Hydrologic Alteration and its Ecological Effects in the Henry's Fork Watershed Upstream of St. Anthony

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*Abstract.—*Stream flow in the Henry's Fork watershed is altered by three storage reservoirs and numerous diversions. We assessed hydrologic alteration and its ecological consequences on the main stem Henry's Fork upstream of St. Anthony and on the entire length of its largest tributary, Fall River, over water years 1972 through 2002. We divided the study streams into 10 reaches based on the location of reservoirs, major diversions, return flow, and unregulated tributaries. Hydrologic conditions in each reach were represented by one of the 10 stream gage stations currently operating in the watershed. We calculated natural flow by adding upstream change in storage, diversions, and reservoir evaporation to regulated flow. We then compared regulated and natural flow using the Indicators of Hydrologic Alteration methodology and the percent deviation of regulated daily flow from natural. We defined annual alteration as the water-year mean of the absolute value of daily alterations and watershed-averaged alteration as the mean of annual alteration over all stream reaches, weighted by reach length. The degree of alteration was assessed by determining deviations from median natural flow that fell within observed ranges of natural flow. Regulation at all three storage reservoirs resulted in lower winter flows and higher late season flows downstream than under natural conditions. These effects were greatest in Henry's Lake Outlet, where winter flows were often less than 20% of natural and late summer flows could be two orders of magnitude greater than natural. Unregulated inflow from groundwater-dominated tributaries moderated the effect of alteration due to Henry's Lake and Island Park dams with distance downstream. Flows in the lowest reach of Fall River and the Henry's Fork below Fall River were affected primarily by irrigation diversion, which resulted in low late summer flows but not in substantial alteration of peak flow characteristics and overall hydrograph shape. A short reach of Fall River affected by the Marysville hydroelectric plant diversion experienced significantly decreased flows throughout the water year. Average annual alterations ranged from less than 10% on most of Fall River and in the Henry's Fork upstream of Island Park Reservoir to 100% on Henry's Lake Outlet. Natural range of variability in the watershed averaged about 25% during the winter, 65% during early summer, and 40% during late summer. Based on these observed ranges of variability in natural flow, we determined that alteration was extreme in Henry's Lake Outlet and high between Island Park Dam and the Buffalo River and in the Marysville power plant reach. Alteration was moderate between the Buffalo and Warm rivers and below Fall River and low everywhere else. Alteration in most reaches and in the watershed as a whole was a decreasing function of annual watershed discharge. Watershed-average alteration was low in 14 of the 31 water years studied and high or extreme in 11 of the 31 years. Hydrologic alteration negatively affects winter survival of juvenile rainbow trout between Island Park Dam and Warm River and probably also in the power plant reach of Fall River. Low late summer flows may result in warm water temperatures and associated effects in lower Fall River and in the St. Anthony area. Where riparian areas naturally exist in the watershed, hydrologic regimes are sufficiently close to natural to maintain riparian and floodplain processes except on Henry's Lake Outlet. The hydrologic regime in the Outlet was altered sufficiently to negatively affect nearly every aspect of aquatic, riparian and floodplain ecology. Although desirable resources could benefit from hydrologic restoration below Henry's Lake and Island Park dams, meaningful reductions in hydrologic alterations cannot be made under existing legal and physical infrastructures. Although not optimal for all aquatic and riparian resources in the watershed, current management provides numerous benefits to diverse users while maintaining floodplain and riparian processes in the lower watershed and low hydrologic alteration throughout most of the watershed in average to wet years.

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Introduction

Like most rivers in the arid western U.S., the Henry's (North) Fork of the Snake River in eastern Idaho is heavily managed, primarily to store and deliver irrigation water and secondarily to generate hydroelectric power. Although the native Yellowstone cutthroat trout *Oncorhynchus clarki bouvieri* was essentially eliminated from the watershed upstream of St. Anthony in the mid-20th century by a combination of the effects of dam construction and fisheries management actions, nonnative wild and hatchery rainbow *O. mykiss*, cutthroat x rainbow hybrid, and brook *Salvelinus fontinalis* trout thrive in the streams and reservoirs of the watershed, making the Henry's Fork the most popular trout fishing stream in the country (Jaeger et al. 2000, Van Kirk and Gamblin 2000). Through lacustrine habitat creation, nutrient concentration and delivery, and downstream export of large reservoir-grown trout, the watershed's two largest reservoirs, Henry's Lake and Island Park, are at least partially responsible for creation and maintenance of the watershed's most popular nonnative trout fisheries (Van Kirk and Gamblin 2000). At the same time, however, the negative effects of flow alteration at Island Park dam on trout populations and other aquatic and resources downstream are well documented (Vinson et al. 1992, Gregory 2000, Van Kirk and Martin 2000). Because of the river's socioeconomic importance to both the agricultural and recreational angling communities, conflicts over water resource management on the Henry's Fork date back to the 1970s, becoming so intense and socially intractable in the early 1990s that parties on all sides of water management issues agreed in 1993 to form the Henry's Fork Watershed Council to address water management and other watershed issues in a collaborative manner (Van Kirk and Griffin 1997).

Water management conflicts, debate, research, and management changes both pre- and post-Council formation in the Henry's Fork watershed have focused on Island Park Reservoir, particularly on the effects of low winter flows on rainbow trout populations in the popular Box Canyon and Harriman State Park reaches downstream (Van Kirk and Griffin 1997, Benjamin and Van Kirk 1999). Analysis of this issue has centered around determination of winter habitat needs for juvenile rainbow trout downstream of Island Park Dam and attempts to deliver minimum stream flows sufficient to provide this habitat (Cochnauer and Buettner 1978, Smith and Griffith 1994, Contor and Griffith 1995, Griffith and Smith 1995, Meyer and Griffith 1997a, Meyer and Griffith 1997b, Benjamin and Van Kirk 1999, Mitro 1999, Gregory 2000). Although the minimum stream flow concept has been the standard method for analyzing stream flow needs of aquatic organisms since the 1970s, the landmark synthesis paper of Poff et al. (1997) set the stage for the modern ecosystem-based approach of using a watershed's natural hydrologic regime as the basis for determining effects of flow regulation on aquatic species and for designing flow management strategies to optimize aquatic and riparian ecosystem functioning in regulated river systems.

The hydrologic regime of a river is defined by magnitude, timing, frequency, duration and rates of change of stream flow (Poff et al. 1997). A river's natural hydrologic regime is determined by regional climate, geology, topography, and watershed vegetative cover and is the primary driver of ecological processes in the stream channel and riparian areas, directly and indirectly affecting energy pathways, water quality, physical habitat, and biotic interactions (Petts 1984, Poff and Ward 1990, Gore 1994, Poff et al. 1997). Anthropogenic alteration of hydrologic regime can therefore have profound direct and indirect effects on all aspects of aquatic and riparian ecosystem function. Although anthropogenic alteration of hydrologic regime can and does occur via changes in vegetative cover, channelization of streams, urbanization, and groundwater withdrawals (Vorosmarty and Sahagian 2000), dams usually cause the greatest hydrologic alteration attributable to human activity (Magilligan et al. 2003). The most common geomorphic alterations observed downstream of dams are caused by decrease in the magnitude and frequency of peak flow events and include increase in fine sediment in the stream channel, simplification of the channel and the aquatic habitat it provides, and disconnection of riparian areas from the stream system (Ligon et al. 1995, Collier et al. 1996). Combination of these indirect (habitat change) factors with direct effects on fish life cycles (e.g., loss of physical cues to initiate spawning behavior, King et al. 1998) have resulted in widespread replacement of native fish species by nonnatives (Bain et al.1988, Freyrer and Healey 2003, Hughes and Noss 1992, Scheidegger and Bain 1995, Richter et al. 1997b). Reduced floodplain inundation has resulted in loss and decadence of native riparian vegetation in both humid and arid climates (Collier et al. 1996, Merigliano 1996, Patten 1998, Nilsson and Berggren 2000, Magilligan and Nislow 2001, Stromberg 2001, Nislow et al. 2002). In arid and semi-arid areas of North America, riparian areas comprise only a percent or two of the landscape but provide critical habitat for a large percentage of terrestrial species and account for the majority of biodiversity in these areas, and thus the effects of their degradation extend far beyond the river/riparian corridor (Patten 1998).

As the role of hydrologic regime in maintaining stream and riparian ecosystem function has become more widely understood and accepted over the past decade, an increasing number of river research and restoration efforts have been based around assessment of hydrologic alteration and restoration of natural hydrologic regimes (Hesse and Mestl 1993, Sparks et al. 1998, Galat and Lipkin 2000, Wildhaber et al. 2000). Restoration of key components of the natural hydrologic regime has resulted in documented recovery of native fish assemblages (Travnichek et al. 1995) and riparian areas (Molles et al. 1998, Rood et al. 2003). Some authors now conclude that in addition to facilitating restoration and recovery of native aquatic and terrestrial species, watershed-scale restoration of hydrologic regime is necessary to maintain sustainable human-desired resource outputs from river systems, including supply and quality of fresh water, recreation, and fish and wildlife (Baron et al. 2002, Richter et al. 2003). These authors propose scientific and sociological methodologies for assessing anthropogenic hydrologic alteration and developing management strategies to restore key features of the natural hydrologic regime under the constraints of meeting human needs.

The first step in the hydrologic restoration processes is quantification of hydrologic alteration and its effects. The most widely used method for accomplishing this is the Indictors of Hydrologic Alteration (IHA), which analyzes flow statistics quantifying each of the five components of the hydrologic regime (Richter et al. 1996, Richter et al. 1997a). The IHA methodology compares hydrologic data from a pre-impact period with those from a post-impact period, where each period is ideally represented by a minimum of 20 water years. The degree of hydrologic alteration is then determined by a range-of-variability analysis based on the frequency with which post-impact hydrologic parameters fall within a range of values selected from the distribution of pre-impact values (Richter et al. 1998). The IHA methodology has been applied to river basins representing a variety of watershed and hydrologic regime types throughout the country (Colorado River, Richter et al. 1998; Henry’s Fork of the Snake River, Benjamin and Van Kirk 1999; Connecticut River, Magilligan and Nislow 2001; Missouri River, Galat and

Lipkin 2000 and Wildhaber et al. 2000). Another method for assessing hydrologic alteration, particularly as it relates to geomorphic processes in the floodplain, is analysis of frequency and magnitude of peak flow events (Magilligan et al. 2003).

Despite the socioeconomic importance of irrigated agriculture and recreational trout fishing in the Henry's Fork watershed and the history of conflict and cooperation over water management among their constituencies, the study of Benjamin and Van Kirk (1999) is the only research conducted to date to assess hydrologic alteration on the Henry's Fork. However, this study was limited to analysis of alteration due to Island Park Reservoir alone, focused primarily on addressing the winter flow issue, and did not assess alteration on other stream reaches in the watershed nor effects of alteration on riparian ecosystem function. Given the increased attention being placed on watershed-scale analysis in general and on reaches of the Henry's Fork other than those immediately downstream of Island Park Reservoir in particular, there is a great need for analysis of hydrologic alteration throughout the Henry's Fork watershed. At the same time, there is need to develop new methods for assessing hydrologic alteration to complement those currently in use. First, the "pre-impact/post-impact" approach of the original IHA methodology is not applicable to the Henry's Fork watershed, where there are almost no flow data available from the pre-impact period. Most gages in the watershed with long periods of record were installed only a few years before construction of major dams, and even those installed decades prior to dam construction measured hydrologic regimes already altered by substantial irrigation withdrawal. Thus, the hydrologic data used to quantify unimpacted conditions on the Henry's Fork must be calculated from data measuring regulated conditions, storage, withdrawals, and in some cases evaporative loss from reservoirs across the entire watershed. Calculation of these unregulated or "natural" hydrologic regimes requires extending the method used by Benjamin and Van Kirk (1999), which incorporated change in storage only at one reservoir in the watershed and did not consider diversions. Calculation of natural flow for the same time period as that over which regulated flow data are collected provides the opportunity to develop methods for direct comparison of daily regulated flow to the natural flow that would have been experienced on that same day in absence of alteration. A range of variability approach similar to that of Richter et al. (1998) can then be developed to apply directly to daily flow and its alteration rather than to annual statistical measures of alteration. Lastly, to have maximum applicability to management, the hydrologic alteration assessment must provide quantitative relationships between annual alteration and water availability at both the river reach and watershed scales to allow prediction of alteration as a function of water year type (wet, dry, average).

Objectives

With these needs and opportunities in mind, the objectives of this study were to

1. reconstruct natural (unregulated) flows for all stream gages in regulated reaches of the Henry's Fork watershed upstream of St. Anthony,
2. develop new methods for comparing regulated and natural flow, computing alteration values, and assessing the dependence of alteration on annual discharge,
3. assess differences in regulated and natural flow regimes,
4. quantify alteration and its relation to annual water yield on the watershed scale, and
5. assess ecological impacts of hydrologic alteration in the watershed.

Study Area

The study area is the Henry's (North) Fork of the Snake River watershed upstream of St. Anthony (Figure 1, see Van Kirk and Benjamin 2000 for a complete description of the geography of the Henry's Fork watershed). The Teton River, the major tributary to the Henry's Fork downstream of St. Anthony, and reaches of the Henry's Fork affected by the Teton will be analyzed in future studies, which will require development of methods to quantify the effects of groundwater and irrigation return flow. The study watershed drains a 1,770 square-mile area bounded on the west by high desert areas of the eastern Snake River Plain, on the north by the Centennial and Henry's Lake mountains along the Continental Divide, on the east by the Yellowstone Plateau, and on the south by a low divide separating the Fall River and Teton watersheds. Elevations in the study area range from about 4,800 feet at St. Anthony to about 10,000 feet along the Continental Divide. Precipitation at St. Anthony is nearly uniformly distributed across the year and averages about 14 inches. Precipitation in the higher elevations is greatest during November through June, falls mainly as snow, and can average as much as 50 inches annually at the highest elevations.

Aside from the Centennial and Henry's Lake mountain ranges, the watershed is dominated by volcanic features associated with apparent northeastward migration of the Yellowstone hot spot. Explosive rhyolitic volcanism occurred in the study area about 4 million years ago in the St. Anthony area and between 2 million and 600,000 years ago in the upper watershed (Christiansen 1982). Subsequent loess deposition and localized basalt flows have covered the rhyolite except along the margins of the Yellowstone Plateau along the watershed's northeastern boundary. These exposed rhyolite flows support large aquifer systems whose groundwater feeds a series of springs in the headwaters area (Benjamin 2000). Whitehead (1978) estimated that 42% of the Henry's Fork discharge at Ashton is derived from these groundwater sources. As a result of this substantial groundwater influence, the natural hydrologic regime of most streams in the study area is much less variable than those of streams in neighboring watersheds with similar climate but without the volcanic geology (Benjamin 2000). Furthermore, the relatively low magnitude peak flow events of the groundwater-dominated hydrologic regime, the short time that has elapsed since the most recent volcanism in the watershed, and the absence of extensive glaciation combine to limit floodplain development in the study area. Riparian areas along the groundwater-dominated streams are dominated by wetland areas and are maintained by local groundwater levels rather than by overbank surface flow (Jankovsky-Jones and Bezzerides 2000). Floodplain riparian forests maintained by overbank flows are present only in the lowest-elevation stream reaches in the study area. The watershed's mountainous areas are mostly forested and are managed by the U.S. Forest Service for multiple uses, including timber harvest and recreation. Nearly all of the lower elevation areas of the watershed, historically sagebrush steppe, are used for agriculture, including livestock operations, dry farming of grain crops, and irrigated farming of potatoes and grain.

We will use the naming and hydrographic conventions of Van Kirk and Benjamin (2000). In particular, we will deviate from U.S. Geological Survey (USGS) conventions by 1) using the apostrophe in "Henry's," 2) calling the stream reach from Henry's Lake Dam to the Big Springs confluence "Henry's Lake Outlet," 3) considering the Outlet-Big Springs confluence to be the headwaters of the Henry's Fork and 4) using "Fall" River rather than "Falls" River. The study streams are Henry's Lake Outlet, the Henry's Fork from its headwaters to St. Anthony, and Fall River from its headwaters to the Henry's Fork confluence (Figure 1). Flow is regulated by three major storage reservoirs, one hydroelectric power plant diversion, and numerous irrigation diversions ranging from small pumps to canals carrying hundreds of cubic feet per second (cfs). The oldest of the three storage reservoirs is Henry's Lake, completed in 1923 by the North Fork Reservoir Company (NFRC) to store water for irrigation of lands in the St. Anthony area. The dam was built on the outlet of the natural Henry's Lake, a shallow lake and wetland complex with an original surface area of 3,767 acres and an estimated capacity of 1,500 acre-feet (a-f, Sorenson Engineering 1995). At capacity, the dam-expanded lake has a surface area of 6,455 acre-feet and contains 90,000 a-f. Island Park Dam was completed by the U.S. Bureau of Reclamation (USBR) in 1938 to store up to 135,500 acre-feet of water for Fremont-Madison Irrigation District (FMID), whose members irrigate lands throughout the Henry's Fork watershed. Grassy Lake, also a USBR facility, was completed in 1939 on Grassy Creek, a Fall River headwater tributary located in Wyoming, just south of Yellowstone National Park. Grassy Lake holds 15,200 a-f of active storage above the 300 a-f volume of the natural lake on whose outlet the dam was built. Grassy Lake provides additional storage for FMID. All three storage reservoirs in the study area are managed under the water rights system common to the entire Snake River watershed upstream of Milner Dam in the Magic Valley. An important consequence of this is that although the storage *capacity* in Henry's Lake, Island Park Reservoir and Grassy Lake belongs to NFRC and FMID, the storage rights held by these entities are junior to a large volume of storage rights held elsewhere in the system (in American Falls Reservoir and Jackson Lake, in particular), and thus physical storage in the three Henry's Fork reservoirs at any given time belongs to NFRC and FMID only after all senior storage rights in the entire system have been filled.

There are five relatively small hydroelectric power plants in the study area, but only one of these, the Marysville plant on Fall River, contributes to hydrologic alteration. The Marysville hydroelectric plant came on line 22 August 1993 with a capacity of 9.1 MW. Although located off stream, the Marysville plant diverts up to 1,200 cfs from Fall River through the Marysville Canal, returning the water to the river at Kirkham Bridge about seven miles downstream (Figure 1). The plant is required to leave a minimum of 200 cfs of flow in the stream reach affected by its diversion. Pond's Lodge power plant on the Buffalo River is the smallest plant in the study area, with a capacity of 0.3 MW. It has been operating since 1936, except for a brief period following a fire in the late 1980s. The Pond's Lodge facility diverts about 25% of the Buffalo River flow a few hundred yards above its confluence with the Henry's Fork, spilling it through the plant and immediately into the Henry's Fork, thus affecting flows to a very minor extent over less than one quarter mile of the Buffalo River and Henry's Fork combined. Another small plant (capacity 0.5 MW) is located at St. Anthony and diverts a small percentage of the flow of the Henry's Fork there for about one quarter mile. The Island Park facility, with a capacity of 4.8 MW, was retrofitted to the existing Island Park Dam and came on line in 1993. The Island Park plant uses only water otherwise delivered at Island Park for irrigation storage and delivery purposes and thus does not have any hydrologic effect over and above that caused by irrigation management. The Ashton power plant, with a capacity of 7.4 MW, has its own small reservoir, built in 1938. However, the reservoir does not store water and so has no effect on streamflow.

Diversion of natural flow and storage water for irrigation occurs throughout the study area, but the vast majority of diversion occurs on lower Fall River and on the Henry's Fork between Fall River and St. Anthony (Figure 1).

Methods

We analyzed hydrologic alteration for water years (1 October to 30 September) 1972 to 2002, the period of modern management operations at Island Park Dam. Benjamin and Van Kirk (1999) found that operational procedures implemented at the beginning of water year 1972 (and remaining in effect to the present) resulted in significant differences in patterns of hydrologic alteration at Island Park between the pre- and post-1972 time periods. All stream flow data were obtained from the USGS surface water database, and all diversion data were obtained from Idaho Department of Water Resources (IDWR)/Water District 1. Reservoir storage data were obtained from the USBR hydromet database when available and from IDWR/Water District 1 otherwise.

Stream Reach Designations

We subdivided the study streams into 10 reaches based on the current locations of reservoirs, large diversions, canal return flow, and large tributaries (Table 1 and Figure 1). Because hydrologic conditions in reaches 7 and 8 (Fall River Marysville to Kirkham Bridge and Kirkham Bridge to Enterprise Canal, respectively) were identical prior to construction of the Marysville hydroelectric plant, these two reaches were combined into the single reach designated as reach 9 for the pre-power plant time period, making a total of 11 reaches used in the study. Each of the nine USGS stream gage stations currently operating in the study area was assigned to represent hydrologic conditions in one of reaches 1, 2, 3, 5, 6, 7, 8, 10, and 11 (Table 1 and Figure 1). Hydrologic conditions in reach 9 on Fall River were represented by the Squirrel gage (pre-power plant) prior to construction of the Marysville power plant. Stream flow in reach 4 (Buffalo River to Warm River) was estimated by adding to daily flow measured at the Island Park gage the mean over water years 1936-1940 (plus a few days in water years 1935 and 1941) of daily flow measured in the Buffalo River near its confluence with the Henry's Fork. This estimate was made because the Buffalo River is a large, unregulated tributary that forms an important reach boundary, but the gage station on the Buffalo River operated only from 1935 to 1941. This estimate is expected to be meaningful, however, as the Buffalo River is fed primarily by groundwater and displays little year-to-year variability in daily flow. Over the period of record of the Buffalo River gage, the maximum coefficient of variation of daily flow was 0.50, and the mean of coefficients of variation on daily flow over the whole water year was 0.12. Allowing for the Buffalo River estimate, daily stream flow data exist over the entire 1972-2002 study period for reaches 1, 3, 4, 5, 7, 9, 10 and 11. Daily data for reaches 2, 6 and 8 are available only from the mid-1990s until the present (Table 1), so these reaches had much smaller sample sizes than the others.

Natural Hydrograph Calculation

All calculations began with the actual (regulated) flow observed at each gage. The basic equation for computing natural flow at a gage station located at point A on the stream is given by

$$Q_{natural}^{A} = Q_{regulated}^{A} + \Delta S^{upstream} + Div^{upstream} + Evap^{upstream}, \quad (1)$$

where

$Q_{natural}^{A}$ is the calculated natural (unregulated) flow at point A,

$Q_{regulated}^{A}$ is the observed (regulated) flow at A,

ΔS is the change in reservoir storage,

Div is the rate of diverted flow,

$Evap$ is the rate of evaporation from reservoirs, and

upstream indicates the sum over the whole watershed upstream of point A.

All terms in equation (1) have units volume/time. Because stream flow and diversions are measured in cfs and reservoir storage in a-f, the change in storage term was converted from a-f/day to cfs using the conversion 1 cfs = 1.98 a-f/day.

In actual calculations, we modified the inputs to equation (1) to handle data irregularities. The first modification was to account for water travel time, which, according to the schedule used by Water District 1, is one day from Henry's Lake to Island Park Reservoir, one day from Island Park to all gages downstream of Warm River, and one day on Fall River from Grassy Lake to all gages downstream. Thus, for example, application of equation (1) to the Ashton gage required the change in storage term to consist of the sum of change in storage at Henry's Lake two days prior and that at Island Park Reservoir one day prior. A second set of modifications was defined to deal with missing data. Prior to 1979, flow data for diversions from the Henry's Fork upstream of Fall River were not recorded every day, although daily data were available for all large diversions during irrigation season. Missing daily diversion values in these reaches were replaced with the median of daily values over all years for which data were available for that particular day. Reservoir contents in Grassy Lake were recorded only once every 10 to 45 days during water year 1972, and we used linear interpolation to calculate missing values. Similarly, reservoir contents in Henry's Lake were measured once every 10 to 45 days prior to water year 1978. We used a combination of 1st, 2nd and 3rd degree polynomial regression and 2nd and 3rd degree polynomial splines to fit a continuous curve of daily values to these data (Figure 2).

Errors associated with ice, wind, and waves in reservoir content data resulted in substantial noise in daily change in storage calculations. We smoothed change in storage data from Grassy Lake and Island Park with a 7-day, centered moving average, which proved sufficient to eliminate the noise without losing daily trends in storage change. This method did not work on data from Henry's Lake, where the narrow bay in which the gage is located amplifies ice, wind and wave errors. Change in storage values an order of magnitude greater than reasonable estimates of inflow were not uncommon. Thus, we smoothed the Henry's Lake data with a 365-day Fourier series filter with minimum period 28 days (maximum frequency about 13 cycles per year, Figure 3). After filtering and adding to regulated flow, the result was smoothed using a 7-day, centered moving average.

The final modification of equation (1) inputs dealt with reservoir evaporation. Due to the cold climate of the study area, reservoir evaporation occurs only from May through September. Evaporation values estimated using observed pan evaporation at the Island Park weather station indicated evaporative loss at only a few percent of reservoir inflow on Grassy Lake and Island Park Reservoir. Thus, we chose to ignore evaporation from Grassy and Island Park. However, even when accounting for evaporation from the natural Henry's Lake, evaporation can be a large percentage of or even exceed inflow to Henry's Lake. These calculations were corroborated by documentation of periods of time during which Henry's Lake Outlet was dry prior to construction of the dam (Idaho Department of Water Resources 1982). Thus, we constructed a daily evaporation model for Henry's Lake based on statistical relationships between observed pan evaporation at the Island Park weather station and temperature at Island Park and Ashton. Pan evaporation was measured during the summers of 1972 through 1977 at the Island Park weather station, which lies at about the same elevation as and 15 miles to the south of Henry's Lake. Linear regression showed a statistically significant dependence of daily evaporation at Island Park on daily maximum temperature at both Island Park ($P = 10^{-42}$, $r^2 = 0.30$, $n = 543$) and Ashton ($P = 10^{-43}$, $r^2 = 0.30$, $n = 541$). These relationships were used to calculate daily evaporation based on maximum daily temperature observed at Island Park when possible and on maximum daily temperature observed at Ashton otherwise. The use of Ashton temperature data was necessary because there is a much larger data set of temperatures from the Ashton station than from the Island Park station. On the few days during the study period when neither Island Park nor Ashton temperature data were available, the Ashton temperature was calculated from a calculated linear relationship between Ashton temperature and St. Anthony temperature ($P = 10^{-10}$, $r^2 = 0.74$, $n = 30$). The calculated daily evaporation was then applied to the difference in surface area between Henry's Lake at its given contents and the natural lake to obtain total daily evaporation due to the dam-created reservoir. When natural flow at Henry's Lake was computed to be negative (evaporation exceeded inflow), the natural flow value in Henry's Lake Outlet was set to be zero.

Comparison of Regulated and Natural Hydrologic Regimes at the Reach Scale

Once natural discharges were calculated, we computed the daily hydrologic alteration index, defined for a gage located at point A as

$$Daily\ alteration(i) = \frac{Q^{A}_{regulated}(i) - Q^{A}_{natural}(i)}{Q^{A}_{natural}(i)}, \qquad (2)$$

where the index i is the day of the water year. This dimensionless quantity measures the percent difference between the regulated and natural discharge on a given day. When the denominator on the right side of equation (2) was zero, the natural flow was set to 1 cfs for use in equation (2). We defined mean annual absolute alteration (usually referred to as mean annual alteration or simply annual alteration) as

$$Mean\ annual\ absolute\ alteration = \frac{\sum_{i=1}^{365} \left| Daily\ Alteration(i) \right|}{365}, \qquad (3)$$

which is a dimensionless quantity measuring the degree of hydrologic alteration over an entire water year. The terms in the sum are absolute values of daily alteration so that negative and positive daily alterations do not cancel. Thus, regulated discharge values that are greater than natural values count as much towards the alteration measure as regulated discharge values of the same magnitude that are less than natural values. We also used the IHA software (Richter et al. 1996) to compute regulated and unregulated values of 90-day minimum, 7-day minimum, 1-day minimum, 90-day maximum, 7-day minimum, and 1-day maximum discharges, and dates of minimum and maximum discharge.

We used linear least-squares regression analysis to investigate the dependence of annual absolute alteration on total annual natural discharge at each gage. Using appropriate transformations, we performed linear regression of annual absolute alteration (or its transformation) against annual natural discharge (or its transformation), testing four two-parameter monotonic models: linear, exponential, power, and reciprocal. If the relationship appeared to be nonmonotonic, we performed quadratic regression. We considered the best fit among these five models to be the regression with the lowest F-test P-value, and we considered the relationships to be not significant if $P > 0.05$.

To provide a quantitative frame of reference from which to determine the degree of hydrologic alteration, we analyzed range of variability in the natural hydrograph at each of the five gages for which continuous daily data were available over the entire 31-year study period: Island Park, Ashton, St. Anthony, Squirrel, and Chester. We defined the natural range of variability for a given day of the water year to be the maximum percent deviation from the 31-year median flow value that fell within the observed extreme values of natural flow on that day. These range of variability values were then plotted across the water year. The “average” effect of a given observed value of percent daily alteration can then be interpreted as a percent deviation from median natural flow and compared with the natural range of variability plot. For example, if the maximum percent deviation from natural median daily flow that falls within the observed range of natural flows ranges from 20% to 30% over the winter, then the average effect of a 20% daily alteration during the winter results in regulated flows that always fall within the natural range of observed flows (low alteration). Percent daily alterations between 20% and 30% from natural median result in daily flows that fall within the natural range of observed flows some fraction of the days during the winter that can be determined from the range of variability plot (moderate to high alteration, depending on the fraction of days), and percent daily alteration values exceeding 30% from natural median result in flows that almost never fall within the observed range of natural variability (extreme alteration).

