expected mean in the absence of any trend. High values for variance indicate the presence of a strong trend (e.g., construction of Bear Creek Reservoir). The ratios are not related to the size of the regulatory low flows. Streams with natural flow regimes generally fall at the low end of the variance spectrum, but the lowest variance is for the South Platte at Julesburg, which is at the downstream end of a highly managed river system.

DISCUSSION

Historical variability of stream flows in the South Platte River basin raises concerns about the extent to which regulatory low flows derived from a short hydrologic record (as is typical for most water quality related analyses) will be protective of water quality.

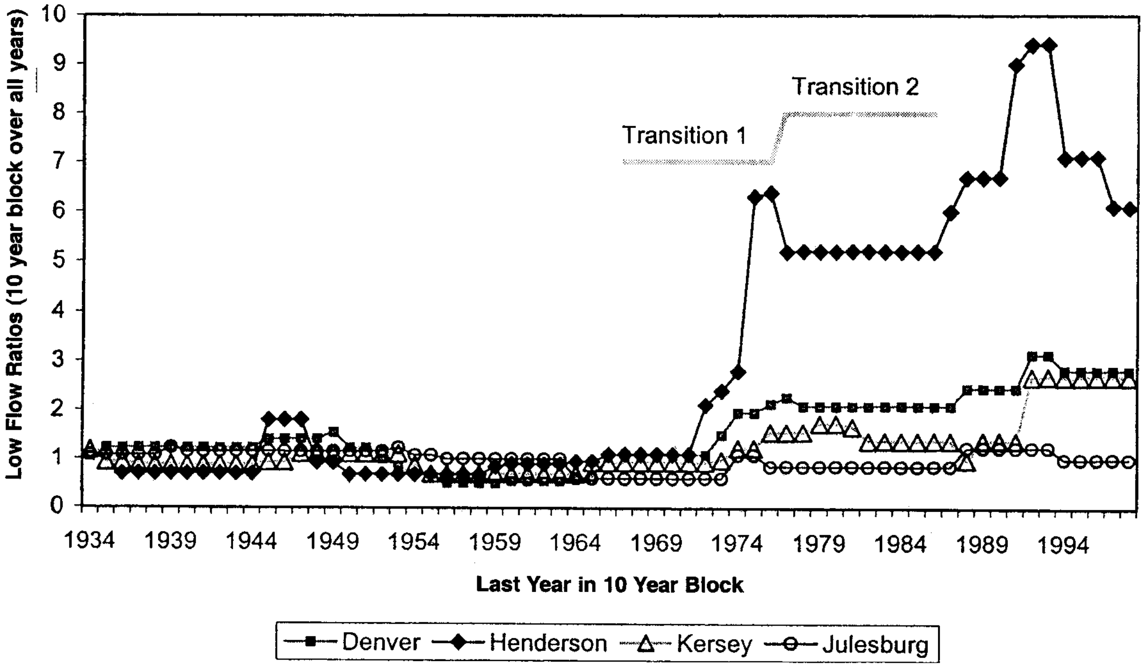

Figure 9. Regulatory Low Flows for Four Gages Expressed as the Ratio of the Regulatory Low FLows for 10-Year Records to the Regulatory Low Flows for the Full Period of Record (1925 to 1998) on the South Platte River (see Figure 1 for locations).

Table 4. Regulatory Acute Low Flows at Stations That Were Included in the Analysis, as Calculated With the Full Period of Record (typically 1925 to 1998). Variance was calculated for ratios of all 10-year records to the regulatory low flow for the entire record. Sites have been sorted on the basis of the variance ratio for regulatory acute low flows.

Location	Low Flow (cfs)	Variance of Ratio	Management Influences
Bear at Sheridan	0.47	19.62	Reservoir
South Platte at Henderson	9.97	11.73	Reservoirs, Wastewater
South Platte Below Cheesman	3.89	4.57	Reservoirs
St Vrain at Lyons	0.79	2.62	Mixed
Poudre Near Greeley	2.97	1.04	Reservoirs, Transbasin
Bear Near Morrison	2.95	0.90	Mixed
South Platte at Denver	21.96	0.85	Reservoirs
South Boulder	1.10	0.76	Reservoirs
St Vrain at Mouth	21.91	0.59	Reservoirs, Transbasin
South Platte Near Kersey	44.99	0.38	Reservoirs, Transbasin
Yampa	25.96	0.28	None
Boulder at Orodell	1.68	0.23	Reservoirs
Middle Boulder	2.29	0.09	None
Poudre at Canyon Mouth	5.39	0.05	Reservoirs
South Platte at Julesburg	12.95	0.04	Reservoirs, Transbasin

In basins with natural flow regimes, regulatory low flows show no trends over the 75 years examined in this analysis. The range of variation increases when record length is shortened to five or three years. In these watersheds, a record length of at least 10 years is necessary for convergence of estimated regulatory low flows on the long term value. Regulatory low flows defined on the basis of a record shorter than 10 years show bias that increases the likelihood of damage to aquatic life and other uses. Even with a 10-

year record, expected variation is large and may differ by a factor of two from the low flow for the full period of record. As a practical matter, however, a record length of 10 years captures much of the influence of climate variability that can be observed in a much longer (i.e., 70-year) record.

Directly relevant to permitting is the likelihood that regulatory acute low flows calculated from a short record will remain protective of water quality for the duration of a permit (typically 5 years). The chance of having excursions during the 5-year period immediately following a 10-year record used to derive regulatory low flows is about the same as for a randomly chosen 5-year period to which is applied the low flow derived from the full data set, but the probability for damage to aquatic life is significantly higher when a record of less than 10 years is used to derive low flows.

Natural variability in stream flows is altered by water management. The effect of water management on the South Platte has been to increase low flows at most gaging stations below the headwaters. This is evident at all stations on the South Platte main stem except Julesburg, where there has been no detectable increase in regulatory low flows since 1925, despite a five-fold increase in storage capacity and importation of more than 200,000 acre feet/year of transbasin water from the CBT project to the basin. The variability in low flows at Julesburg is even less than that of unregulated streams. A likely explanation lies in the spatial relationships between sources and destinations of water. Much of the water that is stored in reservoirs or imported from other basins is used for irrigation. When a gage lies between the source and the destination, an increase in low flows is expected as water use increases. In the case of Julesburg, all sources and almost all destinations are upstream. The distribution of water is so efficient that there has been no detectable increase in the low flows at the downstream end of the system, despite added flows from transbasin sources.

Water development appears to have been advantageous in the sense that it has increased dilution flows in many parts of the South Platte River basin. There may be an unanticipated risk, however, when facilities are designed with great reliance on the availability of dilution flow that can be traced to water management. The risk arises from the assumption that water management practices will remain constant during intervals of extreme climatic conditions. Water conservation during a drought may affect return flows that would ordinarily help sustain low flows downstream. The result would be a reduction in flows available for dilution and a higher probability that water quality standards would be violated.

A serious drought has not occurred in the South Platte basin since the 1970s. A contemporary analysis of low flows in the South Platte River basin for permitting purposes probably would not include drought years because a sufficient period of record is not available or because there are legitimate concerns about the relevance of records antedating current water management. The present basis for permitting of wastewater discharge is subject to uncertainty that can be reduced through a greater understanding of relationships among water management, climate variability, and low flows.

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