Calculation of Alteration Statistics at the Watershed-Scale

We defined the watershed-averaged annual alteration to be the weighted mean of annual absolute alteration over all stream reaches, where the weights were the percent of total study stream length represented by each reach (see Table 1 for reach lengths). Because this calculation required annual absolute alteration values for each reach in each study year and data for reaches 2 (Big Springs to Island Park Reservoir) and 6 (Fall River above Marysville Canal) were available only for a few water years, we replaced missing values of annual alteration for these reaches with medians over all years for which annual values were available. This approximation is likely to introduce very little error into the watershed-averaged alteration calculation. Alteration in reach 2 was relatively low (median 7%), although interannual variability of alteration was moderate (coefficient of variation 0.8). However, the length of reach 2 is less than 7% of the total, so loss of interannual variability in this reach has little effect on the watershed-averaged alteration calculation. Reach 6 is the longest reach in the study area, comprising 26% of the total stream length, but it is the least altered reach in the study area, with annual absolute alteration ranging from 0.9% to 2.4%. Thus, representing alteration in this reach with its median value also has little effect on the watershed-averaged calculation. Annual absolute alteration during period of missing gage data (22 August 1993 to 15 November 1994) in reach 8 (Kirkham Bridge to Enterprise Canal) was computed by removing the effect of Marysville power plant diversion from the alteration calculation for reach 7 immediately upstream. Given that the power plant diversion is the only difference between these two reaches, this calculation provides the exact alteration for reach 8 for this time period, even in the absence of gaging in that reach.

To quantify degree of alteration across gages and for the watershed-averaged total, we analyzed range of variability in natural flow over the whole watershed by computing the mean of the range of variability values analyzed previously at the Island Park, Ashton, St. Anthony, Squirrel, and Chester gages. The resulting plot thus represented the watershed mean of maximum percent deviation from daily median flow that fell within observed extremes of daily natural flow over the whole water year. We then constructed a cumulative frequency distribution of the 365 daily values showing the cumulative number of days of the water year when the range of variability was less than or equal to a given value. We divided the range of variability values into four alteration classes (low, moderate, high, and extreme). The "low" alteration class consisted of all average annual absolute alteration values below the minimum observed natural range of variability value. Thus, on average over the water year, deviations from the median natural flow in the low class result in altered flow values that fall within the range of observed natural flow 100% of the time. Boundaries defining the other three alteration classes were taken to be major changes in slope of the cumulative distribution curve.

Finally, we used linear least-squares regression analysis to investigate the dependence of watershed-averaged annual absolute alteration on total annual natural discharge from the watershed, as measured at the St. Anthony gage. The regression method was exactly as described above for the individual gages.

Assessment of Ecological Effects of Alteration

Ecological effects were assessed primarily qualitatively by comparing observed alteration features to relationships between ecological functions and flow patterns in the published literature, particularly that specific to the Henry's Fork. We quantitatively assessed hydrologic alteration on floodplain and riparian processes by first identifying stream reaches where overbank flows are required to maintain these processes. To do this, we delineated 20 uniformly spaced transects in each reach on aerial photographs and at each transect measured the total width of what appeared on the photographs to be 100-year floodplain (linear distance from one edge of the 100-year floodplain to the other) and the width of the wetted stream channel at mid-summer flow. We then calculated the riparian width as a fraction of total floodplain width as

$$Riparian\ width = \frac{floodplain\ width - stream\ channel\ width}{floodplain\ width}\ . \qquad (4)$$

This dimensionless quantity gives the fraction of the total floodplain that consists of riparian rather than aquatic habitat at moderately low flows. We considered overbank flows to be critical to creation and maintenance of riparian and floodplain processes in all reaches in which the mean riparian width over all 20 transects exceeded 40%. We then computed flood (one-day maximum) frequency plots for natural and regulated flow in these reaches using the method described in Leopold et al. (1992). We assumed that bankfull discharge (the flow above which overbank flow and inundation of the floodplain begins) was the one-day maximum flow met or exceeded every 1.5 years under the natural hydrologic regime (Leopold et al. 1992). We used the flood frequency plots and IHA output related to maximum flow events to assess the effects of alteration on riparian and floodplain processes in these reaches.

Results

Regulated and Natural Hydrologic Regimes at the Reach Scale

The pattern of alteration at Henry's Lake Outlet (reach 1) is typical of that due to a storage and delivery reservoir. During most years, storage season (winter) flows and peak flows (early June) were decreased and irrigation season (late summer) flows were increased under the regulated regime (Figures 4 and 5). The largest percent daily alterations occurred during the late summer, when irrigation delivery was often two orders of magnitude greater than natural flow. Although peak flows under the regulated regime were about the same in magnitude as natural peak flows, they occurred about one month later under the regulated regime (Figure 4). There was a strong decreasing relationship between mean annual alteration and natural annual discharge ($P = 1.2 \times 10^{-8}$, $r^2 = 0.68$, Figure 5). The same pattern of alteration was observed at the Coffee Pot gage (reach 2), but the magnitude of the alteration was only a fraction of that at Henry's Lake Outlet due to the moderating influence of Big Springs and other unregulated, groundwater-dominated tributaries (Figures 7 and 8). Inflow from Big Springs averages about 200 cfs (Benjamin 2000), which by itself exceeds flow in the Outlet under all but the most extreme circumstances. The only large alteration observed over the period of record in the Big Springs to Island Park Reservoir reach was a positive alteration during the summer of 2001 when the amount of water delivered from Henry's Lake was large enough to exceed the moderating effect of Big Springs (Figure 8). There was no significant relationship between alteration and watershed discharge at the Coffee Pot gage (Figure 9).

The reach immediately below Island Park Dam (reach 3) also displayed the pattern typical of storage and delivery reservoirs, with the exception that the timing and magnitude of natural peak (May and early June) was unaltered (Figures 10 and 11). A second peak of about the same magnitude occurred in the regulated hydrograph about 8 weeks after the natural peak. There was again a strong negative relationship between annual alteration and basin yield ($P = 6.5 \times 10^{-9}$, $r^2 = 0.69$, Figure 12). An similar pattern of alteration to that of Island Park was observed below the Buffalo River confluence (reach 4) and below the Warm River confluence (reach 5), but the magnitude of the alteration in both of these reaches was reduced by the moderating influence of the Buffalo and Warm rivers, two large, unregulated, groundwater-dominated tributaries (Figures 13-18). The final study reach affected only by upstream storage and delivery was the Fall River upstream of Marysville canal (reach 6), which was regulated by Grassy Lake. Although the same pattern of decreased storage season flows and increased late summer flows was apparent, the small volume of water stored and delivered at Grassy Lake resulted in very small alteration of the natural hydrologic regime (Figures 19 and 20) and no significant relationship between alteration and discharge (Figure 21).

Fall River between the Marysville and Enterprise canal diversions (reach 9, pre-power plant) was regulated by storage and delivery at Grassy Lake and by irrigation withdrawal at the Yellowstone and Marysville canals and small pumps in the reach. The effect of storage in Grassy Lake was observed as a slight decrease in winter flows, and the effect of withdrawal as a large decrease in late summer flows under the regulate regime (Figures 22 and 23). The effect of delivery from Grassy Lake was apparent in late summer only during one year of record, as storage delivery from Grassy Lake was less than total diversions from the reach during most water years. There was a moderate negative dependence of alteration on discharge in reach 9 ($P = 1.1 \times 10^{-5}$, $r^2 = 0.42$, Figure 24). The only reach in the study area altered primarily by hydroelectric diversion was the Fall River between Marysville Canal and Kirkham Bridge (reach 7, post-power plant). Large negative alteration was observed throughout the water year, with the greatest percent alteration occurring late in the summer, when irrigation diversion added to the effect of power plant diversion (Figures 25 and 26). The lowest alteration occurred during peak flow, when natural flow greatly exceeded the inflow capacity of the power plant. Annual alteration did not depend significantly on natural discharge. Alteration in Fall River immediately below the power plant return flow (reach 8) displayed the same pattern as reach 9 prior to power plant construction (Figures 28-30). Below the large diversions on Fall River (reach 10), alteration was strictly negative for essentially the entire water year during all years (Figures 31 and 32). Negative winter alteration was due more to the effects of winter diversion (used for groundwater recharge) than to the effects of storage at Grassy Lake, which were not noticeable that far downstream. Alteration was greatest during the late summer, when diversions often left less than 40% of the river's natural flow in the channel. There was a weak negative dependence of alteration on discharge in the reach ($P = 0.014$, $r^2 = 0.19$, Figure 33).

Hydrologic regime in the Henry's Fork from Fall River to St. Anthony (reach 11) was altered by a combination of all storage, delivery, and diversions in the watershed upstream, with the exception of the Marysville hydroelectric diversion. Alteration at St. Anthony was almost always negative and more constant throughout the year than at any other gage, resulting in an altered hydrologic regime that was nearly identical in shape to the natural regime but decreased nearly uniformly across the water year in magnitude by about 30% (Figures 34 and 35). There was a moderately strong, negative quadratic relationship between alteration and watershed discharge ($P = 0.0018$, $r^2 = 0.36$, Figure 36). Alteration was highest during moderately dry years and decreased on either side of the maximum to lower values in the driest and wettest years.

In terms of extreme flow events, regulation resulted in significantly lowered minimum flows on Fall River in only two reaches (Figure 37). Minimum flows in the reach affected by the Marysville power plant (reach 7) displayed almost no year-to-year variability and were consistently at the power plant's 200 cfs minimum stream flow requirement, compared with natural minimum flows of about 350 cfs. Regulated minimum flows below Enterprise Canal (reach 10) displayed much more variability than natural minima and were consistently lower than natural. Regulation on Fall River had very little effect on magnitude and variability of maximum flows (Figure 38). The dates of regulated minimum flows on Fall River were generally earlier in the year (fall versus late winter) and more variable from year to year than under the natural regime (Figure 39). Late summer irrigation diversion in lower Fall River resulted in a 6-month shift in the date of minimum flow, from mid-January to mid-July. In contrast, regulation on Fall River had no effect on date of maximum flows (Figure 40).

Extreme flow characteristics on the Henry's Fork were altered to a much greater degree than on Fall River. Regulated minimum flows were significantly lower than natural in all reaches downstream of Island Park Dam, with the greatest percent decrease occurring in the reach immediately below the dam (Figure 41). In contrast, maximum flows were altered significantly only at St. Anthony, where regulated maxima were consistently about 30% lower than natural but displayed the same degree of variability as natural maximum flows. Dates of minimum flow were generally earlier under the regulated regime, although regulated dates of minimum at Henry's Lake moved from late summer to fall and early winter under the effects of regulation (Figure 43). Natural dates of minimum flow generally displayed a greater degree of variability than regulated dates of minimum flow, particularly in the reaches with large groundwater influence. Dates of maximum flow in Henry's Lake Outlet and in the Henry's Fork from Island Park Dam to Warm River (reaches 1, 3 and 4) occurred much later in the year under the regulated regime, with the greatest deviation from natural occurring immediately below Island Park Dam, where dates of maximum discharge were shifted from May to late June/early July (Figure 44). Dates of maximum were not significantly altered in the other Henry's Fork reaches.

Mean annual alteration on Fall River was highest in the Marysville to Kirkham reach (7), averaging around 50% (Figure 45a). Mean annual alteration in the lowest reach of Fall River (10) averaged around 25%. Annual alteration on all other Fall River reaches varied little from year to year and averaged less than 10%. Annual alteration values on the Henry's Fork were generally much greater than that on Fall River, averaging nearly 100% on Henry's Lake Outlet (Figure 45b). Annual alterations exceeding 1000% (regulated flow 10 times greater than natural) occurred on the Outlet during particularly dry years. Despite these extreme alteration values on Henry's Lake Outlet, the moderating effect of Big Springs reduced annual alteration in the Big Springs to Island Park Reservoir reach to an average of less than 10%. Regulation at Island Park resulted in annual alterations in the 40% to 50% range, but the Buffalo River and Warm River acted to moderate this to an average of about 20% in the Warm River to Fall River reach. Annual alteration at St. Anthony was consistently around 30%. The range of variability plots show that natural flows were more variable on Fall River than on the Henry's Fork and that variability in all reaches was lowest during the winter and highest around the time of peak flow (Figure 46). Natural winter flows in the watershed varied across years about 25% to 30% from the median, and peak flows varied about 65% to 70% from the median. Thus, daily flow alterations of about 25% or less in magnitude during the winter, 65% or less during the early summer, and 40% or less in the late summer will result in flows within the natural range of variability during years with natural discharge at or exceeding the median.

Alteration at the Watershed Scale

The watershed-averaged range of variability plot exhibits the same pattern as those for the individual reaches (Figure 47a). Natural flows varied as much as 30% from the median during the winter, 65% during the early summer, and 40% during the late summer. The minimum percent deviation from median was 22.8% and occurred in late February. This represents the maximum value of annual alteration that, on average, will result in daily flows that fall within the range of natural flows over the whole water year. Thus, we defined the "low" alteration category to consist of all annual alterations of less than 22.8% (Table 2). The cumulative distribution of watershed-averaged range of variability shows two distinct changes in slope, one at 42.6% and the other at 64.5% (Figure 47b). The slope change at 42.6% represents the abrupt increase in natural range of variability that occurs in late April. The other change represents the spike around the first of June. These slope changes define the boundaries of the other alteration categories (Table 2). Moderate alterations (22.8% to 42.6%) will result, on average, in daily flows that fall within the natural range during between 100 and 364 days of the water year. The higher the alteration within this category, the more likely altered values are to fall outside of the range of natural values during the winter, although spring and summer flows will fall within the natural range. Alterations in the "high" category (42.6% to 64.5%), on average, will result in natural flows that fall within the natural range for at most 99 days in the spring and early summer. Winter alterations in this range will almost always fall outside of the natural range. Values of alteration exceeding 64.5% will, on average, result in flows that fall within the natural range for only a day or two at peak flow time.

Based on these definitions, alteration was extreme in Henry's Lake Outlet and high immediately below Island Park Dam and in the reach of Fall River affected by the Marysville power plant (Figures 48 and 49). Reaches of moderate alteration were the Henry's Fork from the Buffalo River to Warm River and from Fall River to St. Anthony. Alteration was low on all of Fall River except for the power plant reach, and on the Henry's Fork from Big Springs to Island Park Reservoir and from Warm River to Fall River. Watershed-averaged annual alteration varied greatly, ranging from less than 20% during wet years to over 100% during dry years (Figure 50). Watershed-averaged alteration was low during 14 of the 31 water years between 1972 and 2002 (45%) and uniformly distributed among the moderate, high and extreme classes during the other 17 water years (Figure 51). Watershed-averaged alteration displayed a very strong decreasing dependence on annual natural watershed discharge ($P = 5.8 \times 10^{-10}$, $r^2 = 0.74$, Figure 52). Thirteen of the 14 water years in which watershed-averaged alteration was low occurred in years when annual watershed runoff exceeded the mean value of 2.04 million a-f. The five water years with the highest alteration were the notably dry years of 1977, 1988, 1992, 1994, and 2001.

Peak Flow Analysis

Riparian areas generally comprised less than 20% of the total floodplain area in the study reaches, and riparian width exceeded 40% only on Henry's Lake Outlet, Fall River below Enterprise Canal, and the Henry's Fork between Fall River and St. Anthony (Figure 53). We infer that overbank flows are critical to maintaining floodplain and riparian processes only in these reaches. Flood frequency diagrams showed only small difference in peak flow characteristics between natural and regulated regimes in lower Fall River and the St. Anthony reach (Figure 54). In both of these reaches, the magnitude of one-day maximum flows has been decreased by about 30% (Figures 32 and 35), but one-day maximum flows fell within the observed natural range during almost all water years. Bankfull discharge in these reaches was achieved about once every 2 to 3 years under the regulated regime, compared with once every 1.5 years under the natural regime. The timing of peak flows in these reaches was unaffected by regulation (Figures 40 and 44). The frequency of bankfull discharge was unaltered at Henry's Lake Outlet, but the magnitudes of one-day maximum flows exceeding bankfull (about 200 cfs) were less variable under the regulated regime, resulting in an increased frequency of flows in the range of 200 to 220 cfs and a decreased frequency of flows exceeding 220 cfs (Figure 54 a). Dates of maximum flow in the Outlet were significantly later under the regulate regime (Figure 44).

Discussion

Patterns of Hydrologic Alteration

Hydrologic alteration within a given stream reach was affected by its location relative to storage reservoirs, diversions, return flow, and unregulated tributaries and by annual watershed discharge. Decreased winter flows and increased late summer flows occurred immediately downstream of all three storage reservoirs, with the highest alterations occurring below Henry's Lake. However, inflow from unregulated tributaries nearly completely eliminated the extreme alteration at Henry's Lake in the reach below Big Springs. Alteration due to storage and delivery operations at Island Park affected the Henry's Fork from the dam all the way downstream to the Fall River confluence, but the magnitude of alteration was reduced by unregulated tributary inflow from the Buffalo and Warm rivers. Reduction in effect of regulation at Henry's Lake and Island Park dams with distance downstream from the dams is due entirely to inflow from unregulated groundwater-dominated streams, the largest three of which are Big Springs, Buffalo River, and Warm River (Benjamin 2000). Thus, the same hydrogeologic characteristics that result in the relatively uniform, groundwater-dominated natural hydrographs of the upper Henry's Fork watershed also serve to reduce effects of anthropogenic alteration in the watershed. Although flow in these groundwater-dominated tributaries is affected by climatic processes including drought (Benjamin 2000), response to climatic changes is attenuated in time to a much greater degree than in runoff-dominated systems, resulting in greater moderation of hydrologic alteration by the unregulated tributaries than would be experienced in a runoff-dominated system. Hydrologic alteration in Fall River due to storage and delivery at Grassy Lake was minimal. Diversions substantially altered flow in Fall River in the Marysville reach and in the Chester reach, where the majority of large diversions are located. These diversions, together with large diversions from the Henry's Fork below Fall River consistently reduced flows at St. Anthony throughout the year. Despite the effects of these lower watershed diversions on flow magnitude, the shape of the regulated hydrograph did not differ substantially from the natural hydrograph in either lower Fall River or the Henry's Fork between Fall River and St. Anthony.

A rough estimate of the relative contributions of reservoir storage/delivery and diversions to total alteration in a given stream reach can be made by calculating the ratios of total storage capacity and diversions, respectively, upstream of the reach to mean annual discharge through the reach (Table 3). From these data, it becomes clear that the extreme alterations observed in Henry's

Lake Outlet result from a storage reservoir with a capacity of almost twice total basin yield. Thus, if all of the storage if Henry's Lake were released during a single irrigation season, nearly twice the average annual flow of the watershed would be delivered through the Outlet during a two- or three-month period. Although the entire 90,000 a-f contents of Henry's Lake is never delivered in a single season, a large percentage of this capacity is often delivered during one irrigation season, resulting in late summer flows two orders of magnitude higher than natural in Henry's Lake Outlet. On the other end, refilling an empty Henry's Lake requires two years of natural inflow, resulting in flow reductions in the Outlet often exceeding 80% of natural flow. Average annual alteration values below Island Park Dam and Grassy Lake coincide almost exactly with the ratio of upstream storage capacity to mean annual discharge (Table 3), suggesting that below reservoirs that store and deliver less than one year's worth of discharge per year, this easily-calculated ratio can provide a good estimate of average annual alteration. The only reaches in which alteration was determined almost completely by diversion were the Marysville power plant and the lower reaches of Fall River, where average annual alteration was approximately equal to the ratio of total upstream diversions to mean annual discharge (Table 3). At St. Anthony, annual alteration averaged about 28%, compared to a storage/discharge ratio of 12% and a diversion/discharge ratio of 30%. The weights on these two ratios that produce a weighted average of 28% are 11% and 89%, respectively, indicating that about 11% of hydrologic alteration at St. Anthony is due to the upstream effects of storage and delivery and 89% is due to diversion.

Van Kirk and Benjamin (2001) developed a watershed-scale alteration index based on ratios of reservoir capacity, surface water diversion, and total water consumption relative to mean annual watershed discharge. This coarse-scale alteration index, which can be easily calculated from readily available data, was found to be negatively correlated with an index measuring abundance and distribution of trout in watersheds of the Greater Yellowstone ecosystem. The data presented in Table 3 of this study suggest that the crude watershed-scale index developed by Van Kirk and Benjamin (2001) may in fact be a close approximation to the much more detailed and carefully-defined (but much more time-consuming to calculate) alteration indices developed in this study.

Reach alteration was generally a decreasing function of watershed discharge; the highest alterations occurred during the driest years except at St. Anthony, where maximum alteration occurred during moderately dry years and was slightly lower during extremely dry years. This counterintuitive pattern occurs at St. Anthony because during extremely dry years, total upper Snake system storage is not sufficient to completely fill FMID's relatively junior storage rights. During these years, as much as 70% of the storage in Island Park Reservoir (and in Henry's Lake, for that matter) can belong to more senior rights holders in the Blackfoot and Magic Valley areas rather than to FMID, and this storage water must be delivered through the St. Anthony reach to those downstream users.

Water rights accounting is also responsible in part for the relatively low alteration that occurs at Henry's Lake and Island Park during the spring. Most reservoirs in the western U.S. store the majority of their water during the spring and early summer runoff period, resulting in greatly decreased peak flows in regulated regimes (Collier et al. 1996, Moller and Van Kirk 2003). Storage reservoirs in the Henry's Fork watershed are filled primarily with winter baseflow, in part because this flow is a larger percentage of annual runoff in these groundwater-dominated systems than in runoff-dominated systems, and in part because of the relatively junior storage rights held by NFRC and FMID. Between 1 November and 31 March, all flow in the upper Snake system can be (and in almost all years is) stored in reservoirs throughout the system and credited to storage right holder accounts. After 1 April, the legal beginning of irrigation season, only water in excess of that diverted by natural flow rights holders can be credited to storage right holder accounts when stored. Thus, if the Henry's Fork reservoirs are not filled by 1 April, physical storage accumulated in these reservoirs after 1 April may and frequently does not credit to the storage accounts of NFRC and FMID and thus belongs to more senior users elsewhere in the system. Thus, standard management practice is to attempt to fill the Henry's Fork reservoirs prior to 1 April (Benjamin and Van Kirk 1999), which results in passing of natural peak flows through the full reservoirs during late spring and early summer. Somewhat ironically, then, in a watershed dominated by volcanic geology and groundwater hydrology in which annual peak flows are relatively unimportant on the watershed scale at driving floodplain and riparian processes, peak flow characteristics are relatively unaltered by regulation. This is in stark contrast to the vast majority of regulated rivers in the western U.S., where the single most common effect of regulation is significant reduction in frequency and magnitude of annual peak flows and the resulting loss of channel complexity and riparian habitat (Ligon et al. 1995, Collier et al. 1996, Merigliano 1996, Stromberg 2001).

At the watershed scale, alteration depended very strongly on annual watershed discharge, with the highest alteration occurring during the driest years. The relationship between annual alteration and annual discharge was stronger at the watershed-scale than in any single stream reach, although watershed-averaged alteration pattern was driven in large part by alteration in Henry's Lake Outlet. Watershed-scale alteration was low during 14 (45%) of the water years studied, and annual watershed discharge exceeded the mean during all but one of these years. High and extreme alteration occurred during 11 (35%) of the years studied, and watershed discharge during all but one of these years was less than the mean. Moderate alteration occurred during six of the study years, all of which were drier than average. Thus, substantial effects of alteration in the study area are expected to occur in the 50% of water years that fall below the median in watershed discharge. During the other half of the years, hydrologic alteration is low enough on average that daily flows fall within the natural range during a majority of days during the water year in all reaches except that affected by the Marysville power plant on Fall River.

Ecological Effects of Alteration

Because of the large amount of attention paid in the literature to low winter flows on the Henry's Fork, the most obvious ecological effects of hydrologic alteration to consider are those associated with decreased winter flows. Although regulation decreased winter flows at least somewhat in every stream reach studied, substantial reductions occurred during a majority of water years in Henry's Lake Outlet, the Henry's Fork from Island Park Dam to Warm River, and Fall River in the Marysville power plant reach (Figures 5, 11, 14, 26, 37 and 41). Well-established negative relationships between winter survival of age 0 rainbow trout and flow (Mitro 1999, Gregory 2000) document this effect of winter flow alteration in the reaches from Island Park Dam to Warm River and suggest that a similar effect occurs in Fall River between Marysville Canal and Kirkham Bridge, which has the same channel morphology as the well-studied canyon reaches of Henry's Fork between Island Park Dam and Warm River. Low winter flows are also known to have negative effects on wintering trumpeter swans (*Cygnus buccinator*) and rooted aquatic plants in the Last Chance and Harriman areas below Island Park (Van Kirk and Martin 2000). Although flow alteration below Island Park Dam during March and April is generally lower than it is earlier in the winter, very low flows can occur below the dam during this time period. The reach between Island Park Dam and the Buffalo River is heavily used by spawning rainbow trout (Gregory 1997, Mitro and Zale 2000), and very low flows during March and April may have negative effects on spawning in this reach. Winter flows frequently less than 50% of natural and often close to zero in Henry's Lake Outlet are expected to have negative effects on all types of aquatic life during the winter, although these effects have not been thoroughly assessed in the field. Moderate reductions in winter flow occurred between Warm River and St. Anthony, but there is no documented evidence of effects of winter flow alteration on ecological processes there. High habitat complexity, particularly of cobble-boulder substrate preferred by wintering juvenile rainbow trout (Meyer and Griffith 1997a, Gregory 2000), access to tributary and side-channel habitat, less severe winter weather, and recruitment of wild rainbow trout from tributaries and upstream reaches probably mitigates any negative effects of low winter flow on wintering trout below Warm River. Likewise, the more moderate climate may help to minimize any negative effects of low winter flows on wintering trumpeter swans in the Ashton and St. Anthony areas.

The second major hydrologic effect of storage and delivery operations at Henry's Lake and Island Park Reservoir is to greatly increase late summer flows over those of the natural regime. The effects of this type of alteration have not been studied in the Henry's Fork watershed and do not appear to have been studied extensively in other watersheds. High late summer flows on South Fork Snake River have a negative affect on recruitment of native cutthroat trout but do not appear to have any negative affects on rainbow trout (Moller and Van Kirk 2003). In fact, on a global scale, introduced rainbow trout have had more success at invading streams in which flow is relatively uniform through the spring and summer and less success at invading streams in which very high spring peak flows are followed by a substantial descent in the hydrograph to low late summer flows (Fausch et al. 2001). Regulation at Island Park has resulted in spring and summer flows that are more uniform than under the natural regime (Figure 10). Thus, it is unlikely that high late summer flows have any negative effect on the nonnative rainbow trout populations in the Henry's Fork watershed. If the results of Moller and Van Kirk (2003) from the South Fork apply to Henry's Lake Outlet, the extreme degree of positive late summer alteration there almost certainly has a negative effect on any cutthroat trout fry that may be successfully spawned in the Outlet by adult cutthroat trout migrating downstream from Henry's Lake.

Whereas delivery of irrigation water from Henry's Lake and Island Park resulted in increased late summer flows upstream of Fall River, extensive irrigation withdrawals on lower Fall River and in the Henry's Fork below Fall River resulted in substantial negative flow alteration during late summer in these reaches (Figures 32 and 35). The effects of these low late summer flows have not been studied, but because both stream reaches have high width-to-depth ratios and dark, basalt-derived substrate, low late summer flows may result in high water temperatures, which could negatively affect trout survival. However, data to test this hypothesis are not available.

Floodplain development in the study area is minimal because of the natural hydrologic and geologic characteristics of the watershed. Most of Fall River and much of the Henry's Fork between Island Park Dam and Warm River are confined within narrow, deeply-incised basalt canyons, allowing little if any room for floodplain development. In unconfined reaches of the Henry's Fork upstream of Warm River, groundwater-dominated hydrology and the flat topography of the lava flows and calderas that comprise the underlying geology limit the occurrence of overbank flows and the substrate size that can be mobilized by such flows. Floodplains and riparian areas in these reaches are predominantly influenced by local water tables rather than by overbank flows. Thus, peak flow characteristics, although relatively unaltered, play a minimal role in maintaining morphological and biological processes in floodplain throughout most of the study area. Limited floodplain and riparian areas have formed on lower Fall River and the Henry's Fork between Fall River and St. Anthony due to a combination of hydrologic and geologic factors. While still influenced by groundwater to a greater degree than other rivers of the region, Fall River displays a more runoff-dominated hydrograph than the Henry's Fork upstream. Effects of Pleistocene glaciation, generally absent in the upper Henry's Fork watershed, were substantial enough in the Fall River watershed (Love et al. 2003) to apparently allow recruitment of cobble and gravel into the fluvial system. Stream power afforded by the more flashy hydrograph of Fall River, availability of alluvial material, and the elapse of more time since the last rhyolite volcanism than in the upper Henry's Fork watershed have allowed evolution of floodplains and riparian communities along lower Fall River and the Henry's Fork downstream, particularly when these streams exit the basalt flows that dominate the surface geology of the Ashton area and flow onto areas of the Snake River Plain where loess deposits cover the basalt. Hydrologic regimes in these reaches remain relatively unaltered, particularly with respect to peak flow characteristics and overall hydrograph shape during the spring and summer. Thus, effects of alteration on floodplain processes and riparian communities in lower Fall River and the Henry's Fork near St. Anthony are probably minimal.

The only other reach in the watershed with significant floodplain and riparian area development is Henry's Lake Outlet, where runoff from surrounding mountains, though attenuated somewhat by the natural Henry's Lake, and some glaciation allowed development of a meandering stream channel with abundant willow communities. Alteration of the hydrologic regime and the stream channel itself has resulted in severe degradation of the Outlet and its riparian areas. Although peak flows have been reduced somewhat by alteration at Henry's Lake Dam, the frequency and duration of discharge events just exceeding bankfull have increased. Late summer delivery of irrigation water can result in flows exceeding bankfull for up to three months, as compared with a couple weeks under the natural regime. These high flows exacerbate erosion problems created by channelization, agricultural land use, and loss of riparian vegetation along the Outlet. The majority of the sediment delivered into the upper Henry's Fork comes from Henry's Lake Outlet (HabiTech 1997), even though the Outlet and its tributaries account for only about 20% of the annual flow in the upper Henry's Fork. Seedling establishment of willows and other woody riparian species on streams in the intermountain west is dependent upon the gradual decrease in summer flows that occurs in natural hydrographs following peak flow in the late spring and early summer (Merigliano 1996, Patten 1998). Thus, the greatly altered timing of peak flow and overall shape of the altered summer hydrograph are likely to limit establishment of riparian vegetation on the Outlet. The extreme degree of hydrologic alteration in Henry's Lake Outlet has probably substantially altered all stream and riparian processes there and has probably also limited the success of attempted restoration projects there. Any meaningful long-term restoration activities on the Outlet must start with restoration of a hydrologic regime at least resembling the natural one.

Management Implications

As discussed by Schmidt et al. (1998) in reference to management of the Grand Canyon, there is no single management regime that will provide optimal conditions for the river resources valued by all user groups. In the Henry's Fork watershed, storage and delivery of irrigation water according to the water rights priority system established in the upper Snake River system in the 19th century is and is likely to continue to be the first priority for water management. A careful study of management operations in the entire Snake River system reveals that there is little room for making operational adjustments within the existing legal and physical frameworks that will substantially reduce hydrologic alteration in the Henry's Fork watershed except at the expense of other highly valued resources such as the Henry's Lake trout fishery. A major change in operations was made in the early 1970s, and this change did result in significantly decreased effects of lower winter flows below Island Park Dam (Benjamin and Van Kirk 1999). A change in the legal framework to allow instream flow as a beneficial use that can be designated by a private water rights holder would provide a mechanism for purchasing established water rights for the purposes of hydrologic restoration. However, even if such an approach were legally possible, the effects of alteration are highest during dry years, and these are the years when storage water in the Henry's Fork reservoirs is not likely to belong to rights holders in the watershed. Thus, such a strategy, while only theoretical at this point, would require purchase of senior storage rights generally held in Jackson Lake or American Falls Reservoir to be effective at restoring hydrologic regimes in the Henry's Fork watershed during the years when it would be most needed.

Given that operational and water rights law changes are not likely avenues for reducing the effects of hydrologic alteration in the Henry's Fork watershed at the present time, the only possible mechanisms for reducing alteration necessitate modifying the existing physical infrastructure of the water management system. The results of this research show that the highest degrees of alteration occur in Henry's Lake Outlet, in the Henry's Fork downstream of Island Park Dam, and in the Marysville power plant reach of Fall River. Seasonal alteration can be high between the Buffalo River and Warm River and in lower Fall River, even though annual averaged alterations there are low to moderate. Because the Marysville reach of Fall River is inaccessible, is completely confined within a deep, narrow canyon, and would support minimal aquatic and riparian production even under natural conditions, it is reasonable to assume that restoration of the hydrologic regime there is not a high priority from the standpoint of restoring and maintaining fisheries and other desirable aquatic and riparian resources. These leaves the following restoration possibilities in the study area (listed from upstream to downstream):

1. Henry's Lake Outlet: restore shape of entire hydrologic regime
2. Henry's Fork from Island Park to Warm River: increase winter flows
3. Fall River downstream of Enterprise Canal: increase late summer flows

The easiest of these to address conceptually is the last one, because most of the water diverted from lower Fall River late in the summer is charged to storage accounts in Island Park Reservoir. That is, water physically diverted from Fall River is actually Island Park Reservoir storage water in the accounting scheme. Thus, an obvious way to increase late summer flows on Fall River would be to divert the appropriate amount of Island Park storage water from the Henry's Fork in the Ashton area to Fall River immediately above the Enterprise Canal, the upstream-most large diversion on Fall River. This strategy would greatly reduce late summer alteration in lower Fall River and it would also reduce late summer positive alteration in the Henry's Fork between Warm River and Fall River. It would have no effect on the river downstream of the Fall River confluence. Implementation of such a restoration strategy would require construction, operation, and maintenance of a delivery conduit about ten miles in length capable of delivering about 500 cfs.

Strategies for accomplishing restoration possibilities 1 and 2 above are more difficult to come by. Because the Henry's Lake fishery is benefited by a full Lake, and because passing natural inflow through a full lake is the easiest way to re-establish the natural hydrologic regime in the Outlet, one fairly obvious, but very unlikely, strategy for optimizing multiple resource values is to retire Henry's Lake as a storage reservoir and replace its capacity with a new storage facility further downstream but still upstream far enough that water can be delivered to NFRC shareholders in the St. Anthony area. Such a storage facility would have to be off stream for a variety of reasons, and there is no area topographically suitable for construction of a 90,000 af reservoir anywhere in watershed other than in the Teton River canyon above the site of the failed Teton Dam. Storage at this site could not be delivered by gravity to NFRC users, so delivery would most likely occur downstream of St. Anthony via the Teton River to replace diversion of natural flow from the Henry's Fork upstream. This natural flow diversion would further increase late summer hydrologic alteration in the St. Anthony area, where late summer flows are already low enough to have possible impacts on aquatic life. Groundwater storage is a possibility, but water recharged into the aquifer on the west side of the river near St. Anthony would most likely feed the regional Snake Plain aquifer rather than the local one from which irrigators would pump this water. Pumping of the local aquifer west of St. Anthony would likely result in increased loss of surface water from the river in this area, again increasing hydrologic alteration in the Henry's Fork at and downstream of St. Anthony. Groundwater storage and recharge would require construction, operation and maintenance of recharge and pumping facilities.

One final possibility for an engineered approach to hydrologic restoration in Henry's Lake Outlet is to construct a pipeline between Henry's Lake and the Henry's Fork in the Big Springs to Island Park Reservoir reach. Natural winter flows could then be delivered through the Outlet and pumped back up into the lake for storage. A small amount of additional storage water could be taken from the Big Springs reach through this pipe system as well, allowing a smaller ratio of storage capacity to inflow at Henry's Lake while still keeping alteration in the upper Henry's Fork in the low category. Similarly, during natural peak runoff, natural flow could be delivered through the Outlet and returned via the pipe to the lake for storage. During irrigation season, delivery in excess of the Outlet's natural flow could be delivered via the pipe downstream into the Henry's Fork, thereby eliminating the effects of high late summer flows in the Outlet. This strategy would require construction, operation and maintenance of a pump and pipeline system capable of transporting up to 300 cfs over a distance of about 10 miles with only a minor elevation difference.

The strategies that would reduce alteration in Henry's Lake Outlet could also be applied to the Henry's Fork below Island Park Reservoir, only on a much larger scale. The pipeline option, for example, even if applied only to increase winter flows and not to eliminate high late summer flows, would have to have a capacity of about 400 cfs and cover a distance of over 25 miles and an elevation difference exceeding 1000 feet. A smaller, shorter version designed to increase winter flows only through the Box Canyon and Harriman reaches would need to cover a distance of 10 miles and an elevation difference of about 200 feet.

Regardless of whether hydrologic restoration on the Henry's Fork is accomplished through a change in legal framework or physical infrastructure or some combination of these two, any restoration actions short of irrigators willingly relinquishing water rights for free will be expensive. In addition, engineered solutions, including possibilities for storage off stream or in aquifers, will require a great deal of change in the way irrigators, water managers, and aquatic resource advocates view water management in eastern Idaho and will probably in and of themselves require at least some minor changes to existing water law. Socioeconomic factors may not be in place for such a dramatic departure from the current state of water management for a long time, if ever. In the mean time, it should be emphasized that existing management of water resources in the Henry's Fork watershed results in relatively unaltered conditions in about half of all water years and high to extreme alteration in only about the driest one third of all water years and provides

- A world-class trout fishery in Henry's Lake that is negatively affected by lake drawdown only during the driest years,
- A world-class wild trout fishery below Island Park Dam that derives a large amount of its productivity from trophic processes in the reservoir itself,
- A relatively unaltered stream reach from Warm River to Fall River that supports what are rapidly becoming more popular wild trout fisheries than those upstream in Island Park,
- 60 miles of Fall River that are essentially unaltered, and
- properly functioning riparian and floodplain communities along the lower Fall River and Henry's Fork near St. Anthony that support a high abundance and diversity of plants and animals.

Any attempts at reducing hydrologic alteration in one stream reach under the existing legal and physical system will simply result in increased alteration elsewhere in the watershed and possible degradation of its resources. A fundamental principle of ecological restoration is to not degrade resources that currently exist and ecological processes that currently function. With this in mind, any future management designed to reduce hydrologic alteration to benefit one stream reach or resource should not jeopardize existing resources elsewhere in the system, particularly the ones listed above.

Acknowledgments

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TABLE 1.—Stream reaches and gage stations used in this study.

Reach No.	Reach	Length (mi.)	USGS gage	Gage number	Drainage Area at gage (sq. mi.)	Mean annual discharge at gage (acre-ft)*	Water years used in this study
1	Henry's Lake Dam to Big Springs	9.9	H.F. near Lake	13039500	99	47,876	1972-2002
2	Big Springs to Island Park Res.	9.2	H.F. below Coffee Pot Rapids nr. Macks Inn	13041010	261	350,131	1996-2002
3	Island Park Dam to Buffalo River	0.38	H.F. near Island Park	13042500	481	498,851	1972-2002
4	Buffalo River to Warm River	34	H.F near I.P. + Buffalo R. at I.P.	13042500 + 13043000	521	636,147	1972-2002
5	Warm River to Fall River	17	H.F. near Ashton	13046000	1,040	1,254,364	1972-2002
6	Fall River above Marysville Canal	35	F.R. ab. Yellowstone Canal near Squirrel	13046995	322	676,708	11/16/94-9/30/02
7	F.R. Marysville Canal to Kirkham Bridge***	6.6	F.R. near Squirrel (post power plant)	13047500	326	659,118	8/22/93-9/30/02
8	F.R. Kirkham Bridge to Enterprise Canal	9.2	F.R. near Ashton (Kirkham Bridge)	13047600	334	669,754	11/16/94-9/30/02
9	F.R. Marysville Canal to Enterprise Canal	16	F.R. near Squirrel (pre power plant)	13047500	326	630,411	10/1/72-8/21/93
10	F.R. Enterprise Canal to H.F.	5.0	F.R. near Chester	13049500	520	738,862	1972-2002
11	H.F. Fall River to St. Anthony	6.8	H.F. at St. Anthony	13050500	1,770	2,036,085	1972-2002

*Mean of annual natural discharge computed over water years listed in last column.

** Buffalo River daily discharge for all study years taken as mean discharge each day over water years 1936-1940 (only years for which data are available).

***Marysville hydroelectric power plant diverts water at Marysville Canal and returns flow at Kirkham Bridge.

TABLE 2.—Alteration classes based on watershed-averaged natural range of variability analysis.

Alteration Class	Alteration Range	Number of days during water year alteration from natural daily median flow falls within natural range
Low	< 22.8%	365
Moderate	22.8% - 42.6%	100-364
High	42.6% - 64.5%	3-99
Extreme	> 64.5%	≤ 2

TABLE 3.—Comparison of average annual alteration with upstream storage and diversion statistics for each stream reach.

Reach No.	Reach	Median of mean annual alteration	Mean of mean annual alteration	Upstream storage/ mean ann. discharge	Upstream diversions/ mean ann. discharge
1	Henry's Lake Dam to Big Springs	87%	420%	190%	0.00%
2	Big Springs to Island Park Res.	7.4%	10%	26%	0.00%
3	Island Park Dam to Buffalo River	43%	44%	45%	0.00%
4	Buffalo River to Warm River	32%	33%	35%	0.00%
5	Warm River to Fall River	17%	17%	18%	0.60%
6	Fall River above Marysville Canal	1.3%	1.4%	2.2%	0.00%
7	F.R. Marysville Canal to Enterprise Canal	5.3% (pre power plant)	5.4% (pre power plant)	2.4%	4.6%
8	F.R. Marysville Canal to Kirkham Bridge	50% (post power plant)	51% (post power plant)	2.3%	41%
9	F.R. Kirkham Bridge to Enterprise Canal	4.5%	5.0%	2.3%	4.3%
10	F.R. Enterprise Canal to H.F.	21%	23%	2.1%	21%
11	H.F. Fall River to St. Anthony	27%	28%	12%	30%

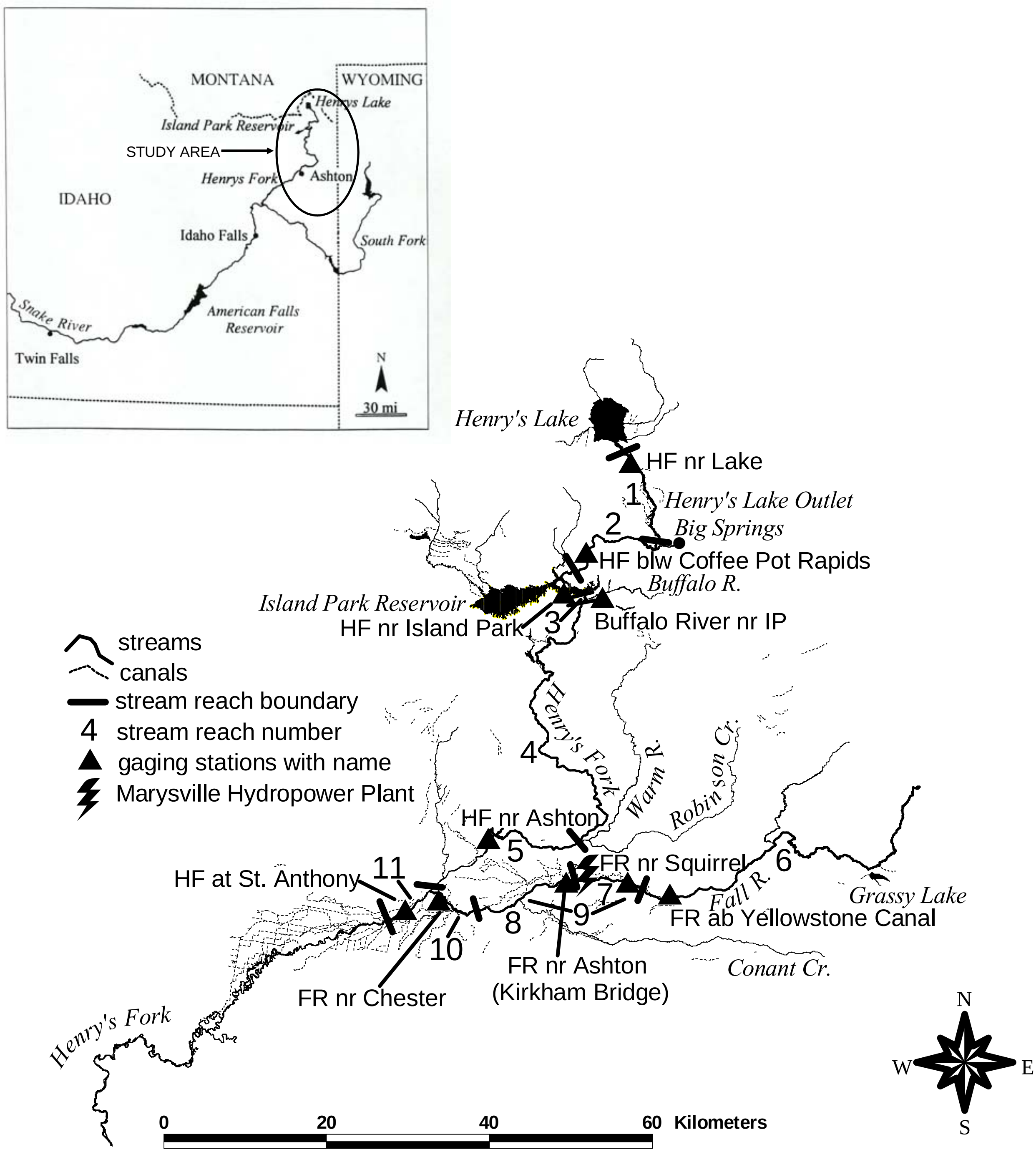


FIGURE 1.—Study area map. Reach numbers and gage station names correspond to those listed in Table 1.

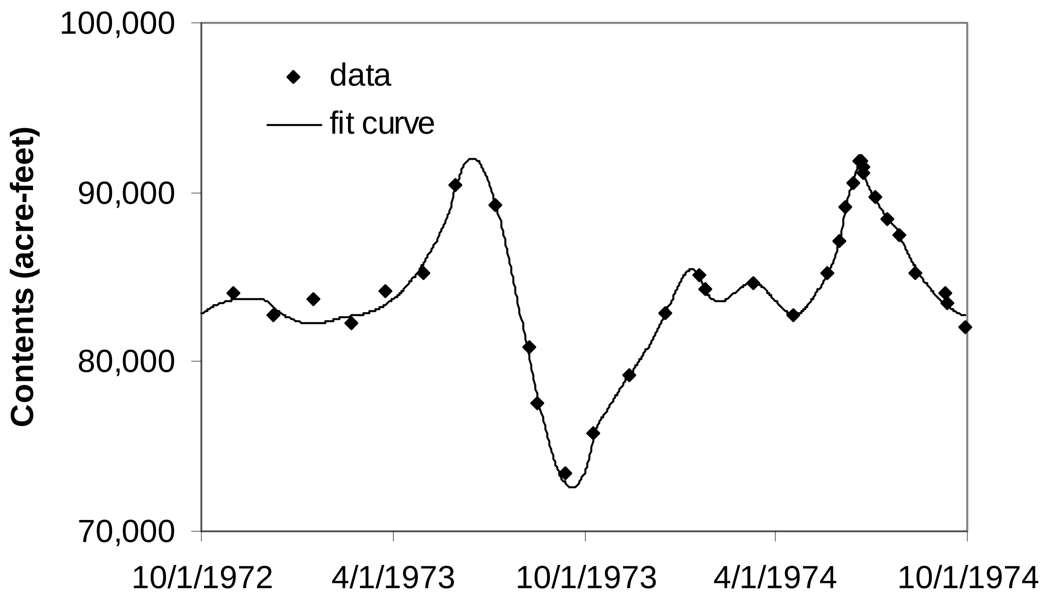


FIGURE 2.—Example of Henry's Lake contents curve fit to data collected prior to installation of the continuous recording gage using a combination of polynomial regression and splines.

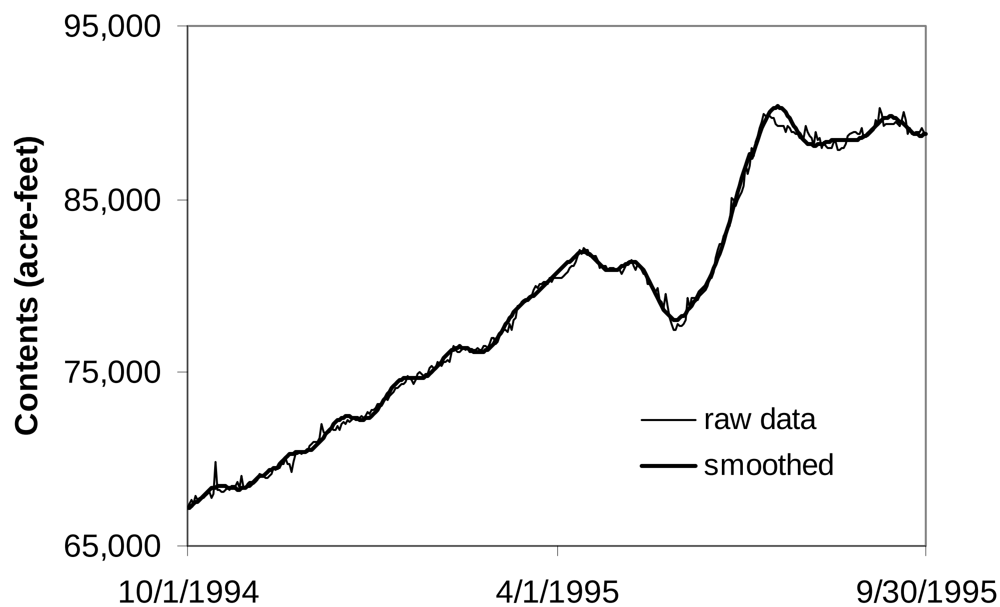
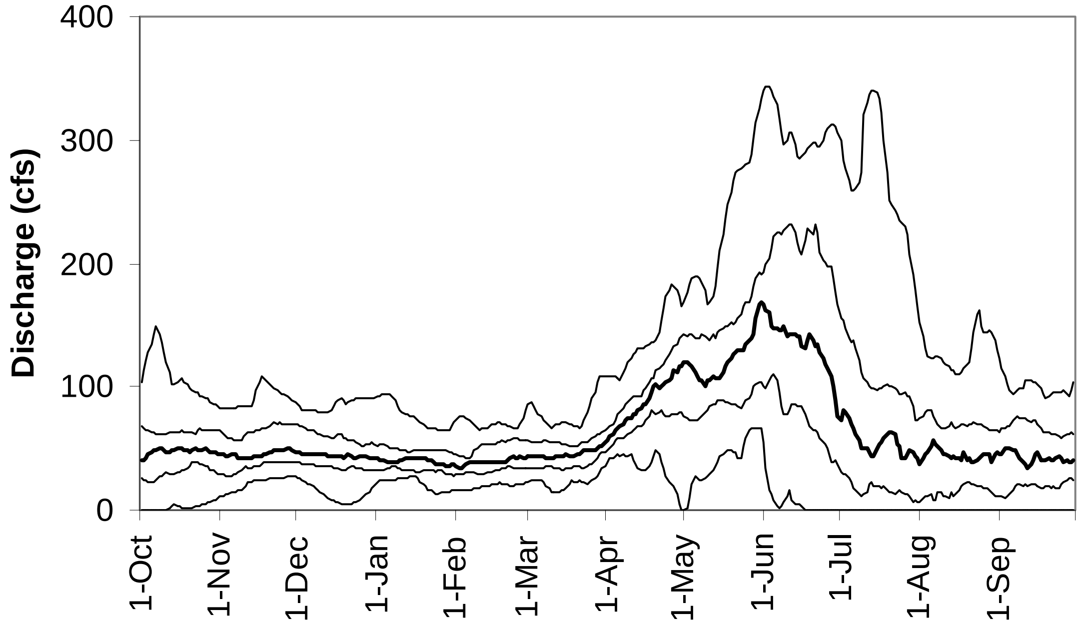
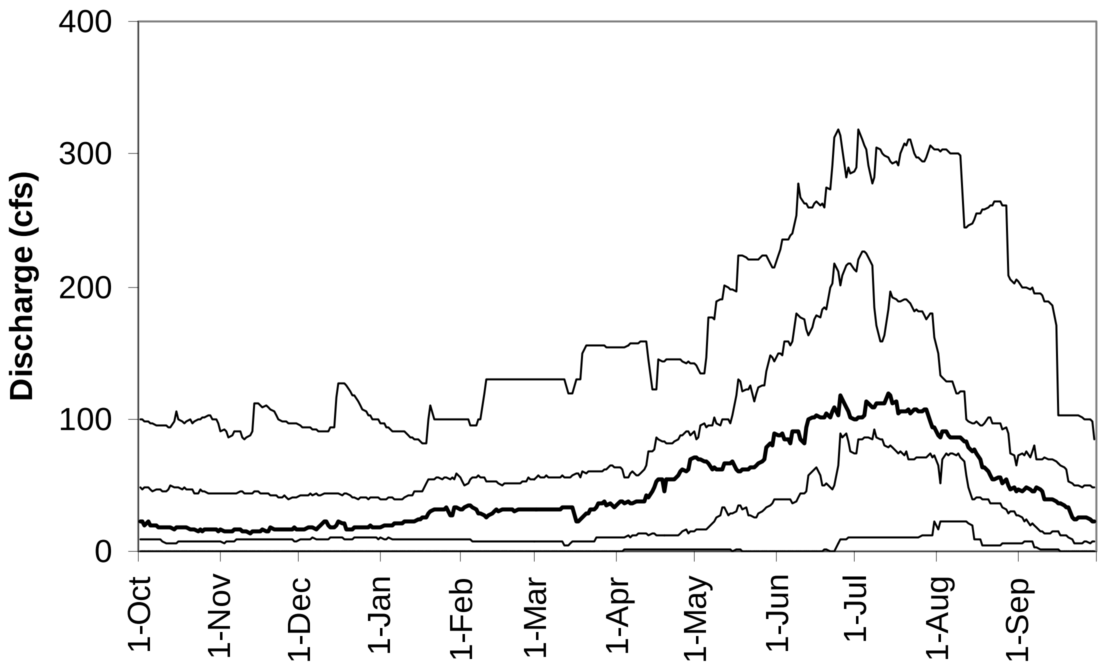


FIGURE 3.—Example of Henry's Lake contents curve smoothed from daily data collected by the continuous recording gage using a Fourier series filter with minimum period of 28 days.



a. Natural Flow.



b. Regulated Flow.

FIGURE 4.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow at Henry's Lake Outlet for water years 1972-2002.

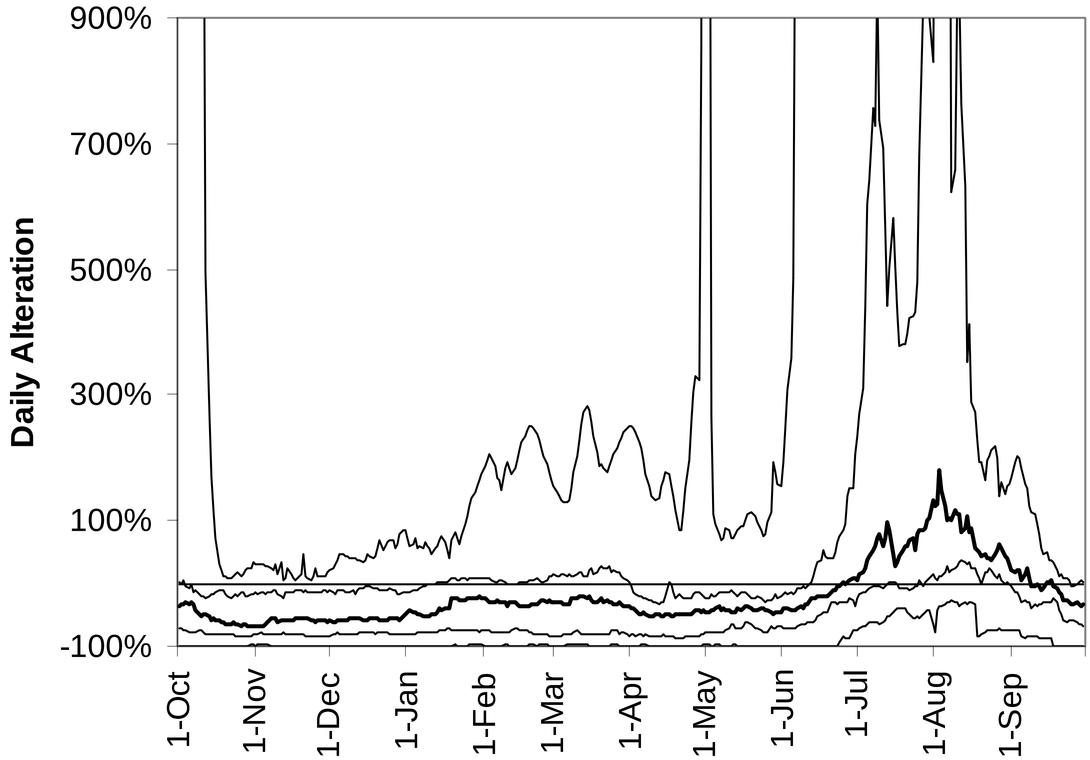


FIGURE 5.—Median, 25th and 75th percentiles, and extremes of daily flow alteration at Henry's Lake Outlet for water years 1972-2002.

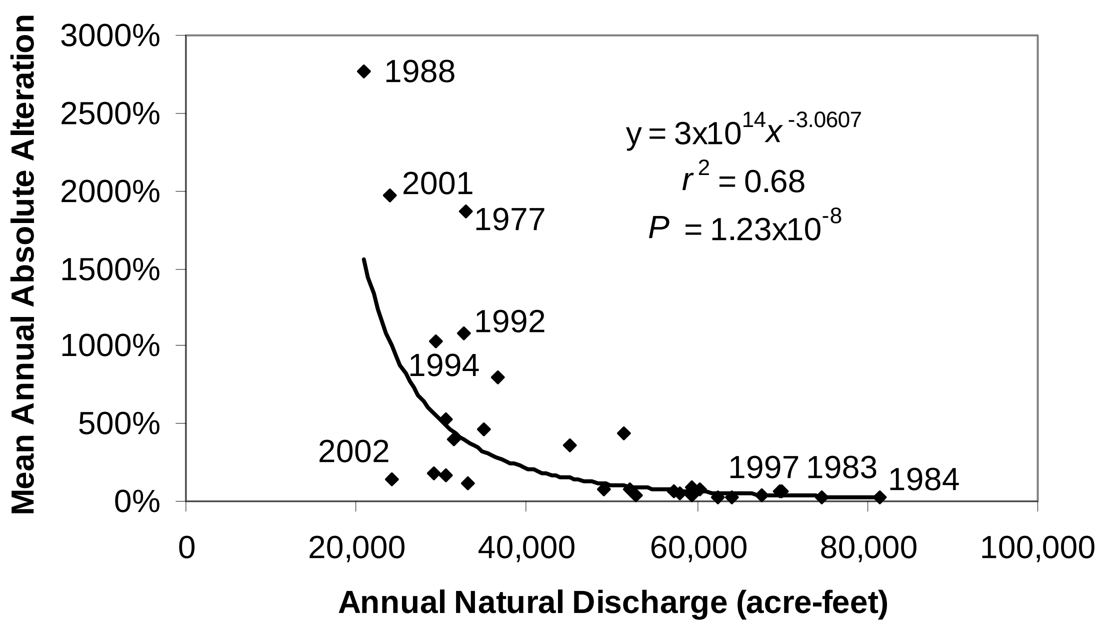
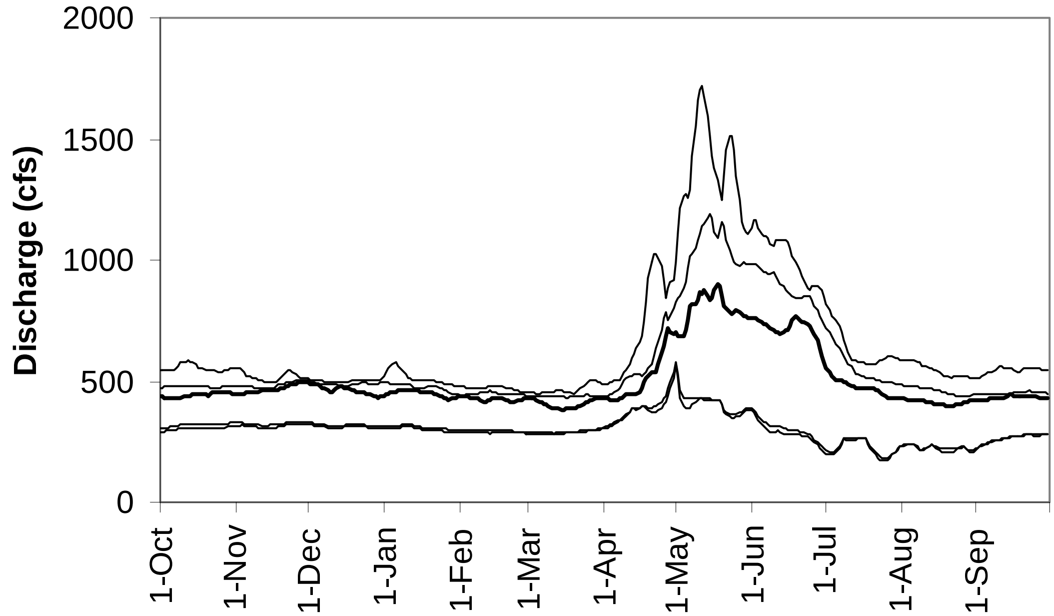
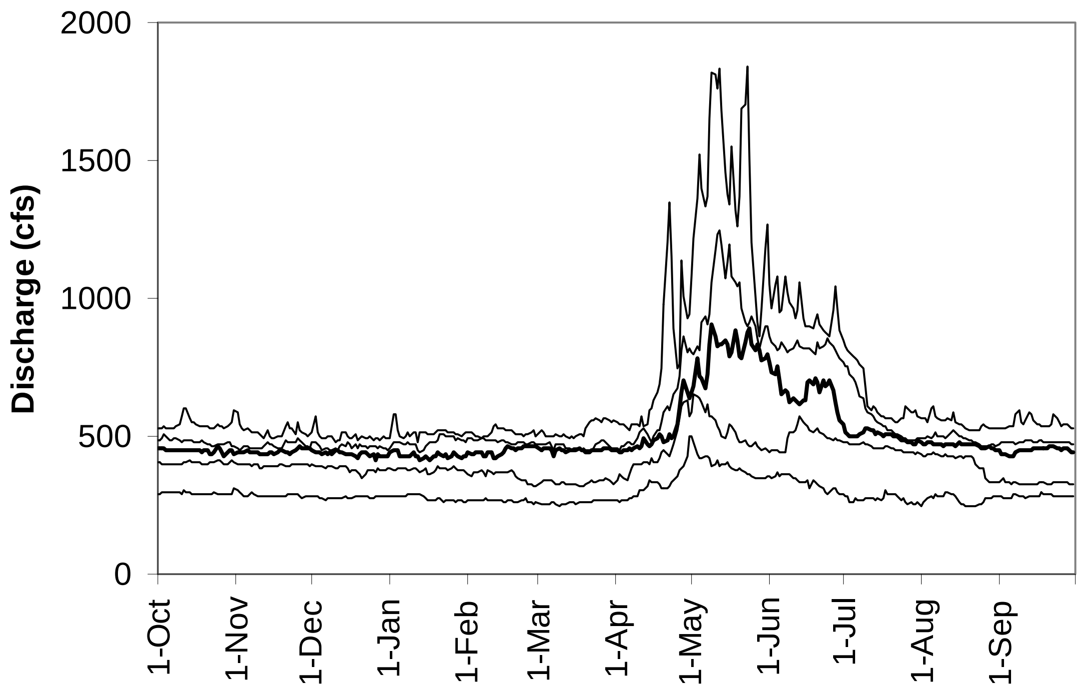


FIGURE 6.—Relationship between annual alteration and discharge at Henry's Lake Outlet for water years 1972-2002. Water years of extreme data points are labeled.



a. Natural Flow.



b. Regulated Flow.

FIGURE 7.—Median, 25^{th} and 75^{th} percentiles, and extremes for natural (a) and regulated (b) flow at Coffee Pot water years 1996-2002.

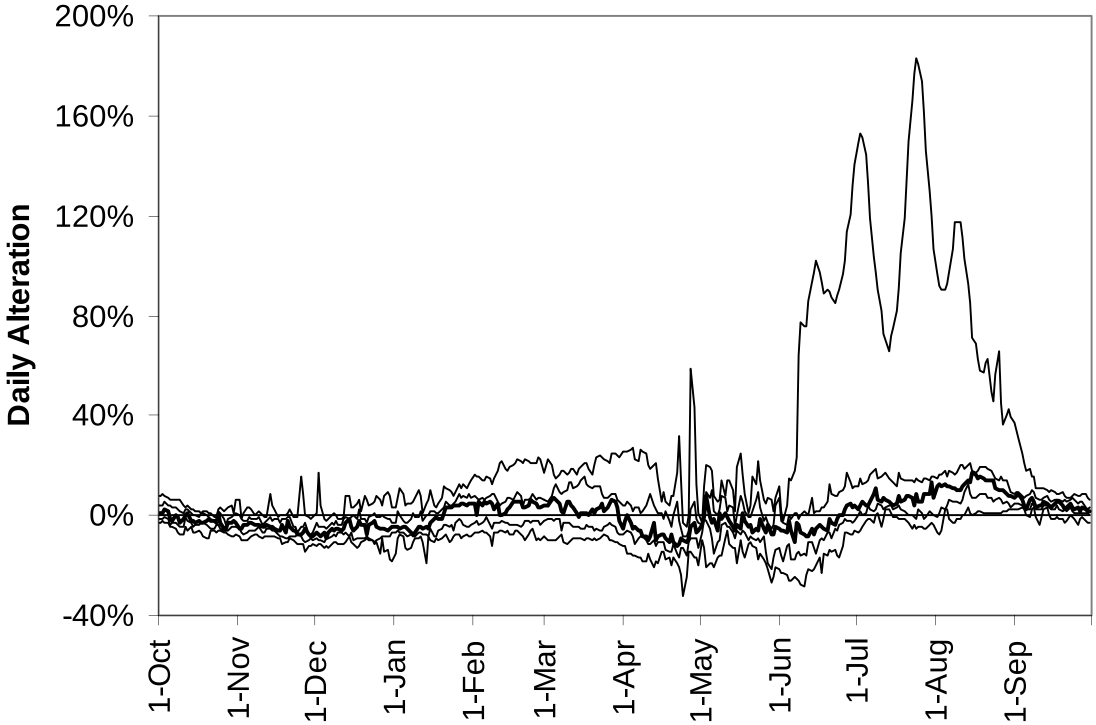


FIGURE 8.—Median, 25th and 75th percentiles, and extremes of daily flow alteration at Coffee Pot water years 1996-2002.

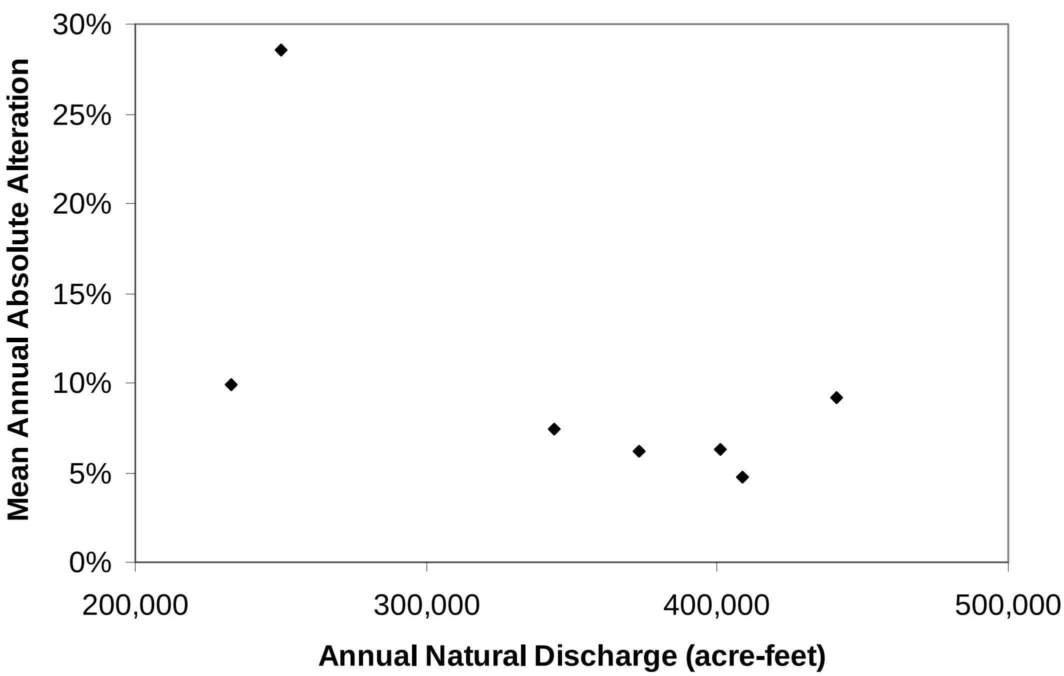
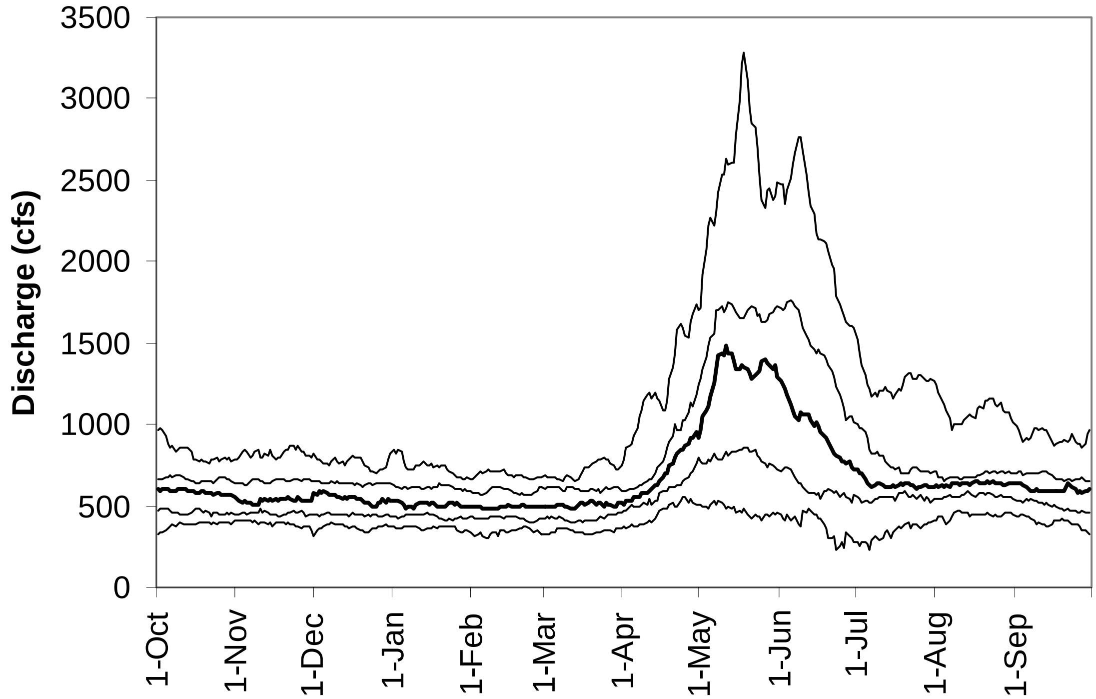
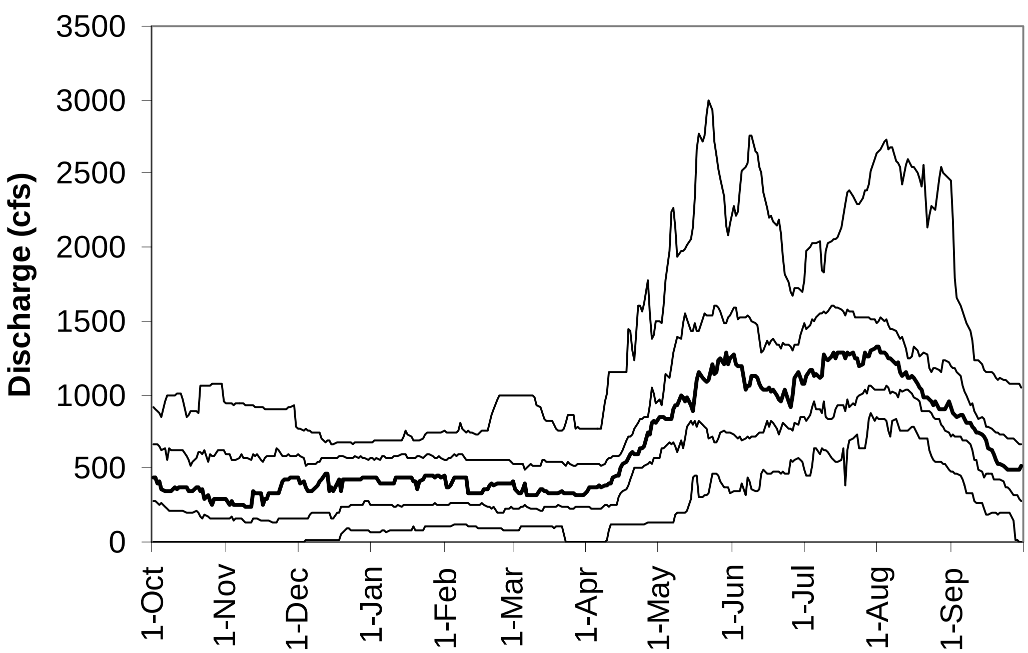


FIGURE 9.—Relationship between annual alteration and discharge at Coffee Pot for water years 1996-2002.



a. Natural Flow



b. Regulated Flow

FIGURE 10.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow at Island Park for water years 1972-2002.

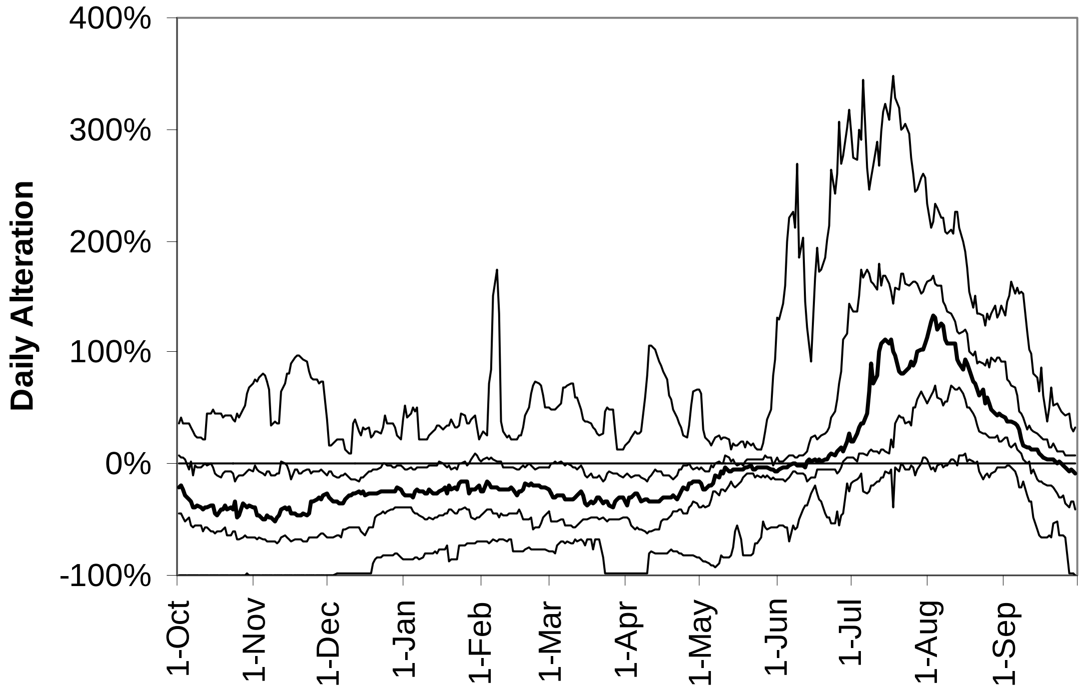


FIGURE 11.—Median, 25th and 75th percentiles, and extremes of daily flow alteration at Island Park for water years 1972-2002.

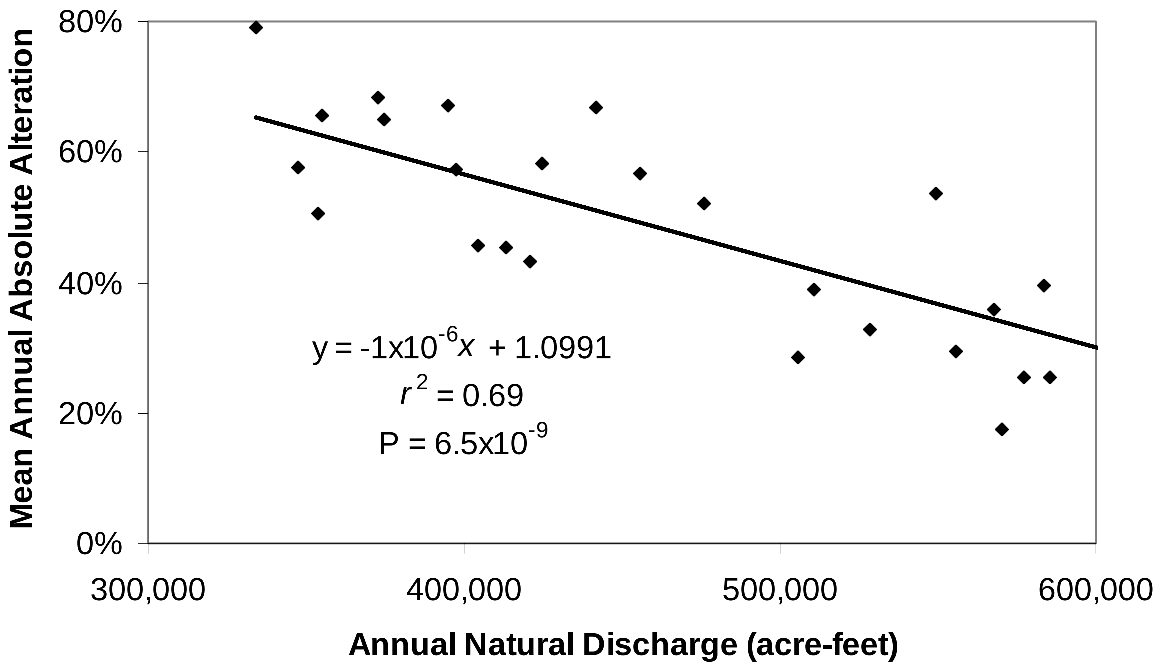
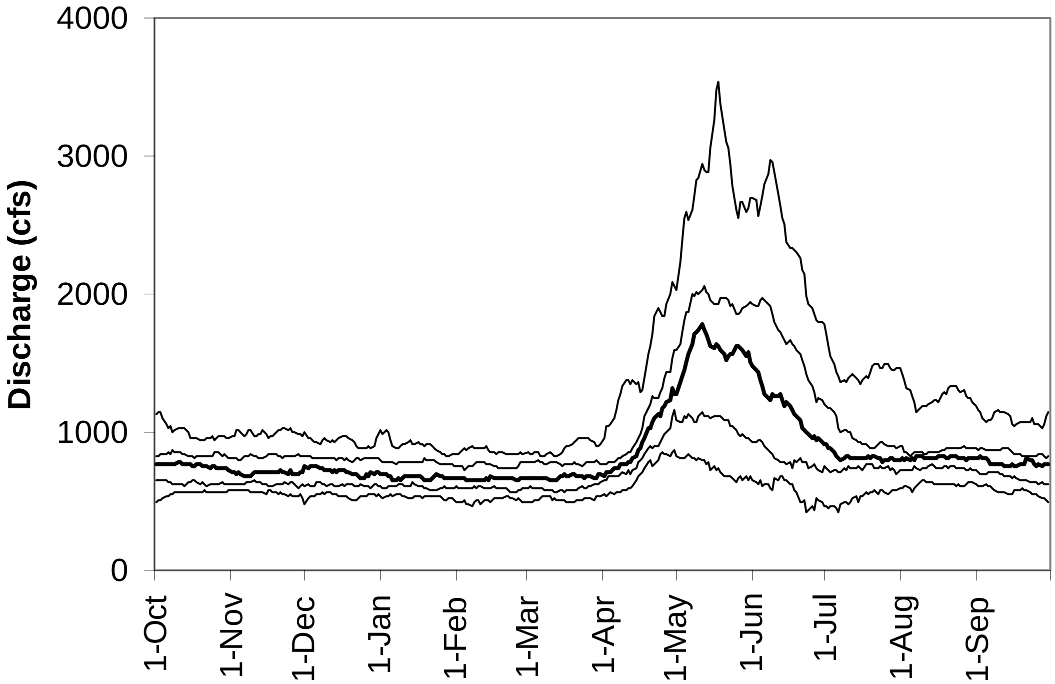
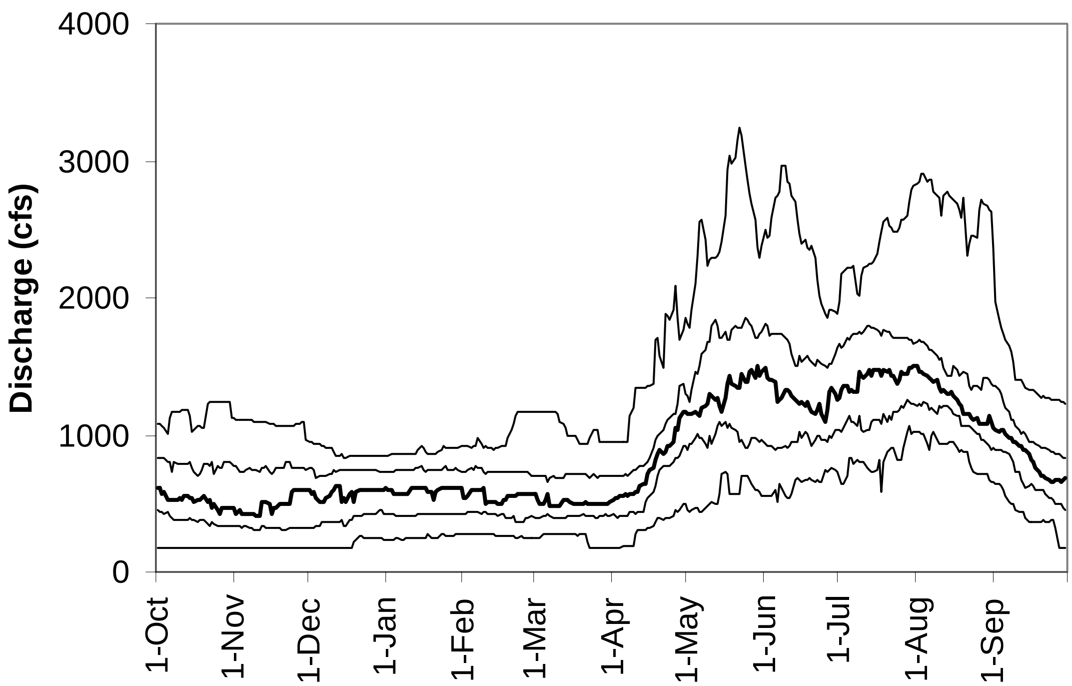


FIGURE 12.—Relationship between annual alteration and discharge at Island Park for water years 1972-2002.



a. Natural Flow.



b. Regulated Flow.

FIGURE 13.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow below Buffalo River for water years 1972-2002.

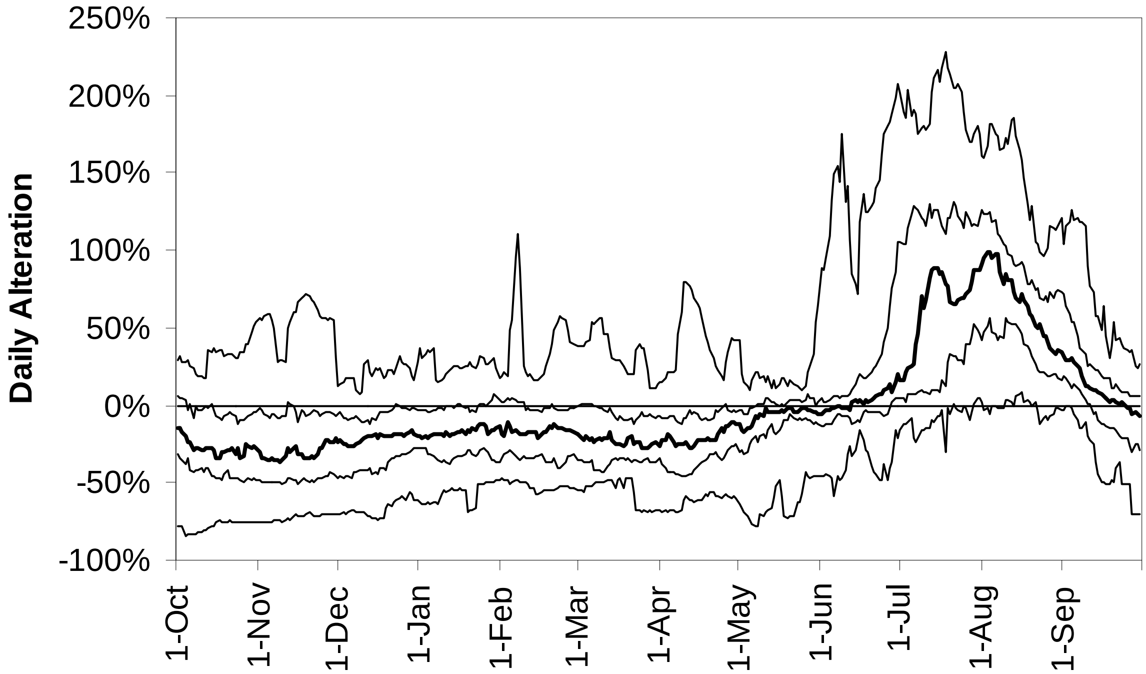


FIGURE 14.—Median, 25th and 75th percentiles, and extremes of daily flow alteration below Buffalo River for water years 1972-2002.

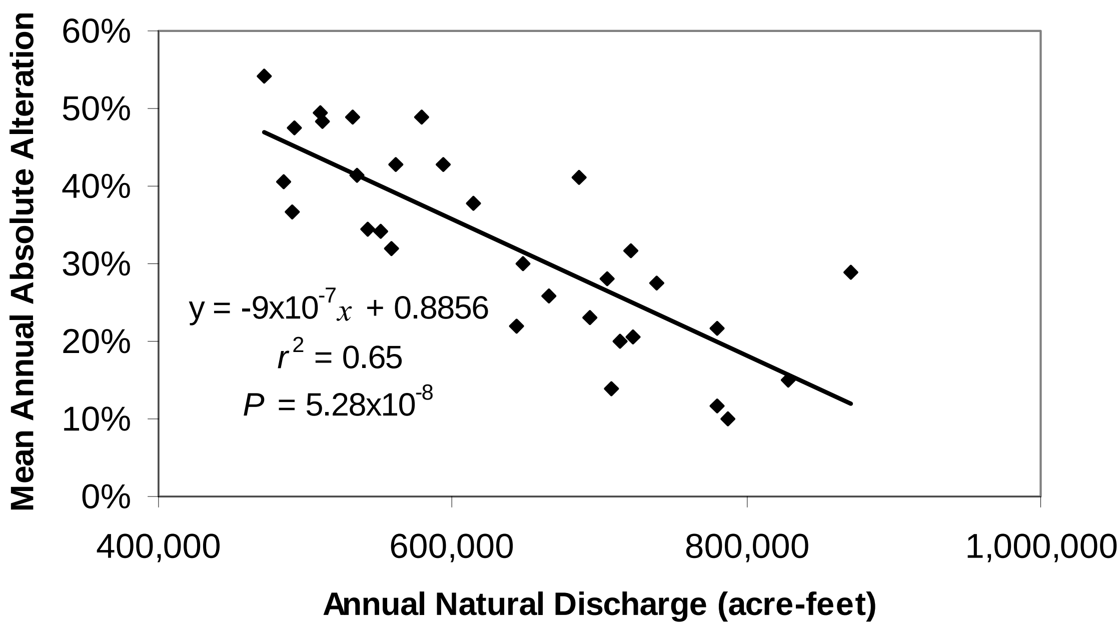
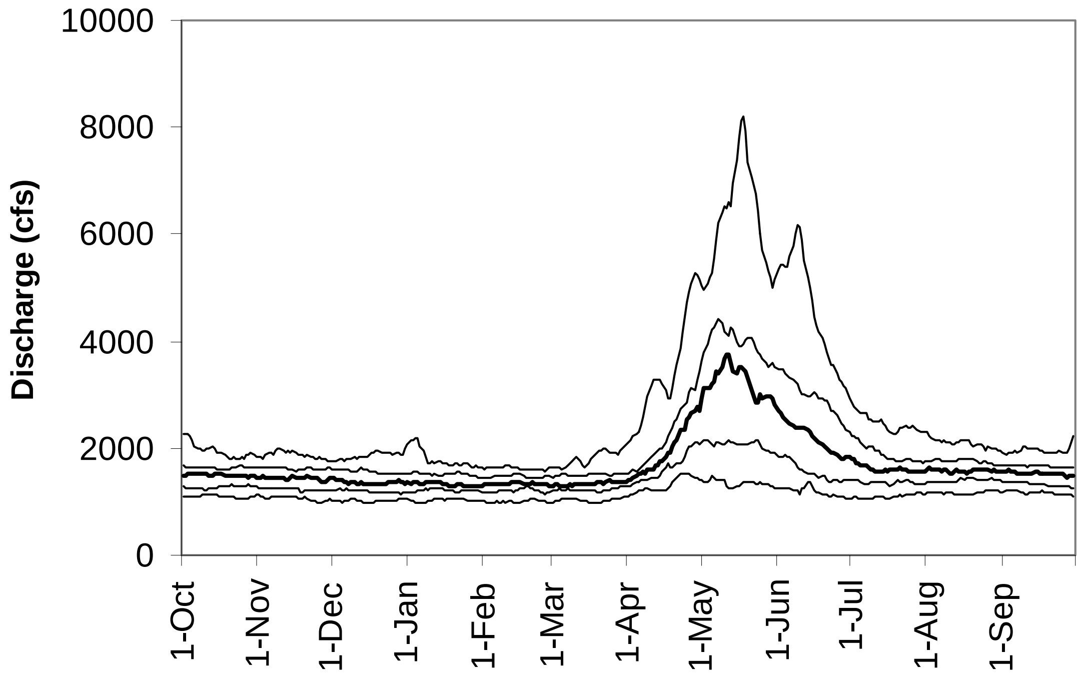
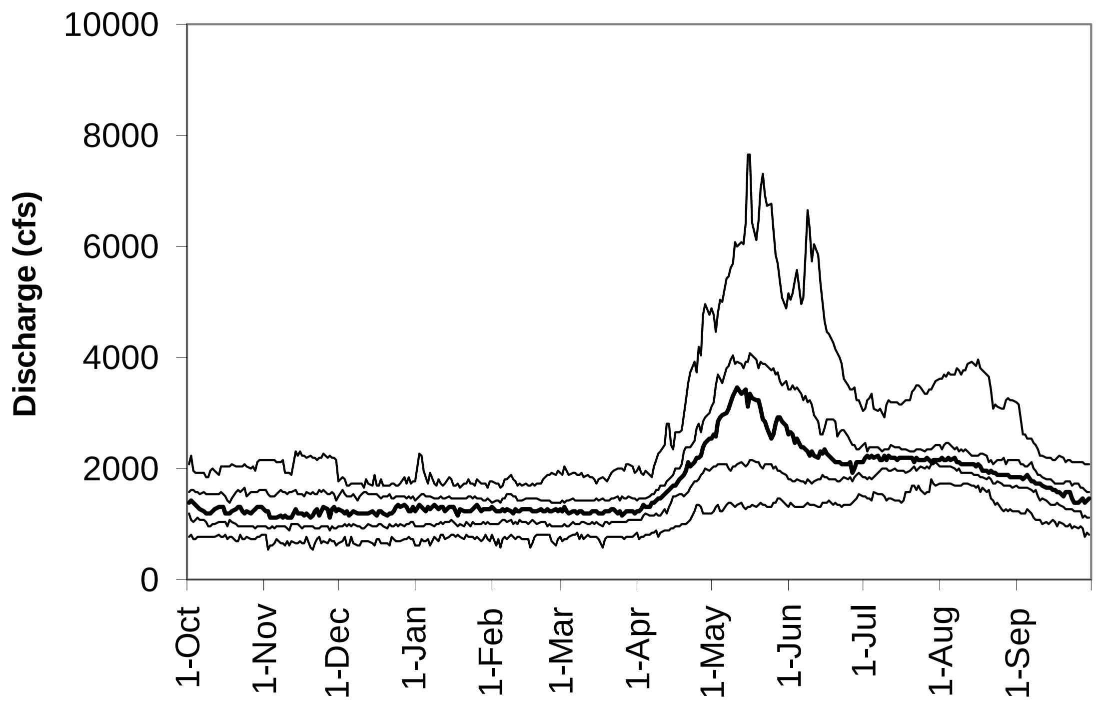


FIGURE 15.—Relationship between annual alteration and discharge below Buffalo River for water years 1972-2002.



a. Natural Flow.



b. Regulated Flow.

FIGURE 16.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow at Ashton for water years 1972-2002.

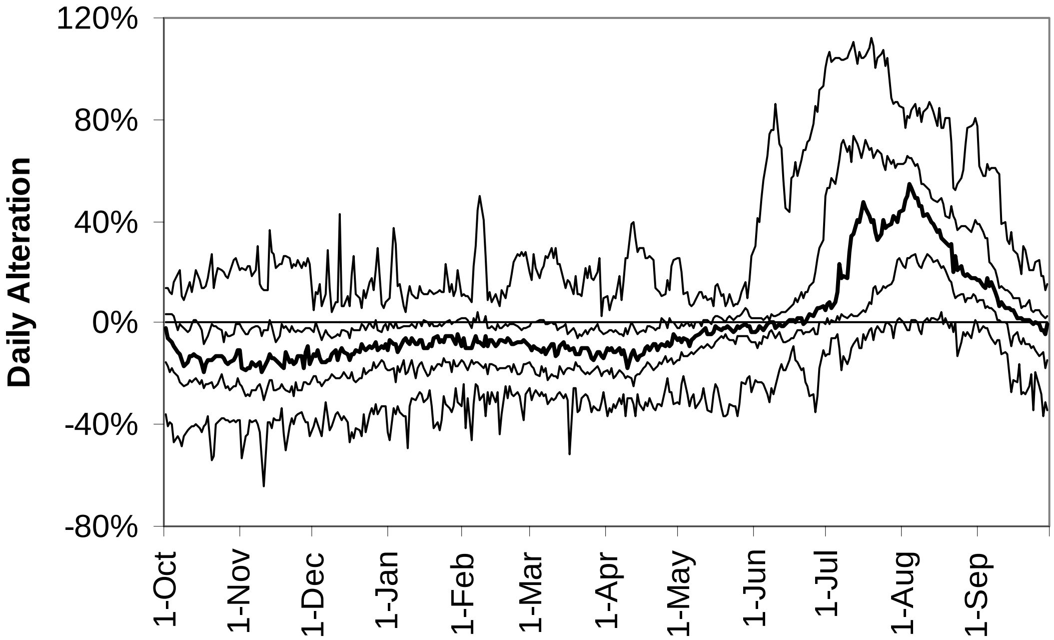


FIGURE 17.—Median, 25th and 75th percentiles, and extremes of daily flow alteration at Ashton for water years 1972-2002.

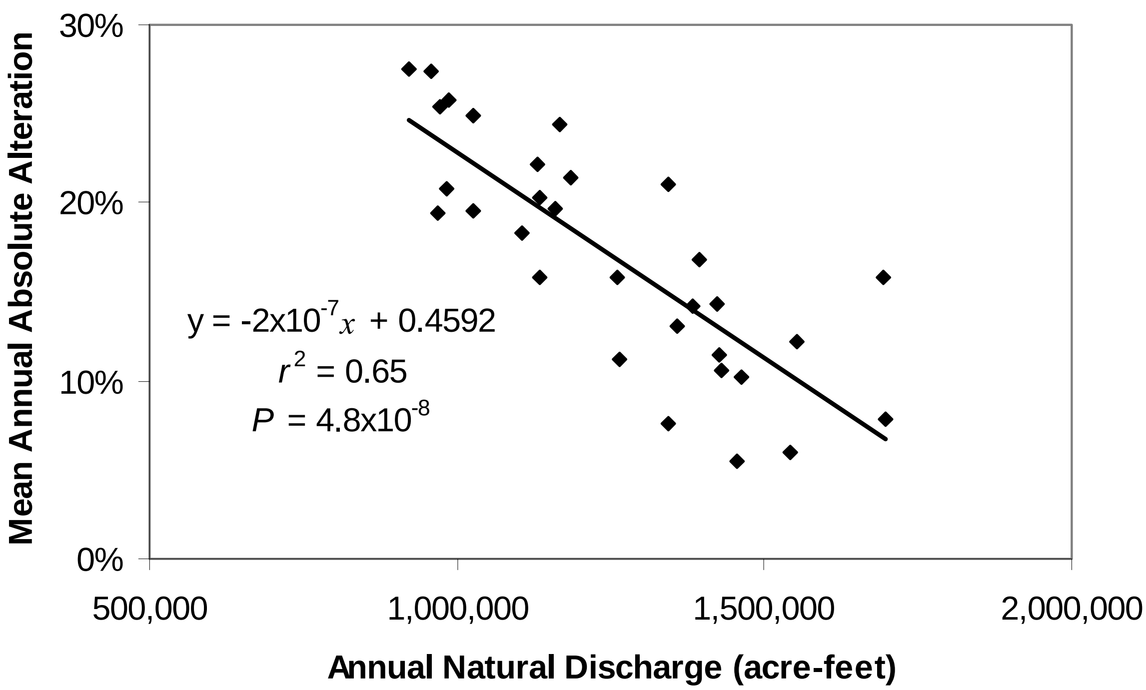
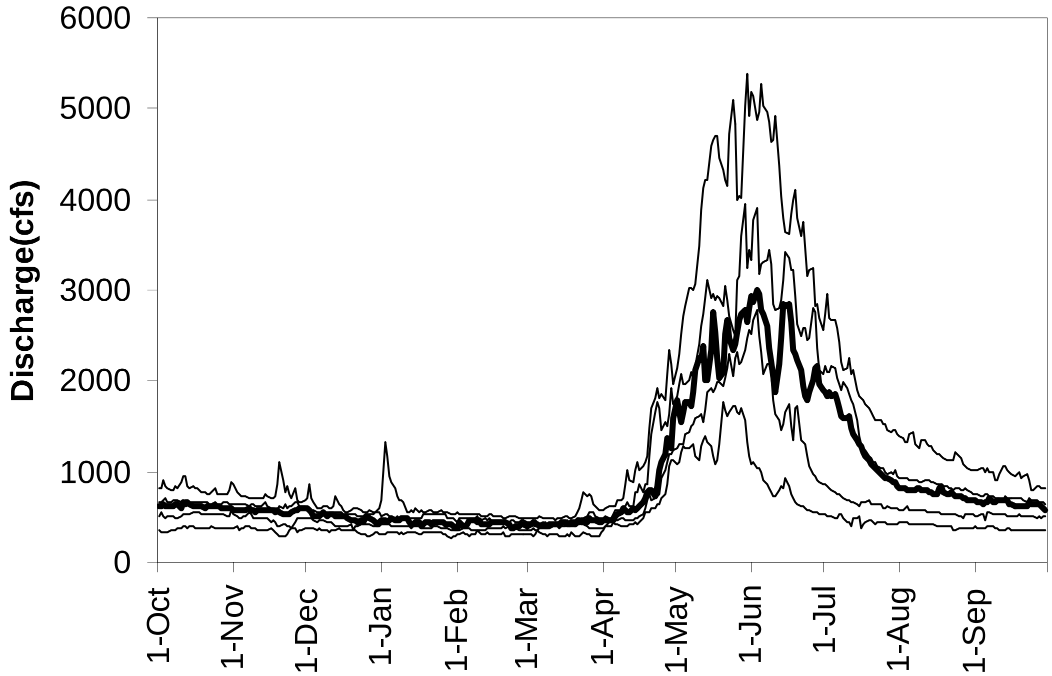
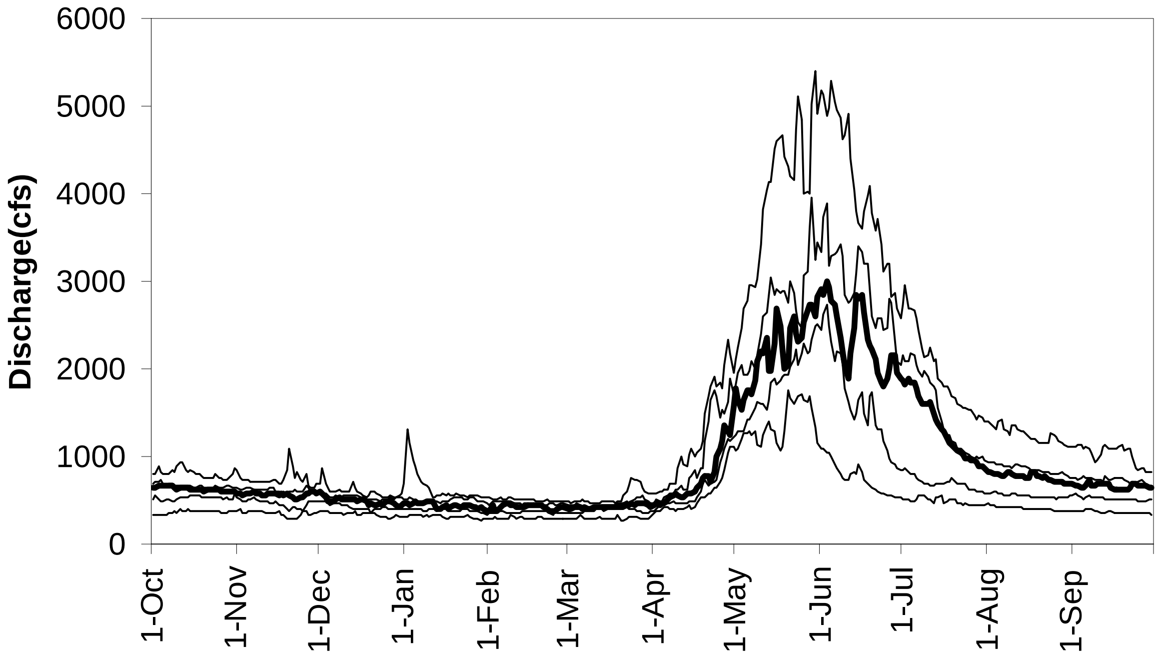


FIGURE 18.—Relationship between annual alteration and discharge at Ashton for water years 1972-2002.



a. Natural Flow



b. Regulated Flow

FIGURE 19.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow in Fall River above Yellowstone Canal 16 November 1994 to 30 September 2002.

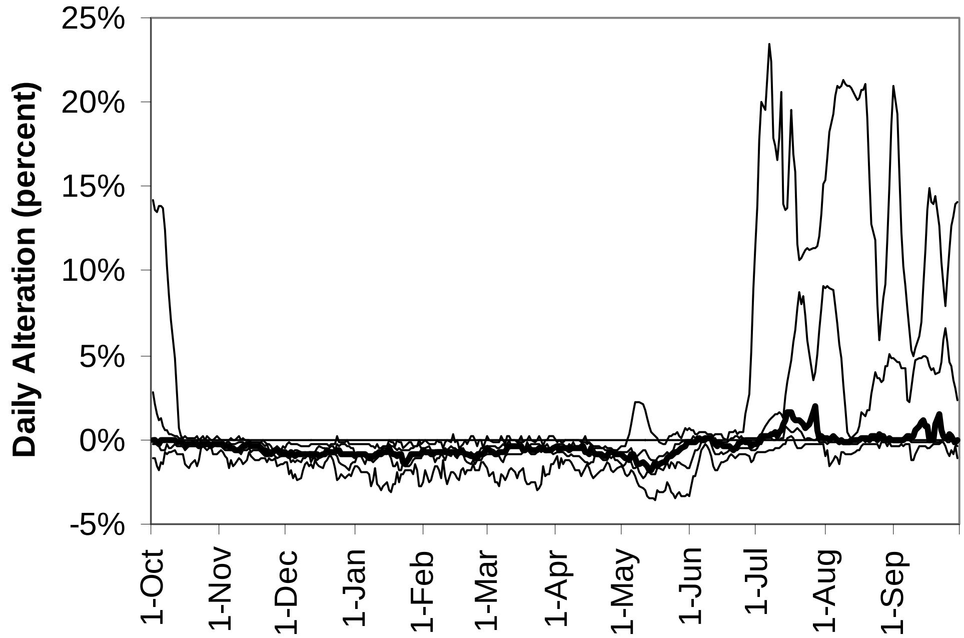


FIGURE 20.—Median, 25th and 75th percentiles, and extremes of daily flow alteration in Fall River above Yellowstone Canal 16 November 1994 to 30 September 2002.

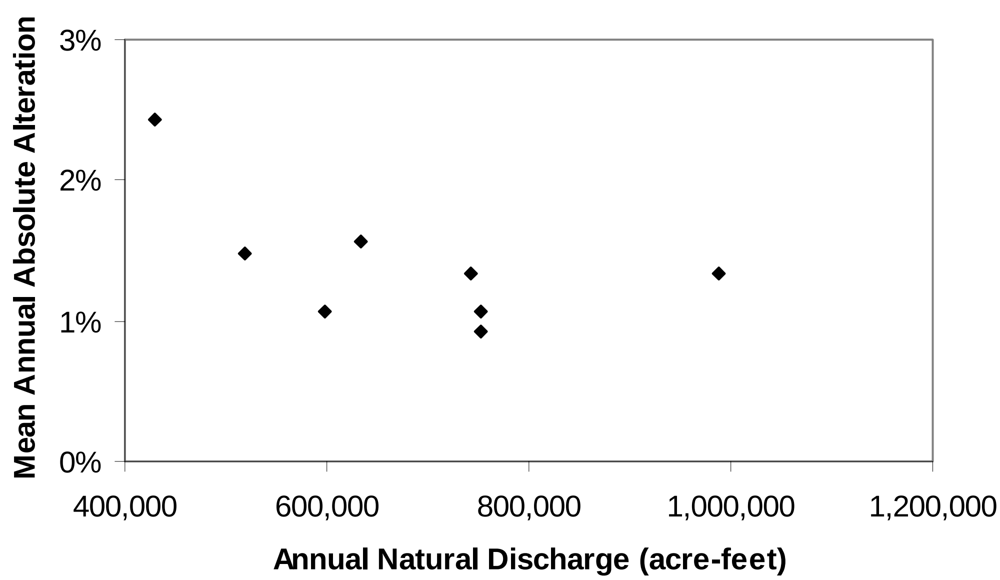
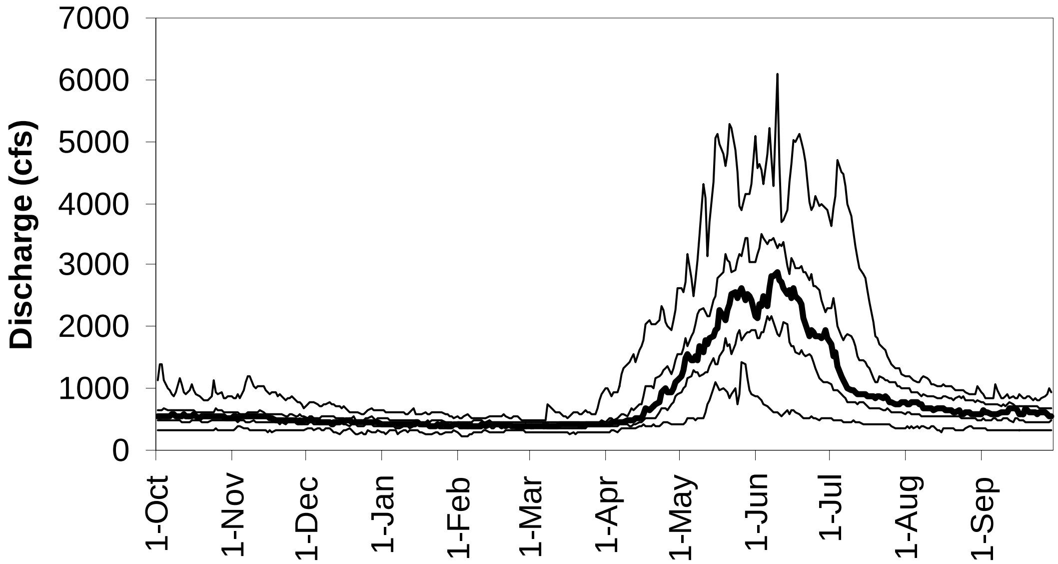
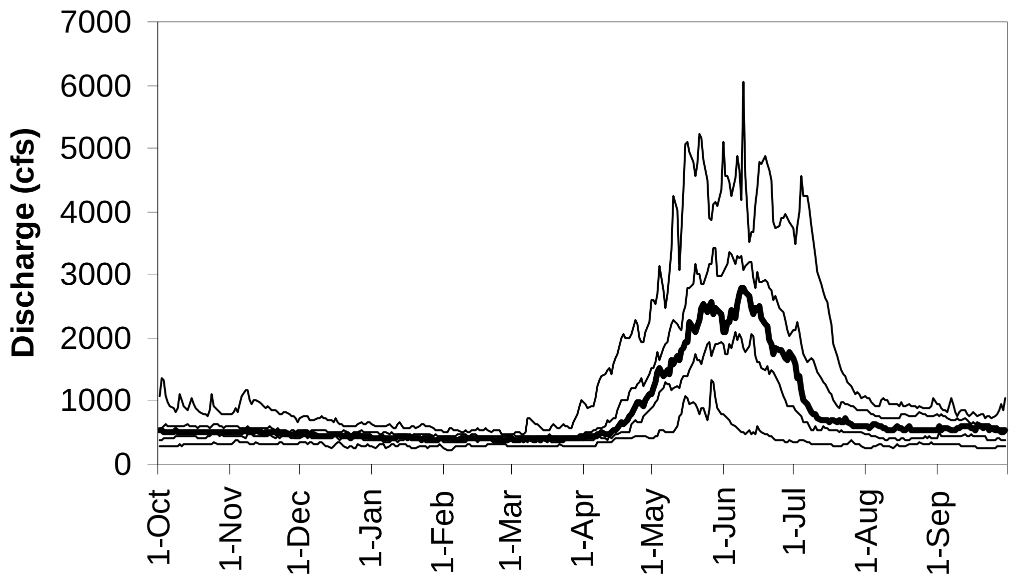


FIGURE 21.—Relationship between annual alteration and discharge in Fall River above Yellowstone Canal for water years 1995-2002.



a. Natural Flow



b. Regulated Flow

FIGURE 22.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow in Fall River at Squirrel 1 October 1972 to 21 August 1993 (pre power plant).

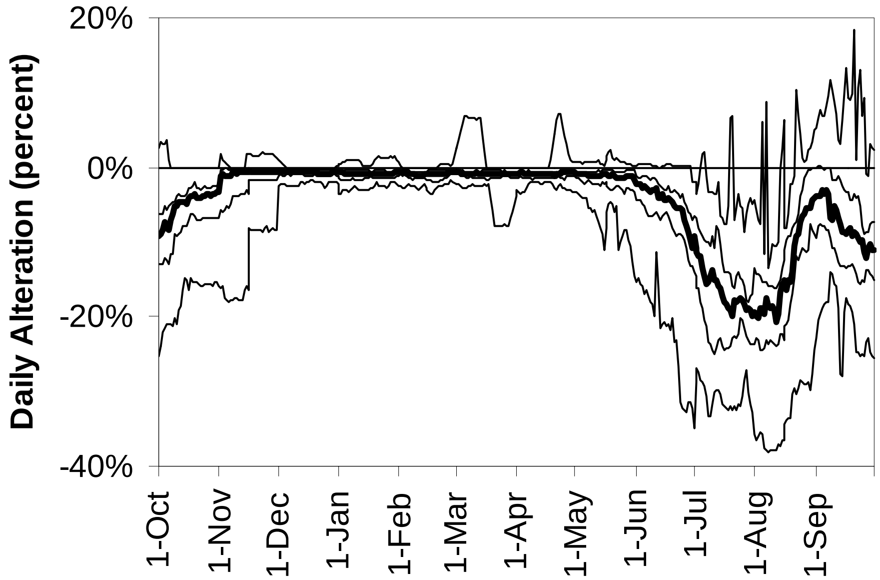


FIGURE 23.—Median, 25th and 75th percentiles, and extremes of daily flow alteration in Fall River at Squirrel 1 October 1972 to 21 August 1993 (pre power plant).

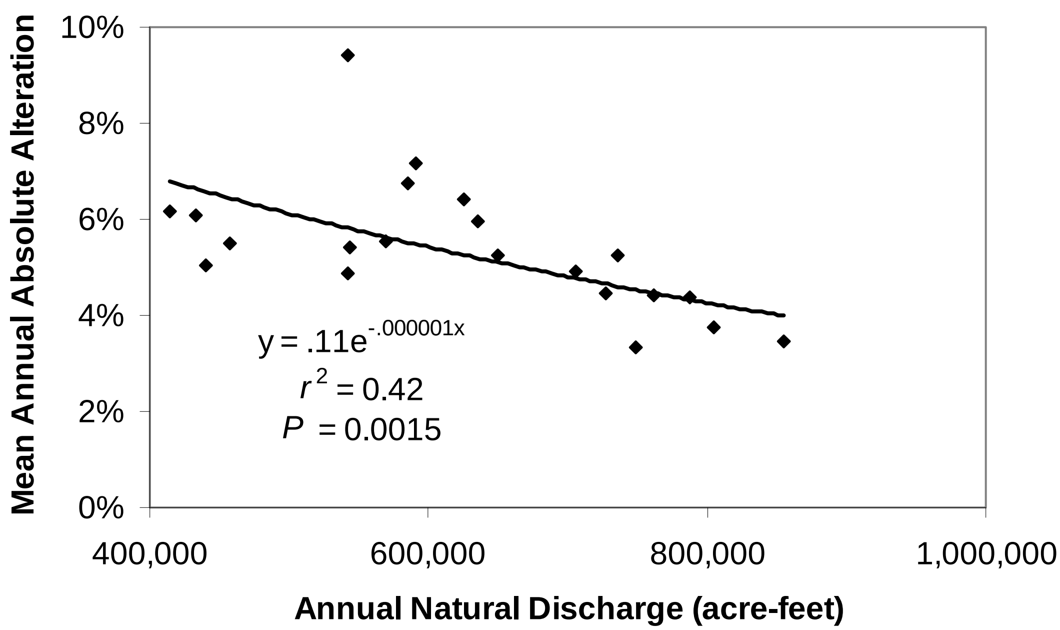
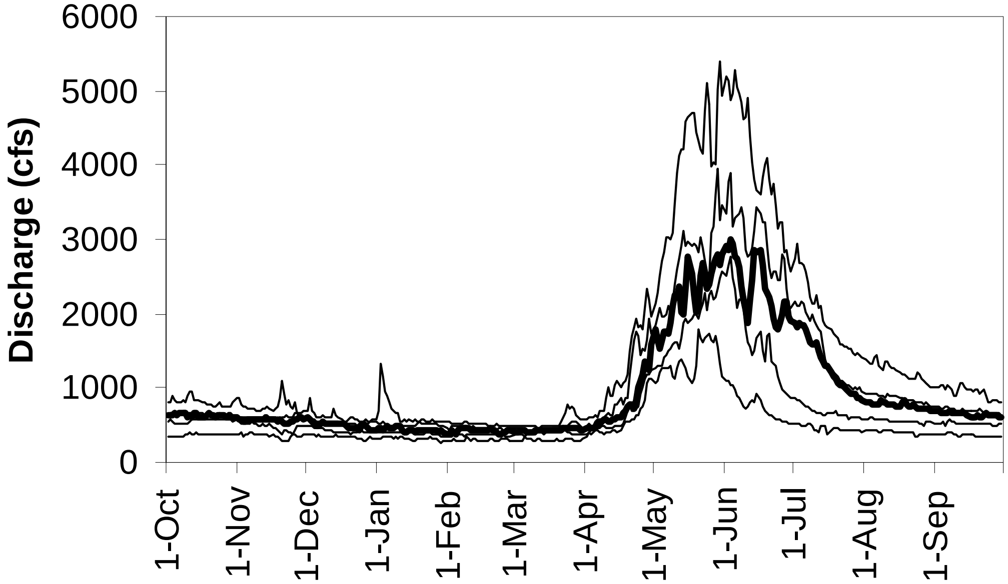
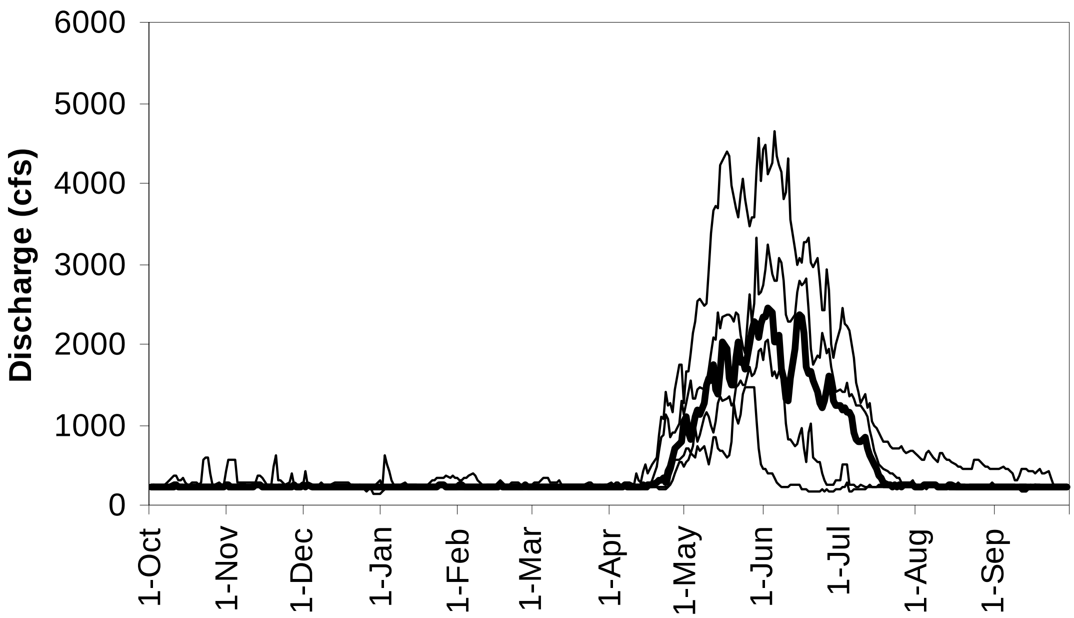


FIGURE 24.—Relationship between annual alteration and discharge in Fall River at Squirrel for water years 1972-1992 (pre power plant).



a. Natural Flow



b. Regulated Flow

FIGURE 25.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow in Fall River at Squirrel 22 August 1993 to 30 September 2002 (post power plant).

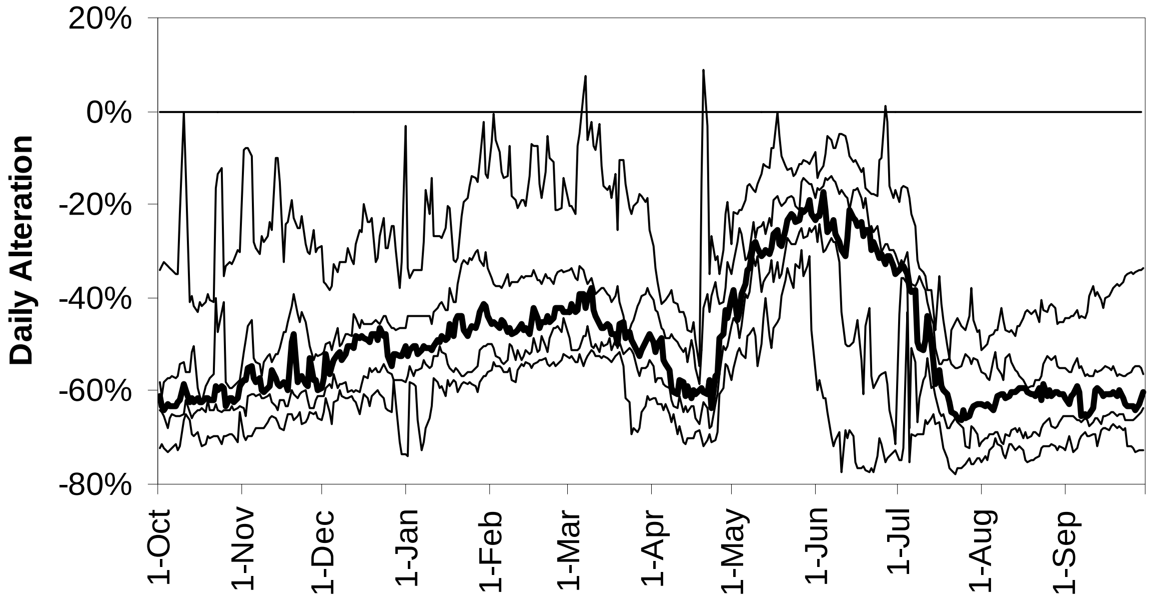


FIGURE 26.—Median, 25th and 75th percentiles, and extremes of daily flow alteration in Fall River at Squirrel 22 August 1993 to 30 September 2002 (post power plant).

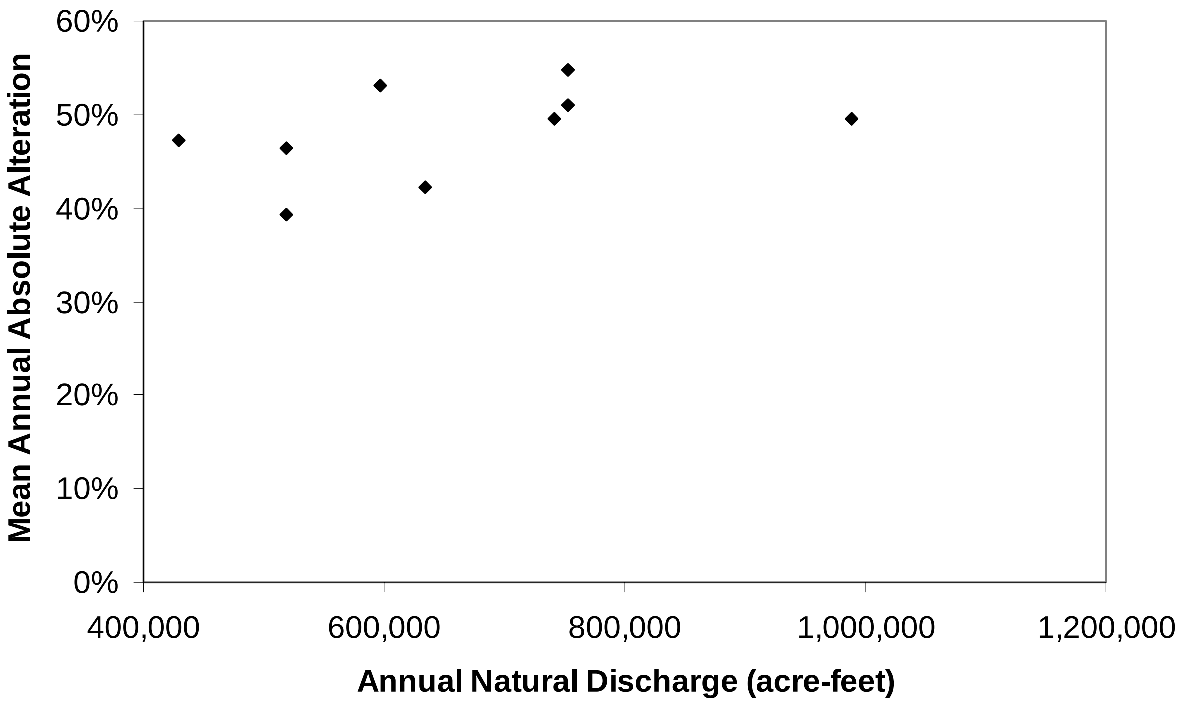
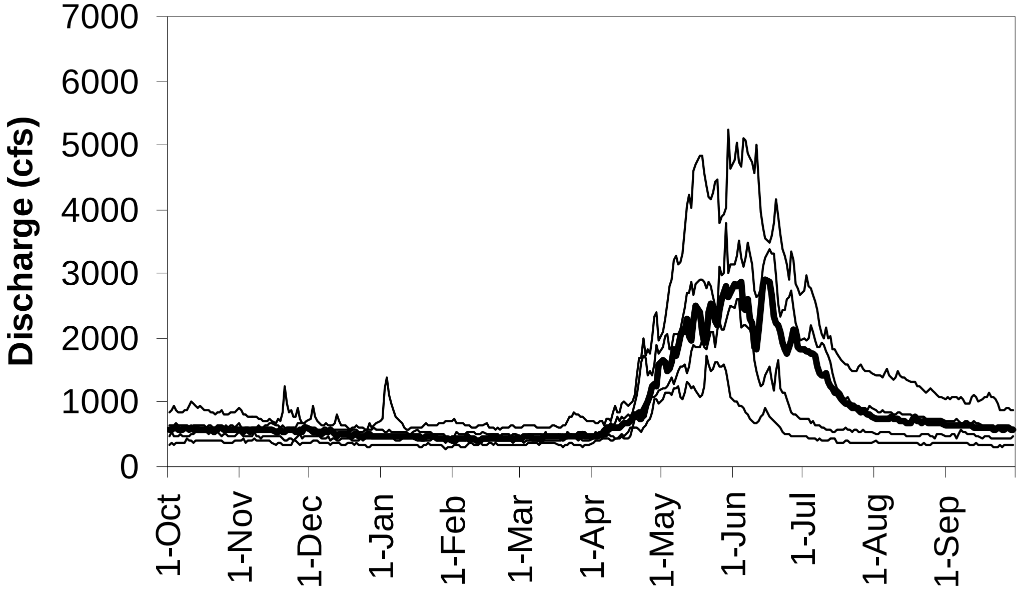
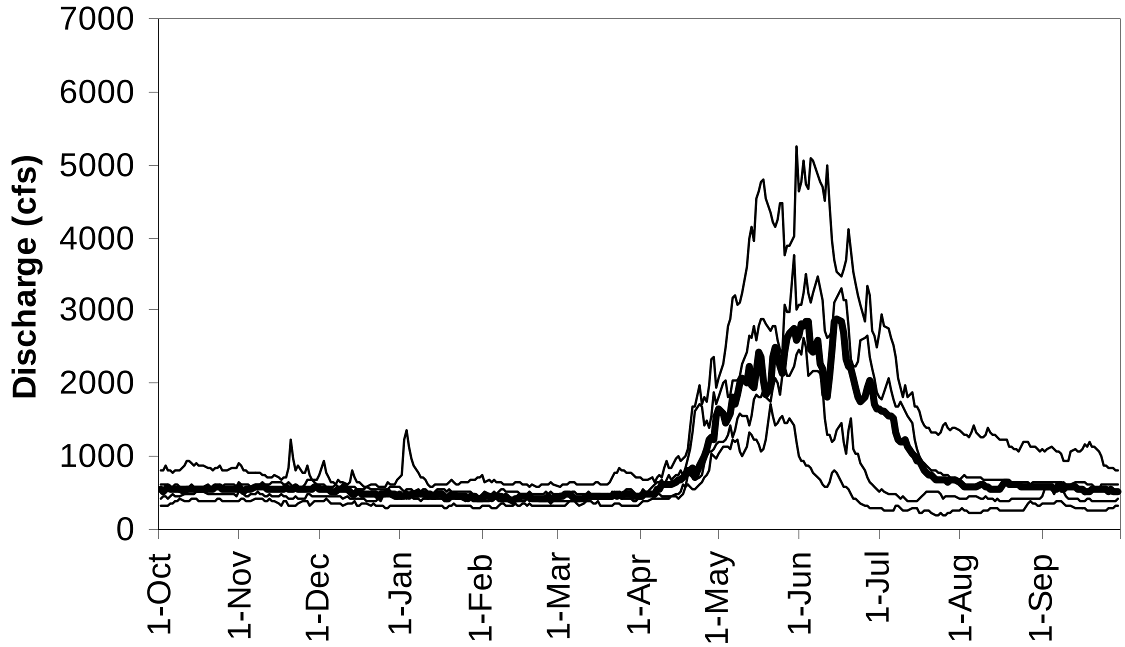


FIGURE 27.—Relationship between annual alteration and discharge in Fall River at Squirrel for water years 1994-2002 (post power plant).



a. Natural Flow



b. Regulated Flow

FIGURE 28.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow in Fall River near Ashton (below power plant) 11 November 1994 to 30 September 2002.

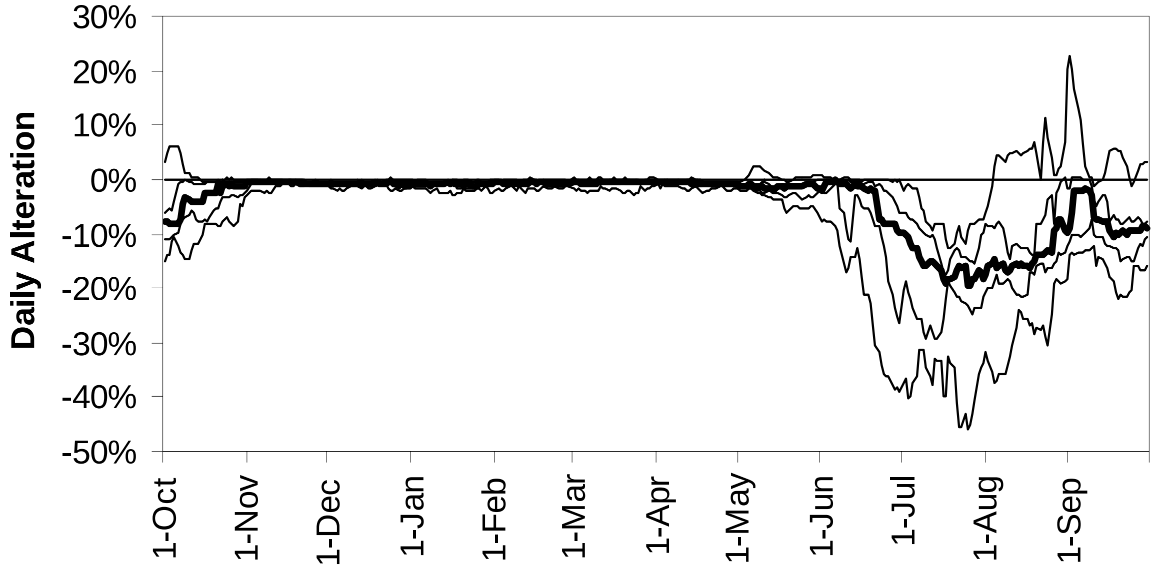


FIGURE 29.—Median, 25th and 75th percentiles, and extremes of daily flow alteration in Fall River near Ashton (below power plant) 11 November 1994 to 30 September 2002.

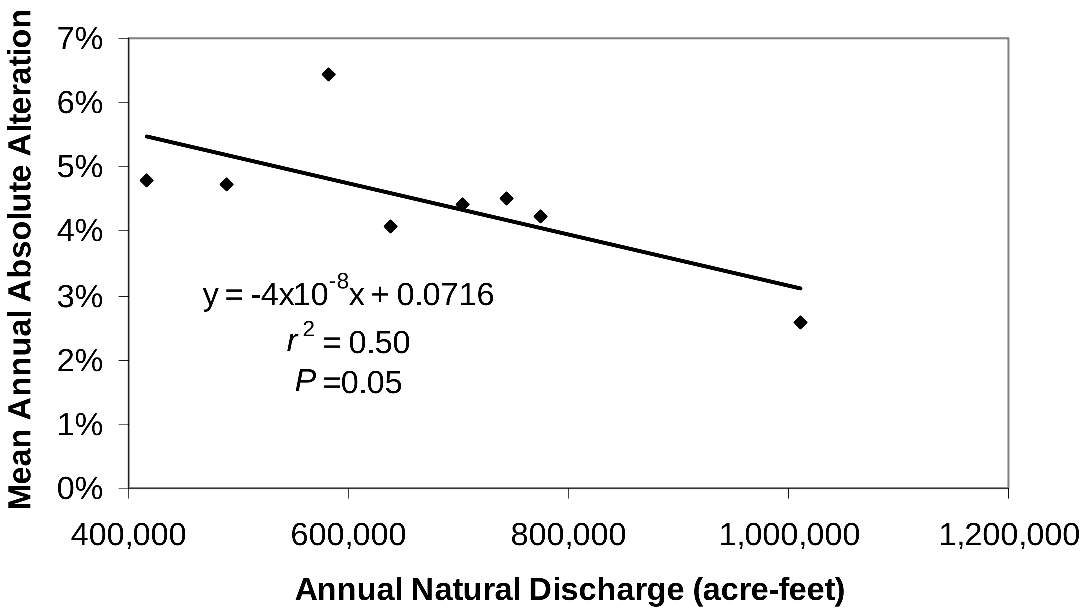
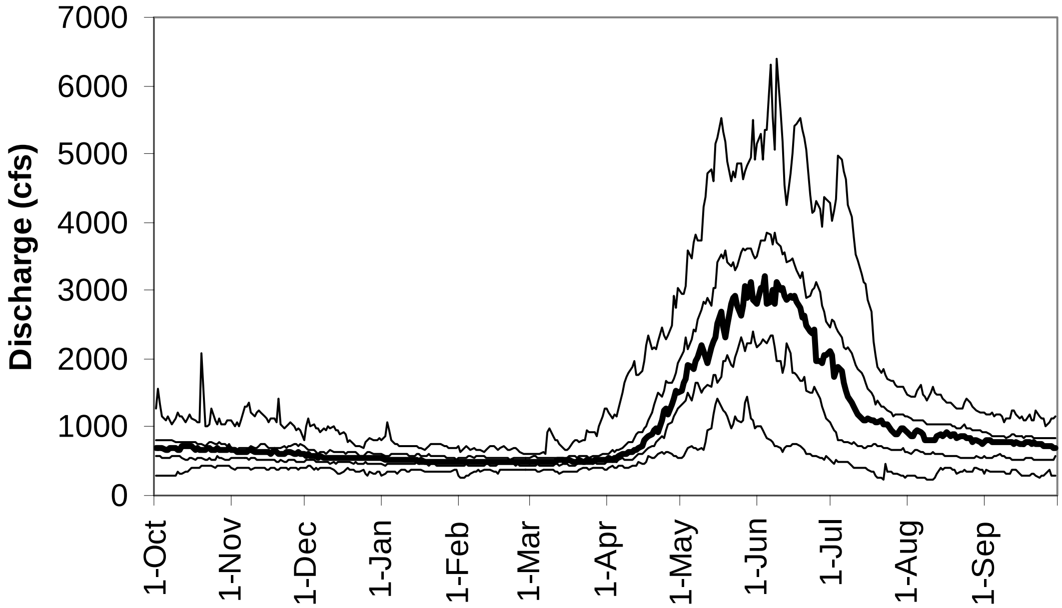
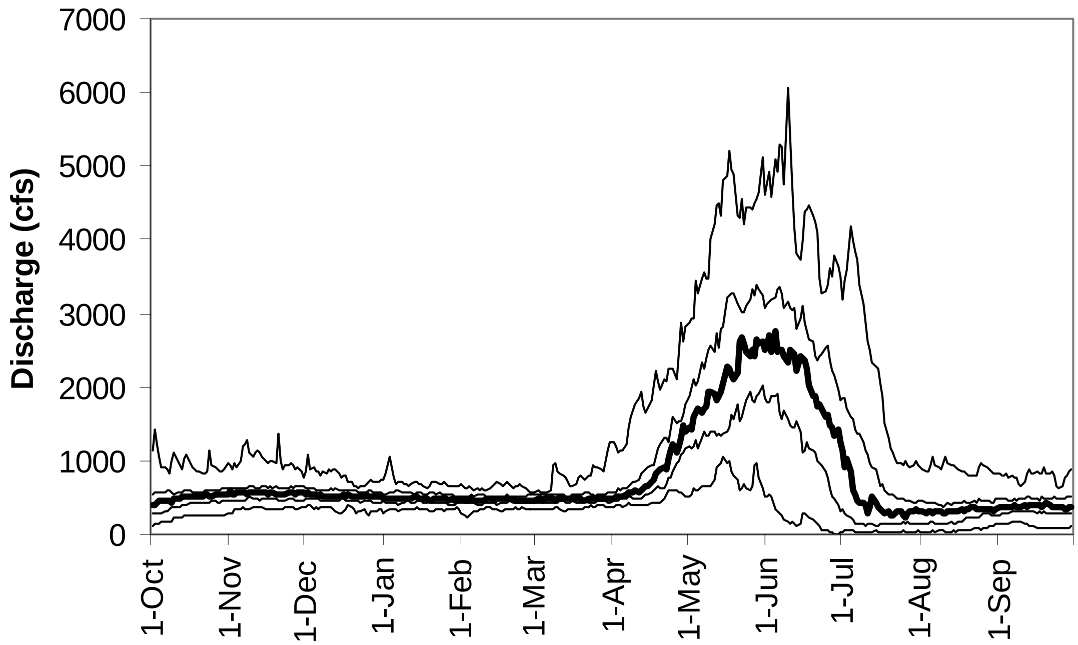


FIGURE 30.—Relationship between annual alteration and discharge Fall River near Ashton (below power plant) for water years 1995-2002.



a. Natural Flow



b. Regulated Flow

FIGURE 31.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow in Fall River at Chester for water years 1972-2002.

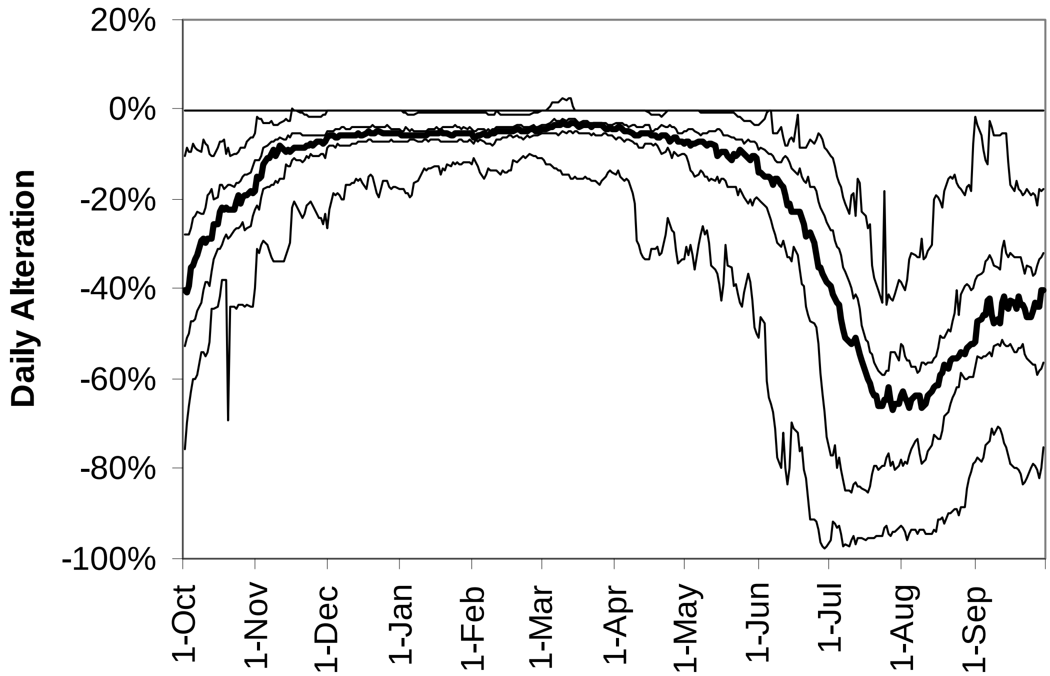


FIGURE 32.—Median, 25th and 75th percentiles, and extremes of daily flow alteration in Fall River at Chester for water years 1972-2002.

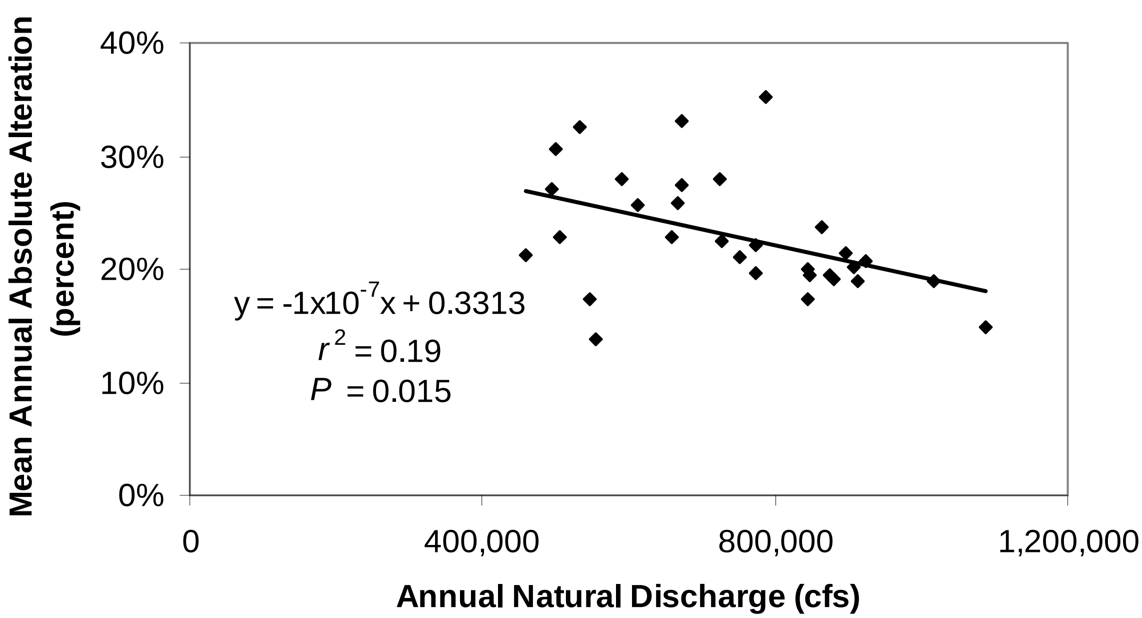
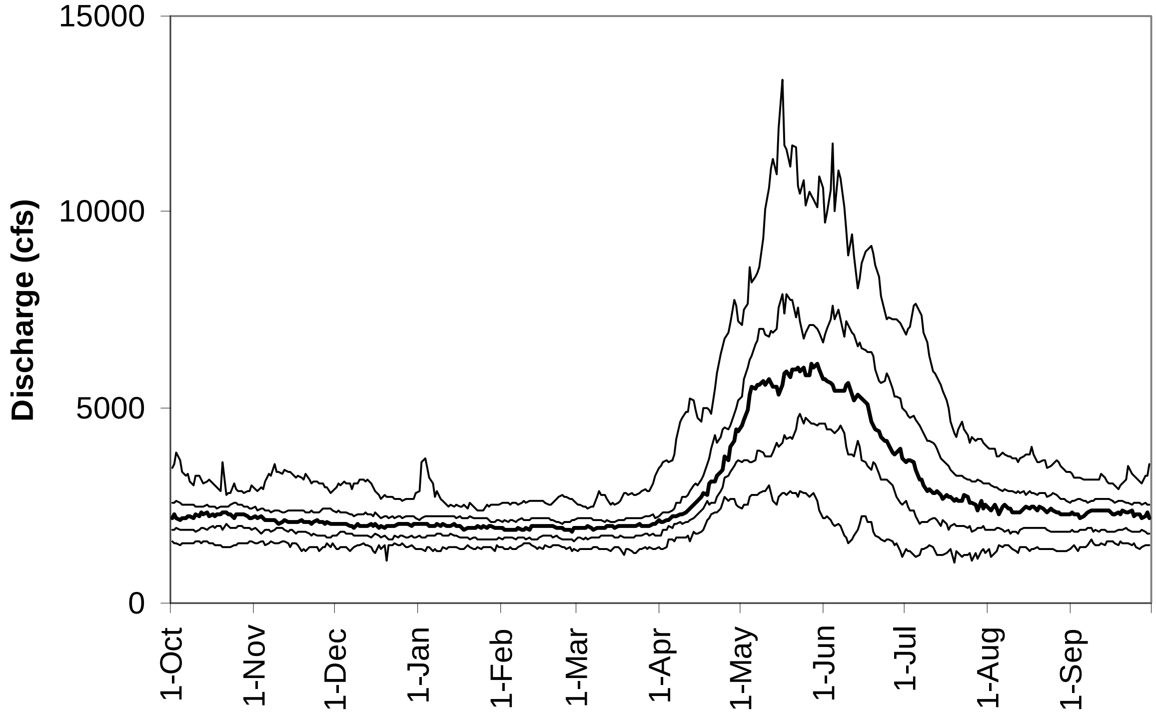
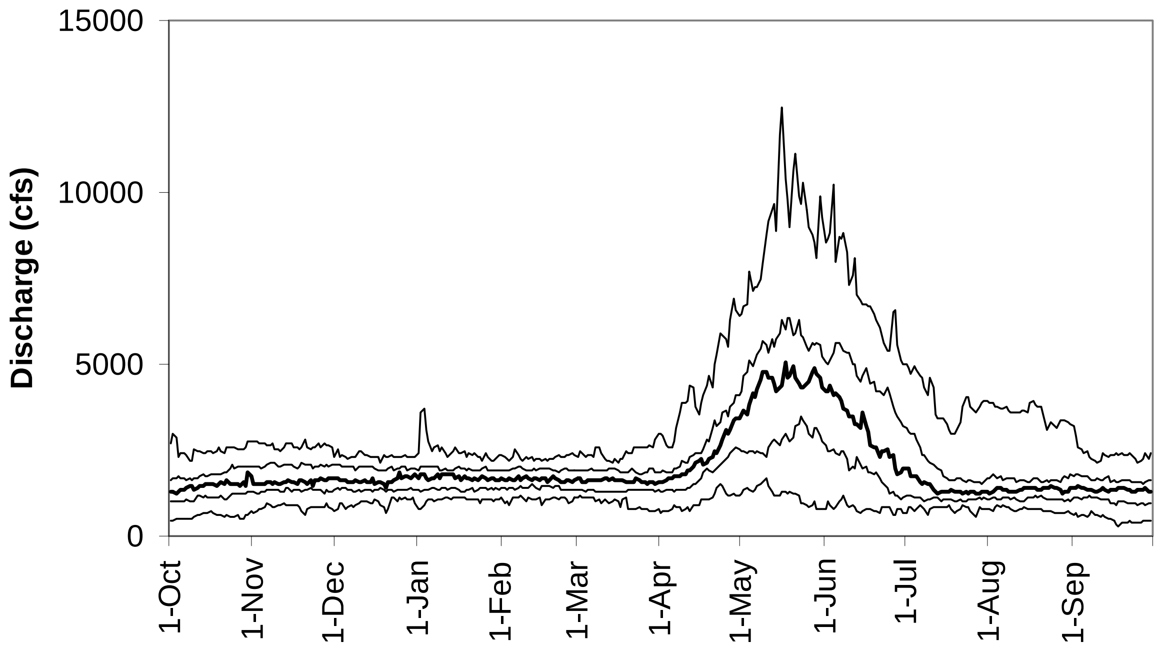


FIGURE 33.—Relationship between annual alteration and discharge in Fall River at Chester for water years 1972-2002.



a. Natural Flow.



b. Regulated Flow.

FIGURE 34.—Median, 25th and 75th percentiles, and extremes for natural (a) and regulated (b) flow at St. Anthony for water years 1972-2002.

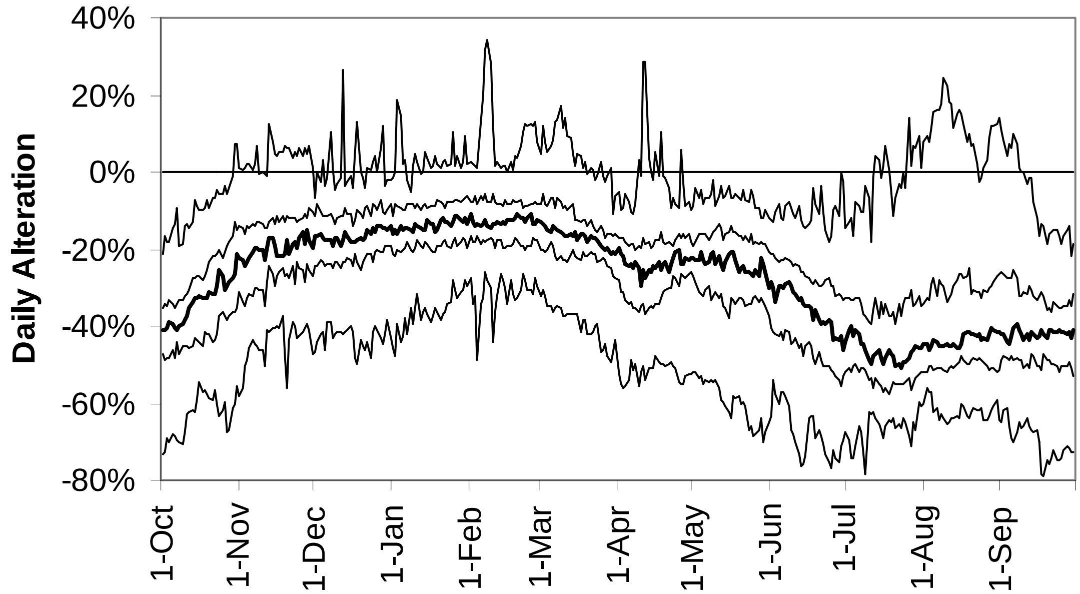


FIGURE 35.—Median, 25th and 75th percentiles, and extremes of daily flow alteration at St. Anthony for water years 1972-2002.

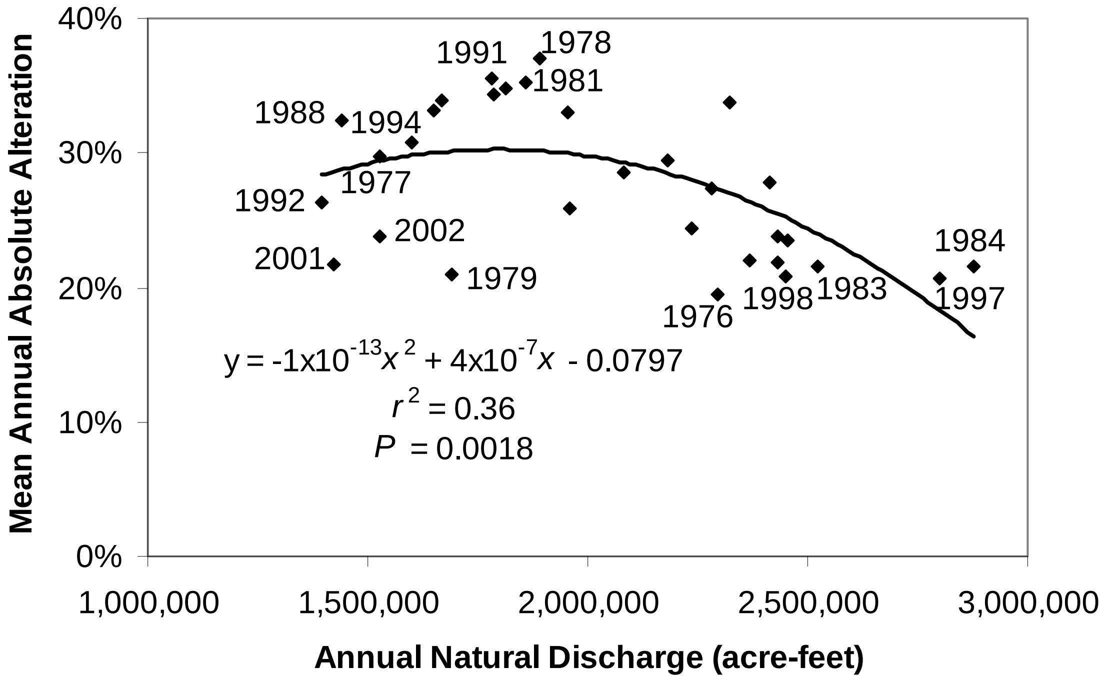
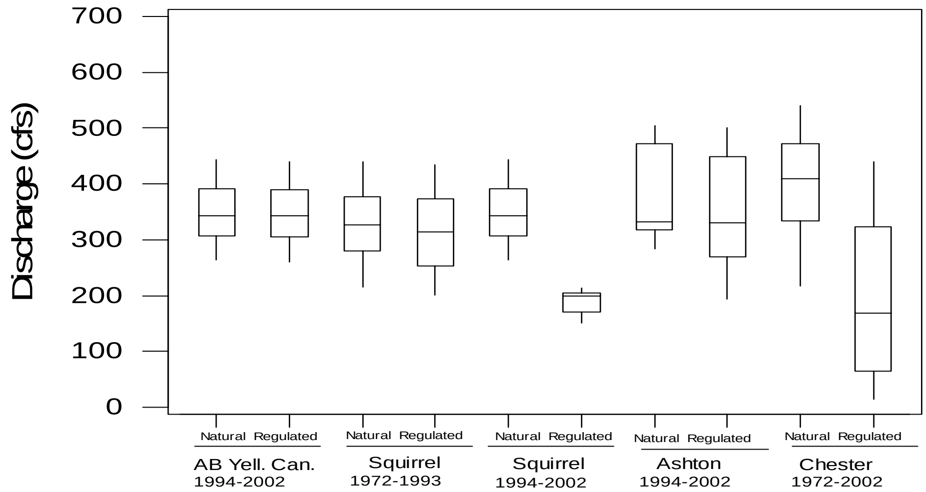
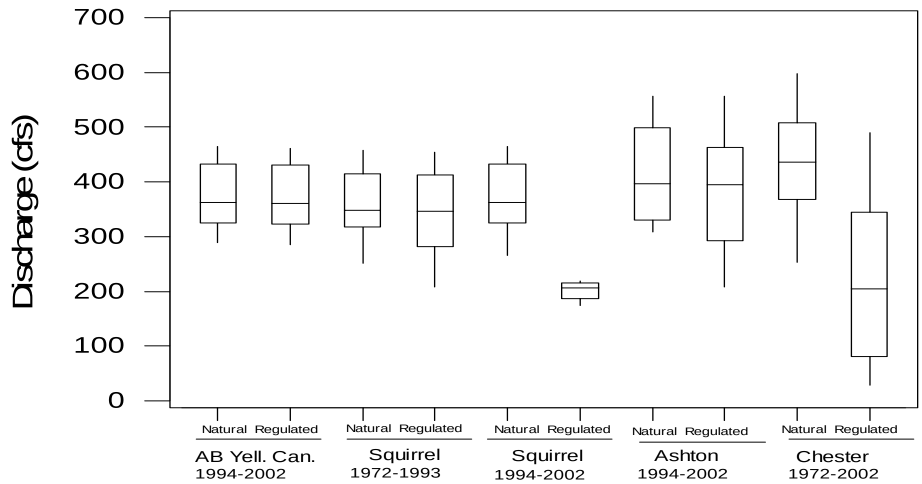


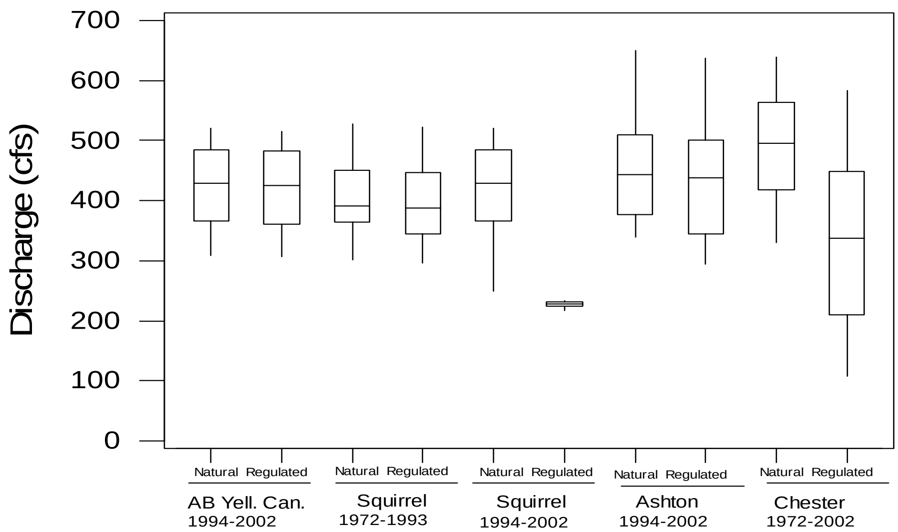
FIGURE 36.—Relationship between annual alteration and discharge at St. Anthony for water years 1972-2002. Water years of extreme data points are labeled.



a. 1-day minimum flows

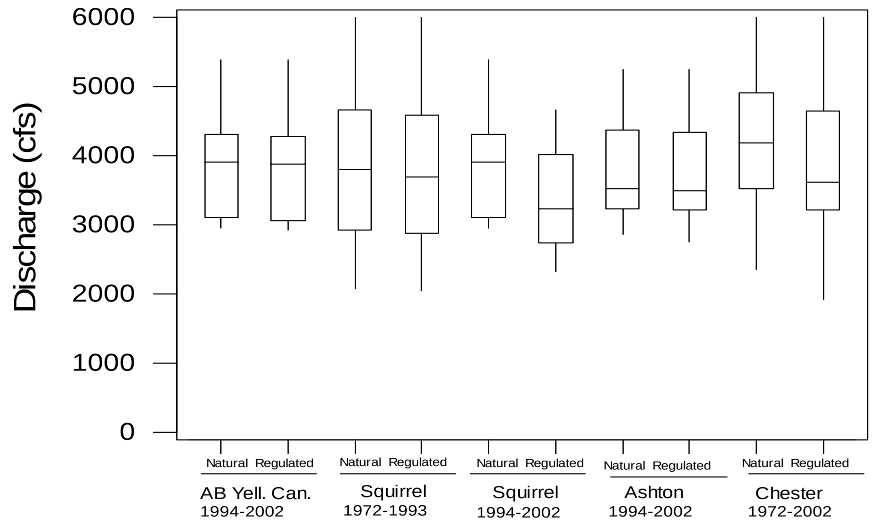


b. 7-day minimum flows.

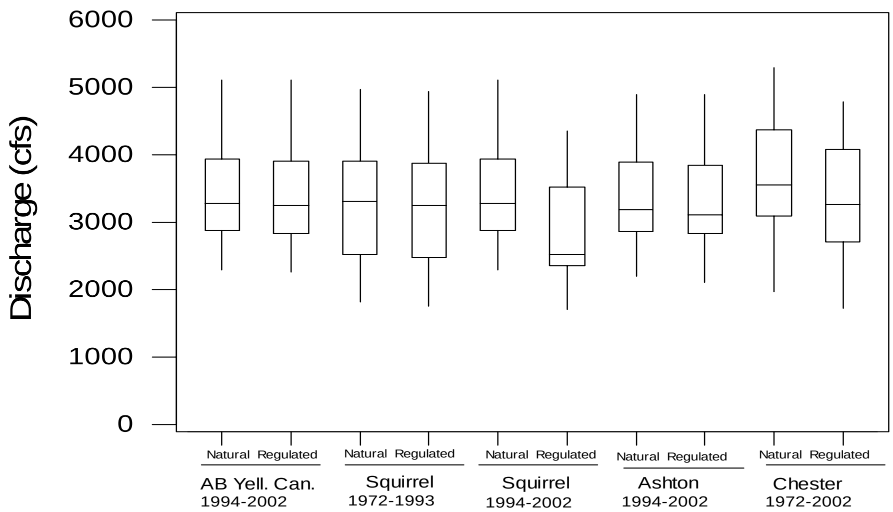


c. 90-day minimum flows.

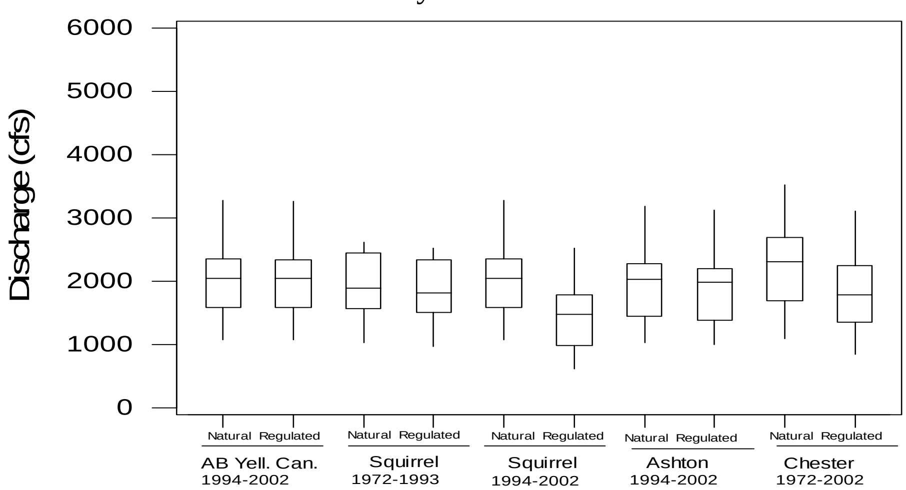
FIGURE 37.—One-day, 7-day, and 90-day minimum natural and regulated flows in Fall River.



a. 1-day maximum flows.



b. 7-day maximum flows.



c. 90-day maximum flows.

FIGURE 38.—One-day, 7-day, and 90-day maximum natural and regulated flows in Fall River.

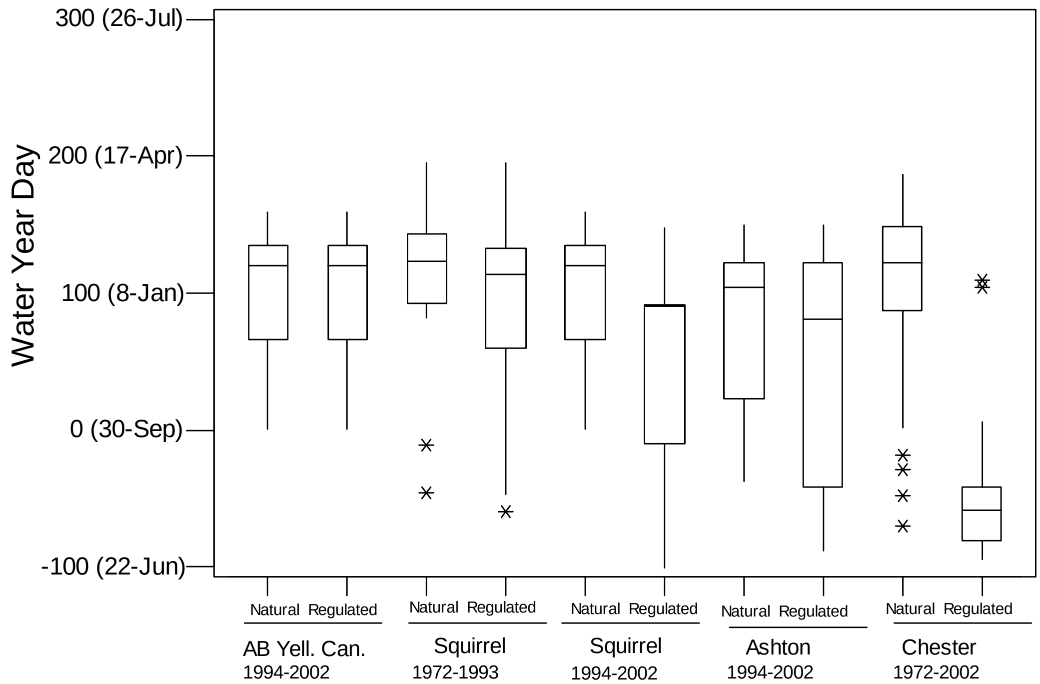


FIGURE 39.—Date of minimum flow for natural and regulated hydrologic regimes on Fall River.

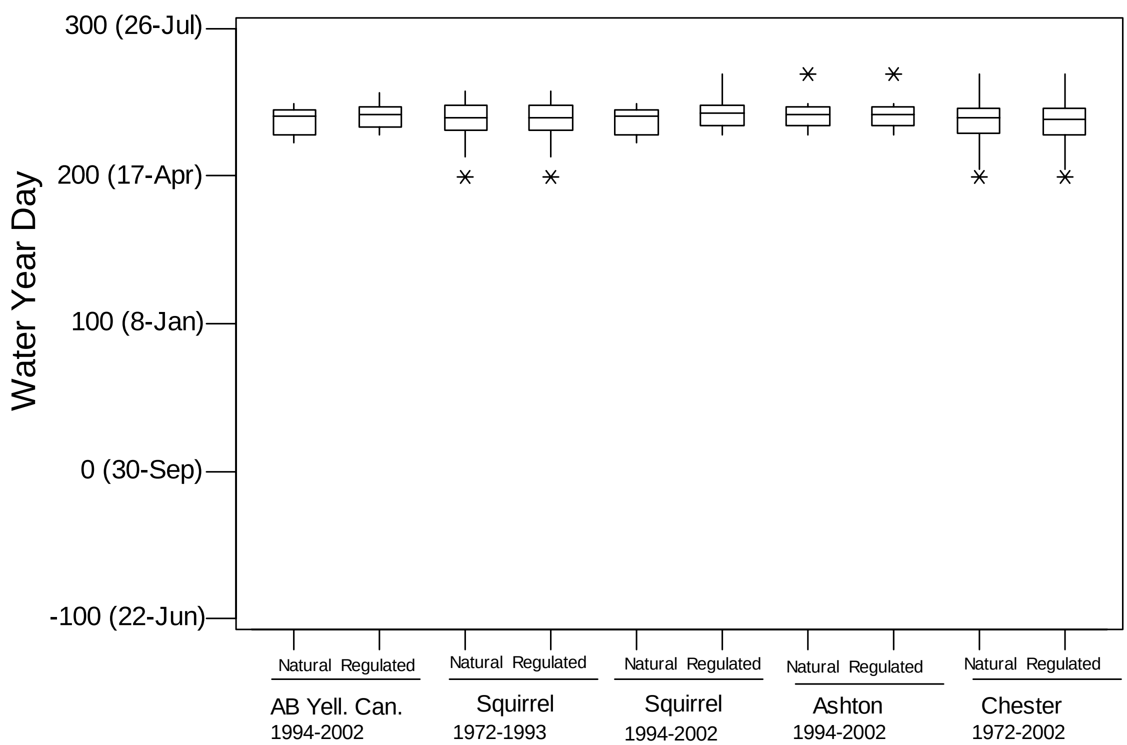
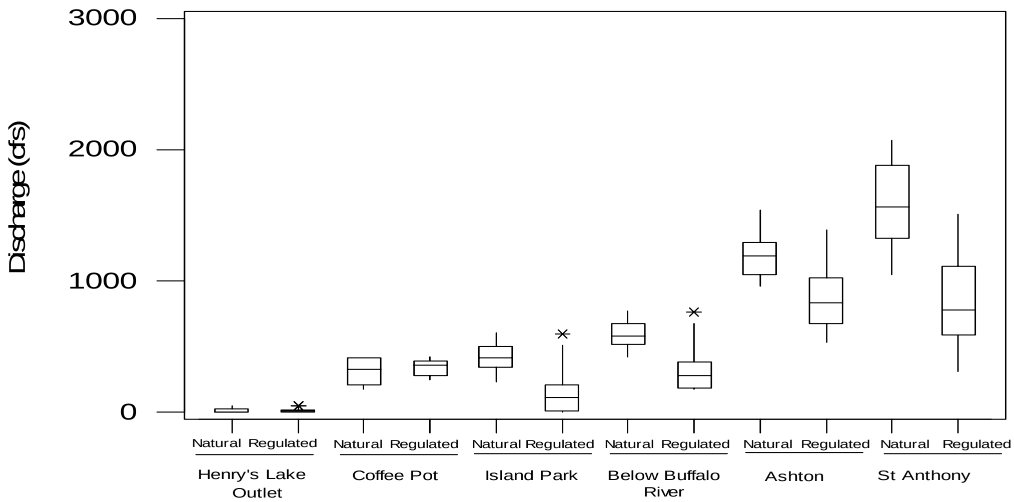
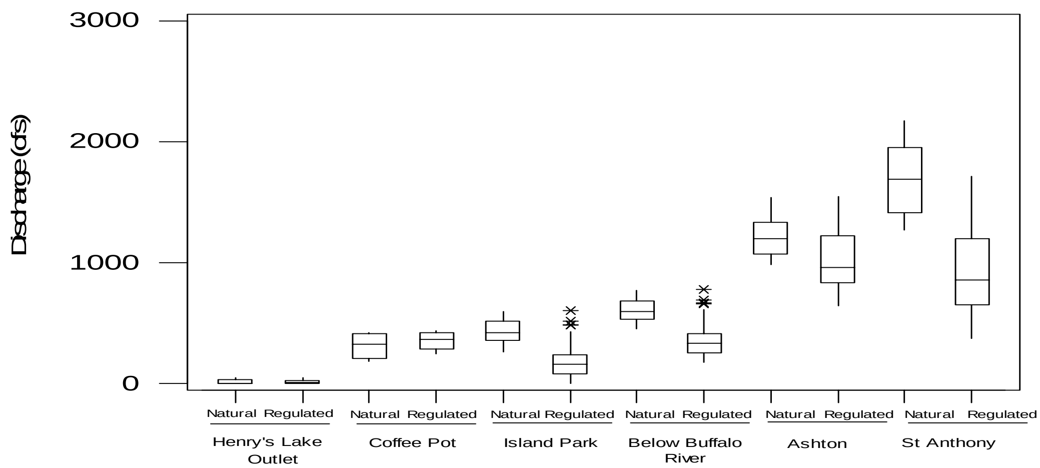


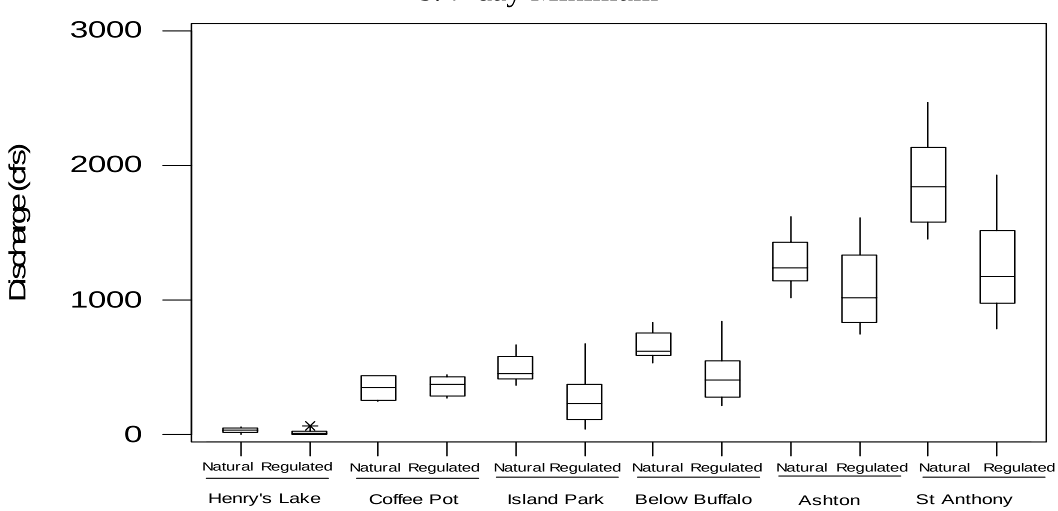
FIGURE 40.—Date of maximum flow for natural and regulated hydrologic regimes on Fall River.



a. 1-day Minimum

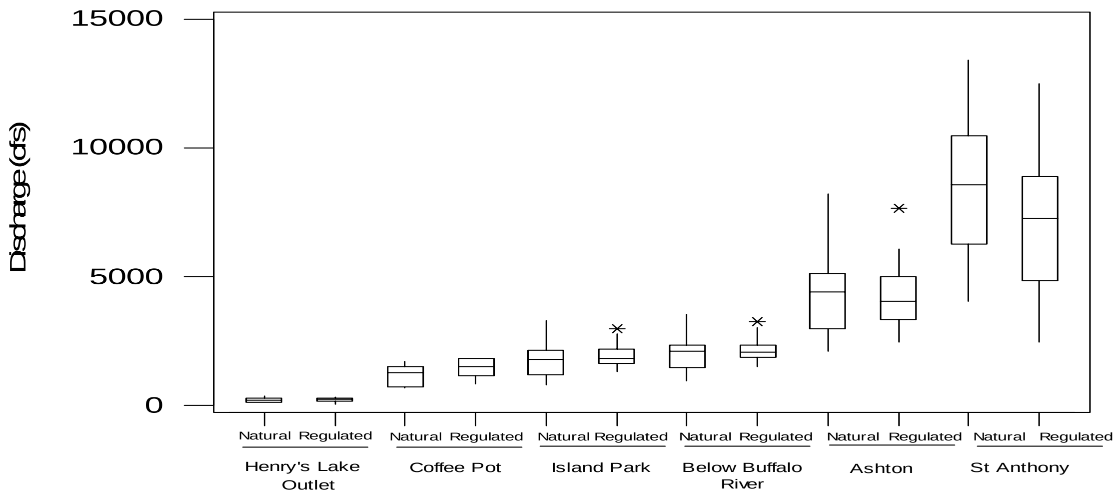


b. 7-day Minimum

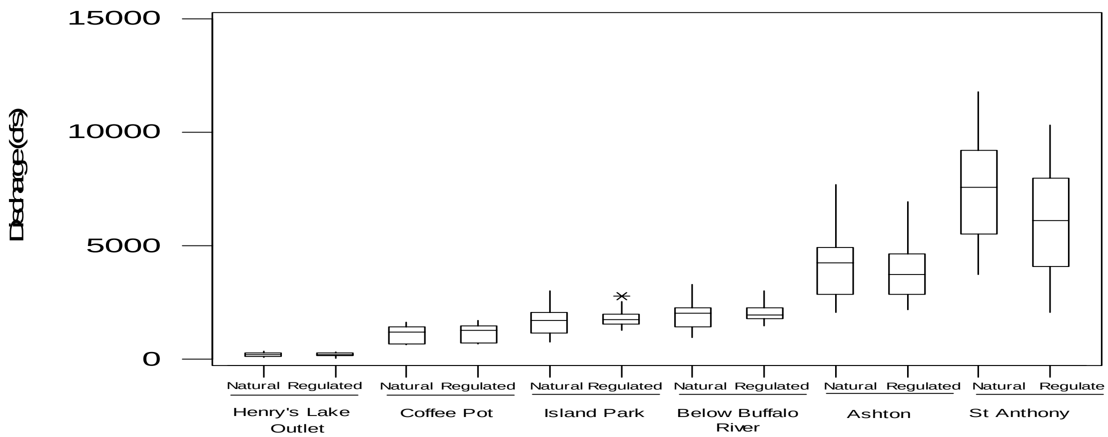


c. 90-day Minimum

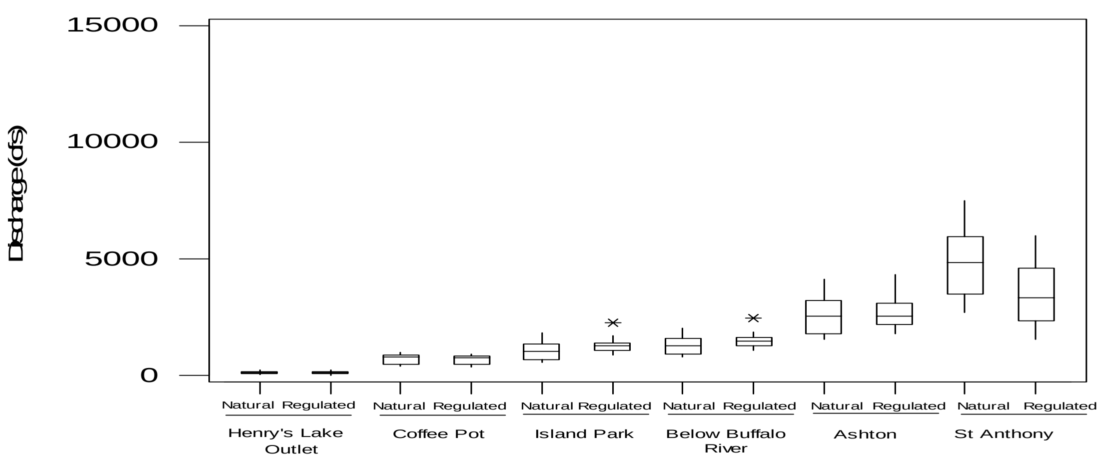
FIGURE 41.—One-day, 7-day, and 90-day minimum natural and regulated flows on the Henry's Fork.



a. 1-day Maximum



b. 7-Day Maximum



c. 90-day Maximum

FIGURE 42.—One-day, 7-day, and 90-day maximum natural and regulated flows on the Henry's Fork.

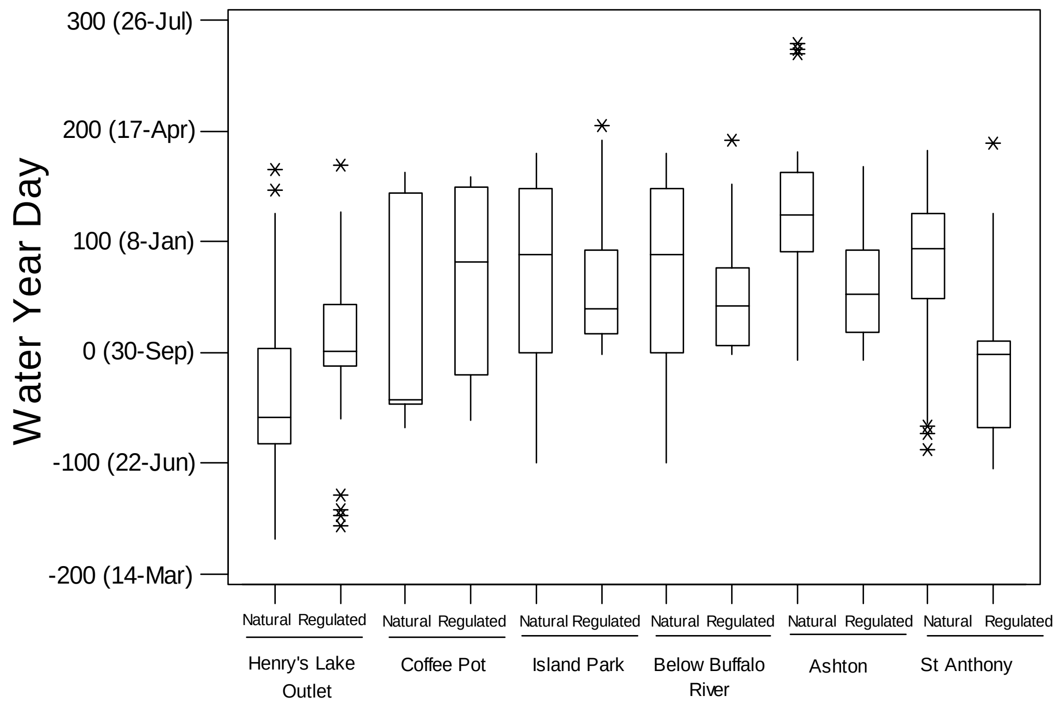


FIGURE 43.—Date of minimum flow for natural and regulated hydrologic regimes on the Henry’s Fork.

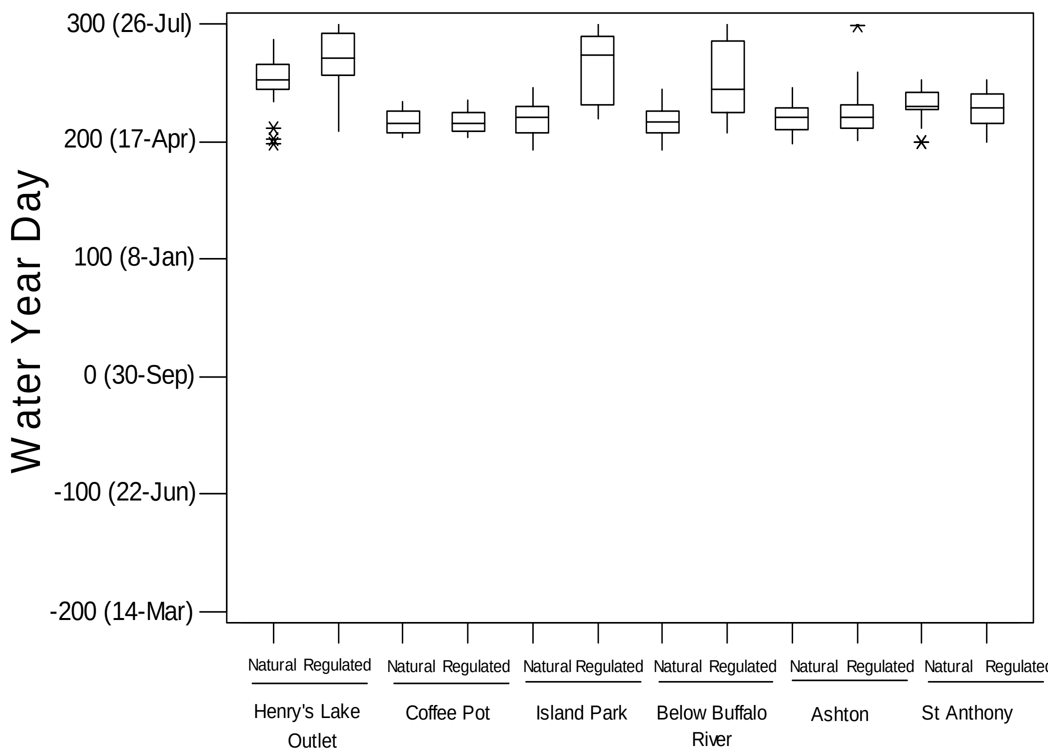
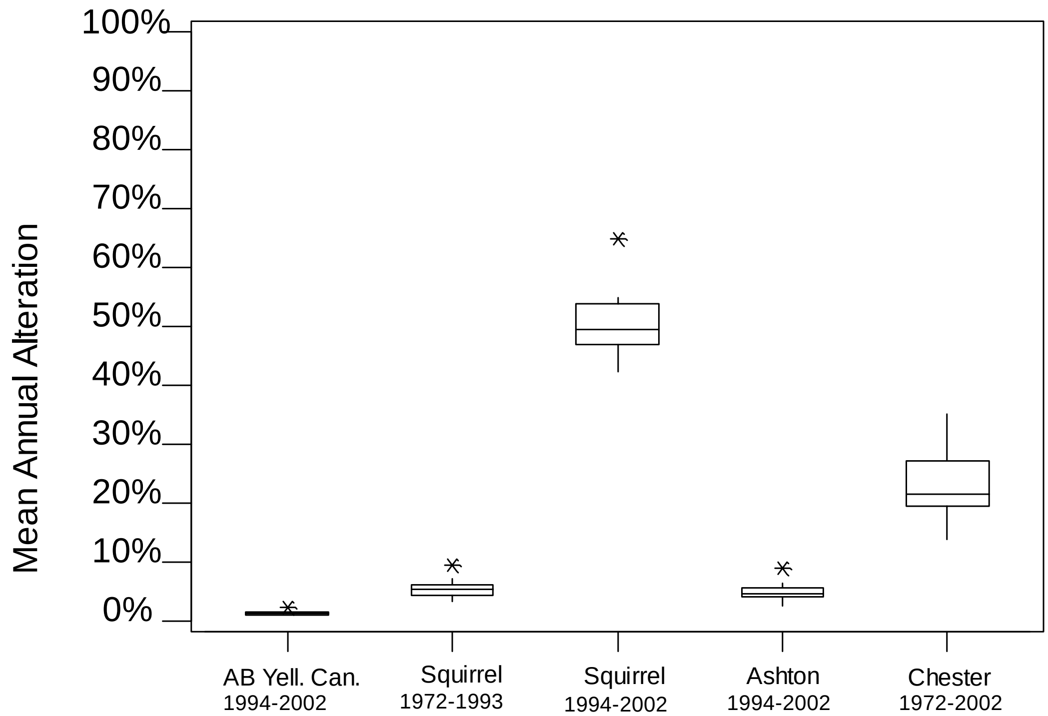
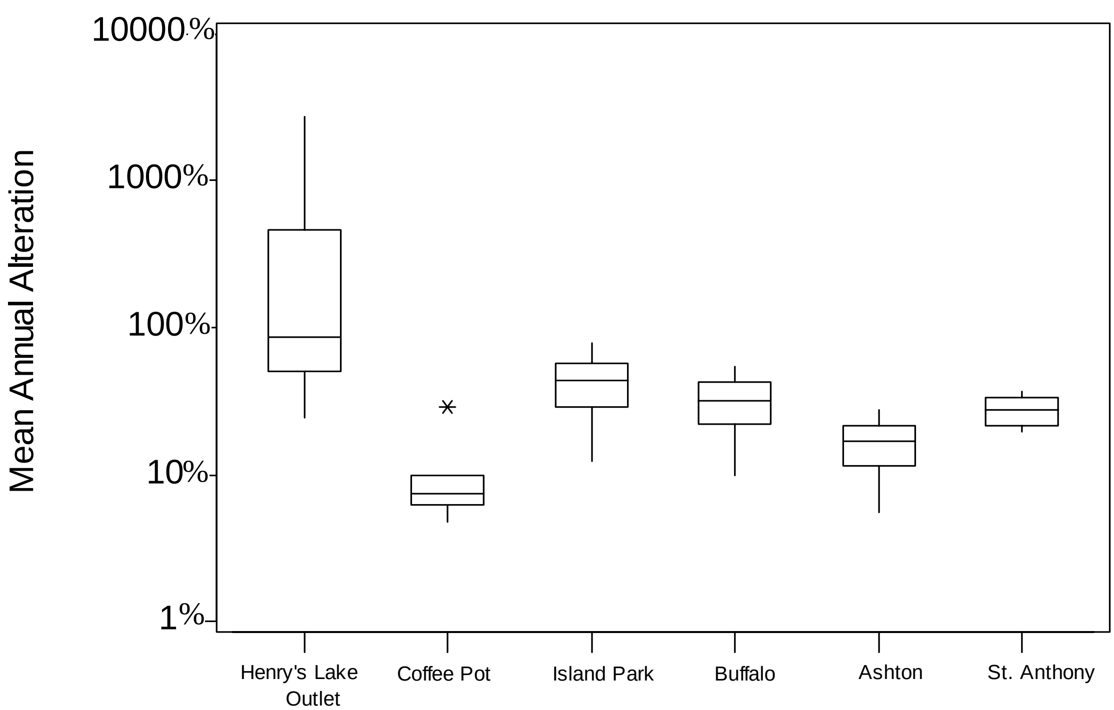


FIGURE 44.—Date of maximum flow for natural and regulated hydrologic regimes on the Henry’s Fork.

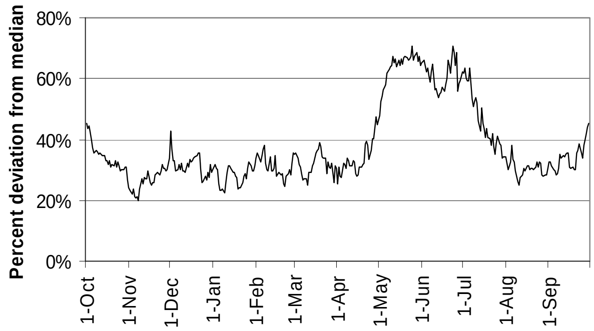


a. Fall River Gages

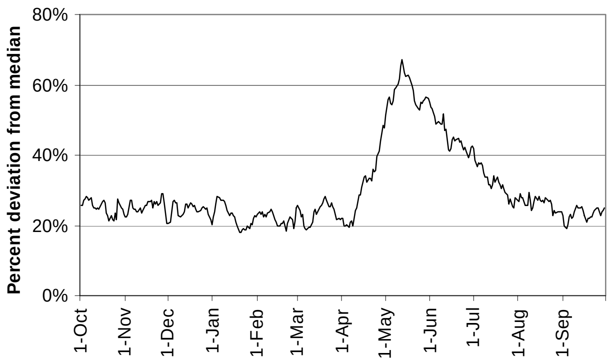


b. Henry's Fork Gages

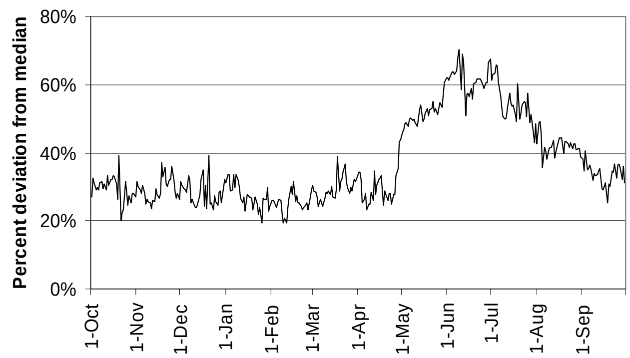
FIGURE 45.—Mean annual absolute alteration at all gages.



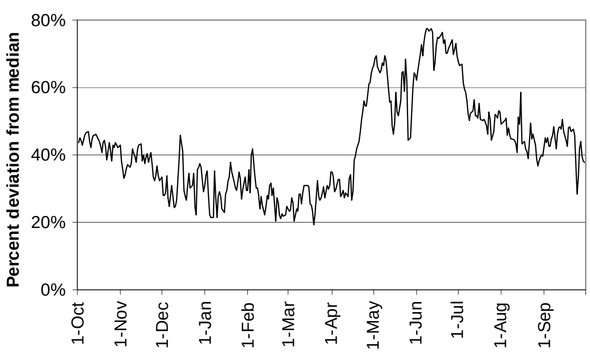
a. Henry’s Fork near Island Park



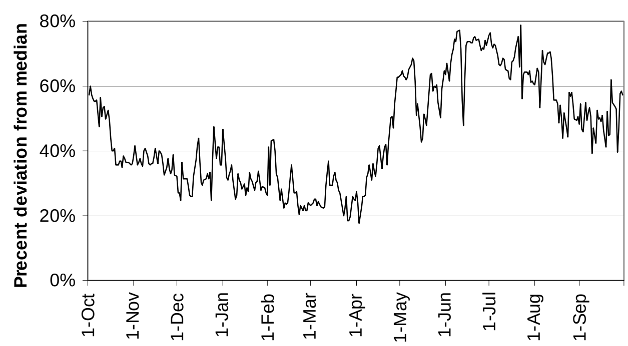
c. Henry’s Fork near Ashton



d. Henry’s Fork near St. Anthony

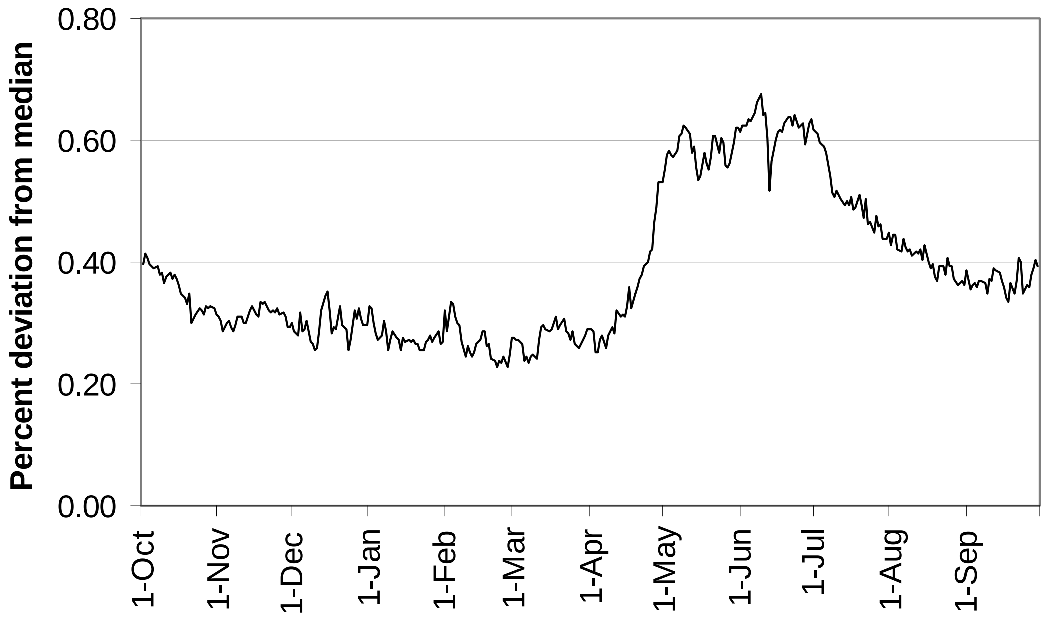


e. Fall River near Squirrel

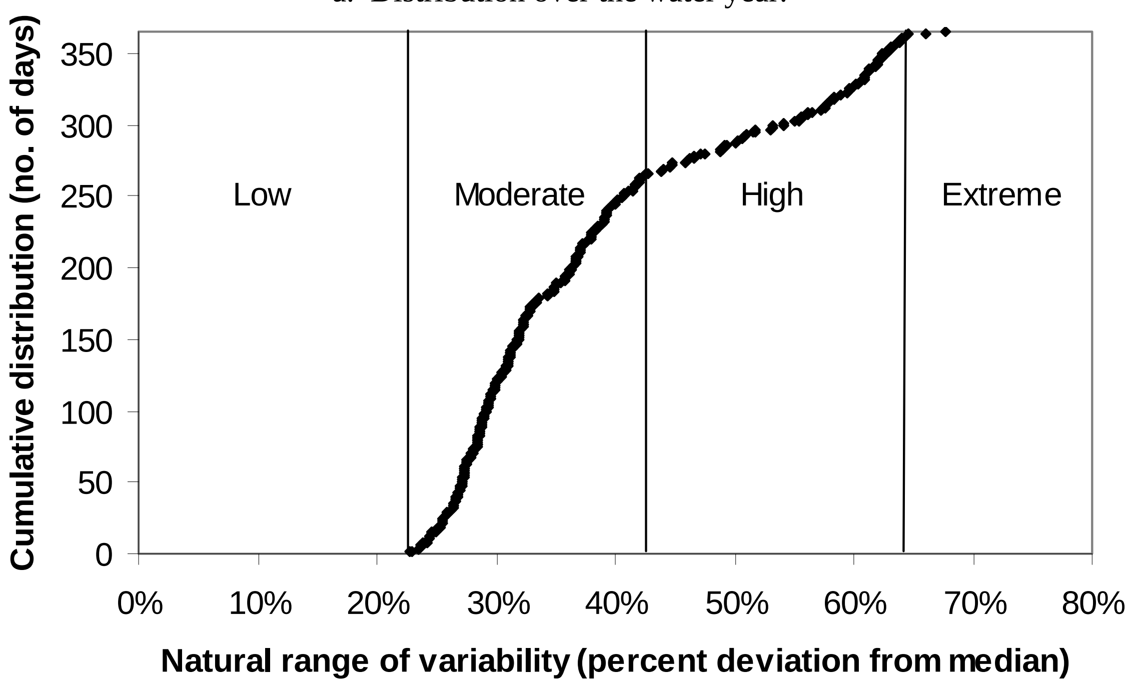


f. Fall River near Chester

FIGURE 46.—Range of variability in natural daily flow. Graphs show maximum percent deviation from median natural flow that falls within observed extreme values of natural flow.



a. Distribution over the water year.



b. Cumulative frequency distribution and corresponding definitions of hydrologic alteration.

FIGURE 47.—Distribution of watershed-averaged range of variability in natural daily flow. Plot a shows mean over the five gages in Figure 46 of maximum percent deviation from median natural flow that falls within observed extreme values of natural flow. Plot b shows cumulative distribution of these values.

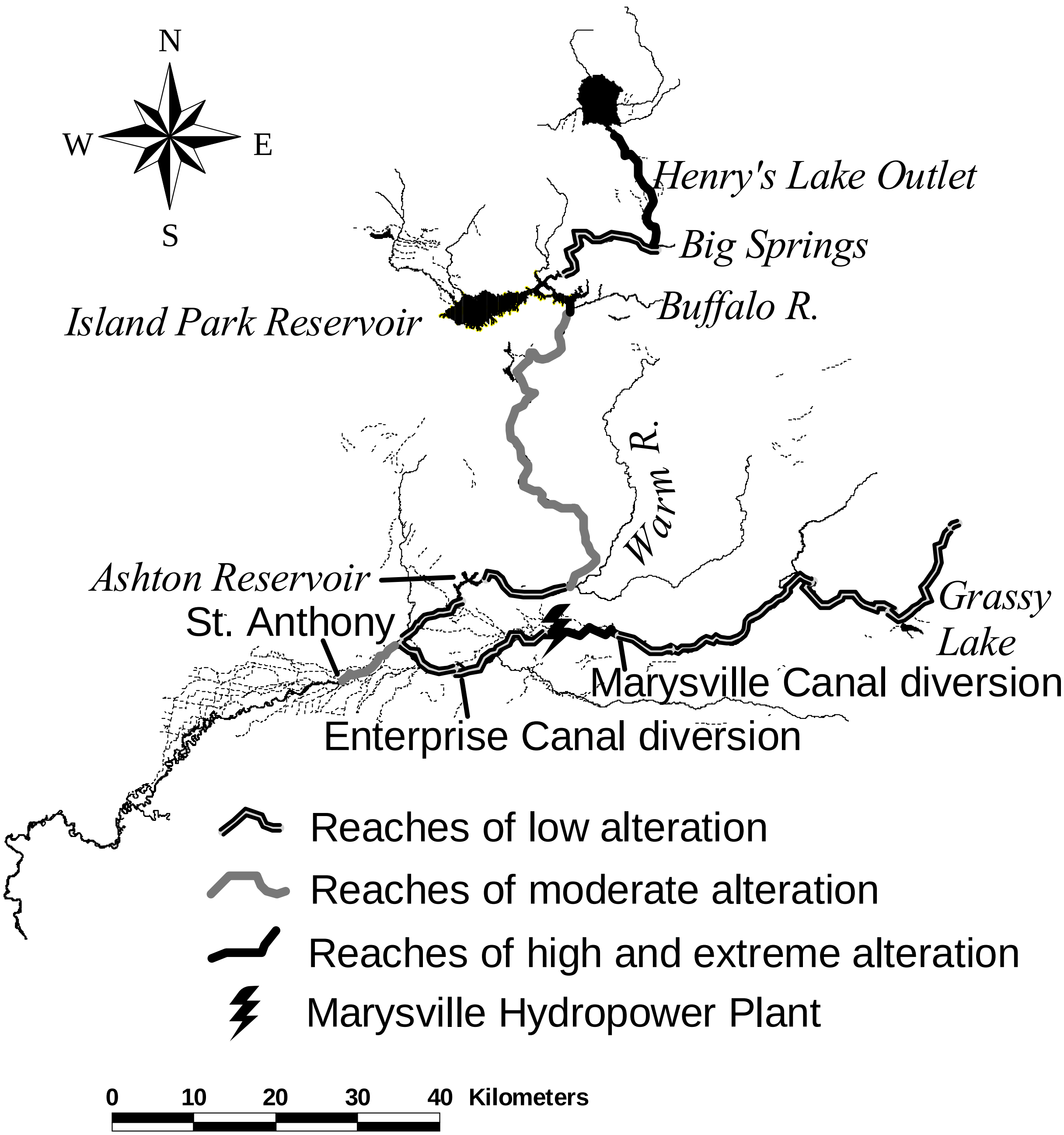


FIGURE 48.—Spatial distribution of hydrologic alteration in the Henry's Fork watershed above St. Anthony.

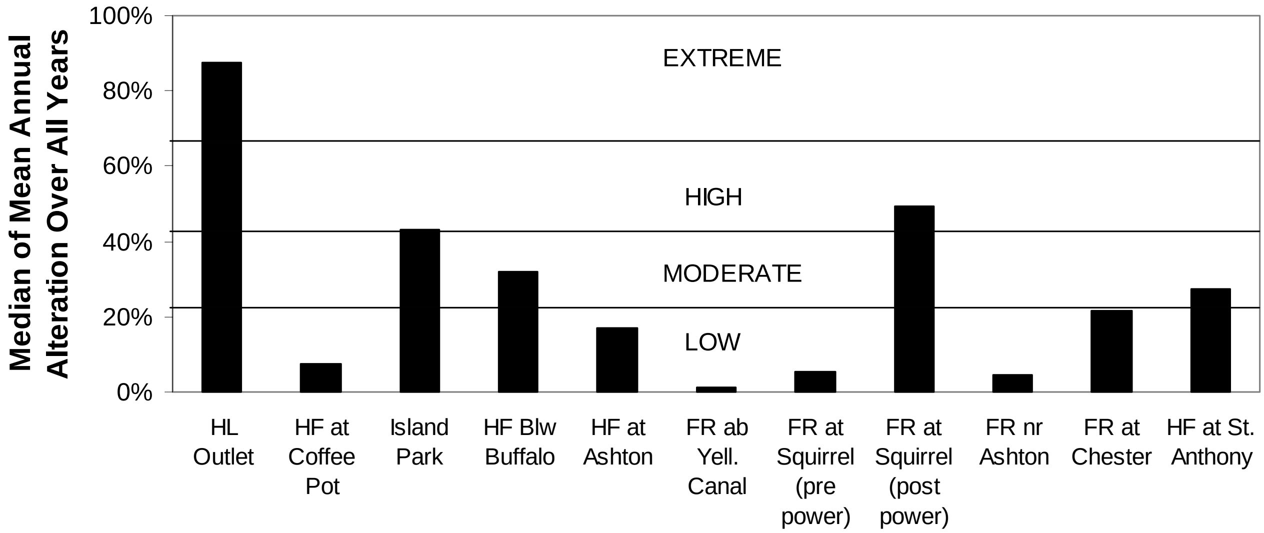


FIGURE 49.—Median of mean annual absolute alteration at all gages over all years.

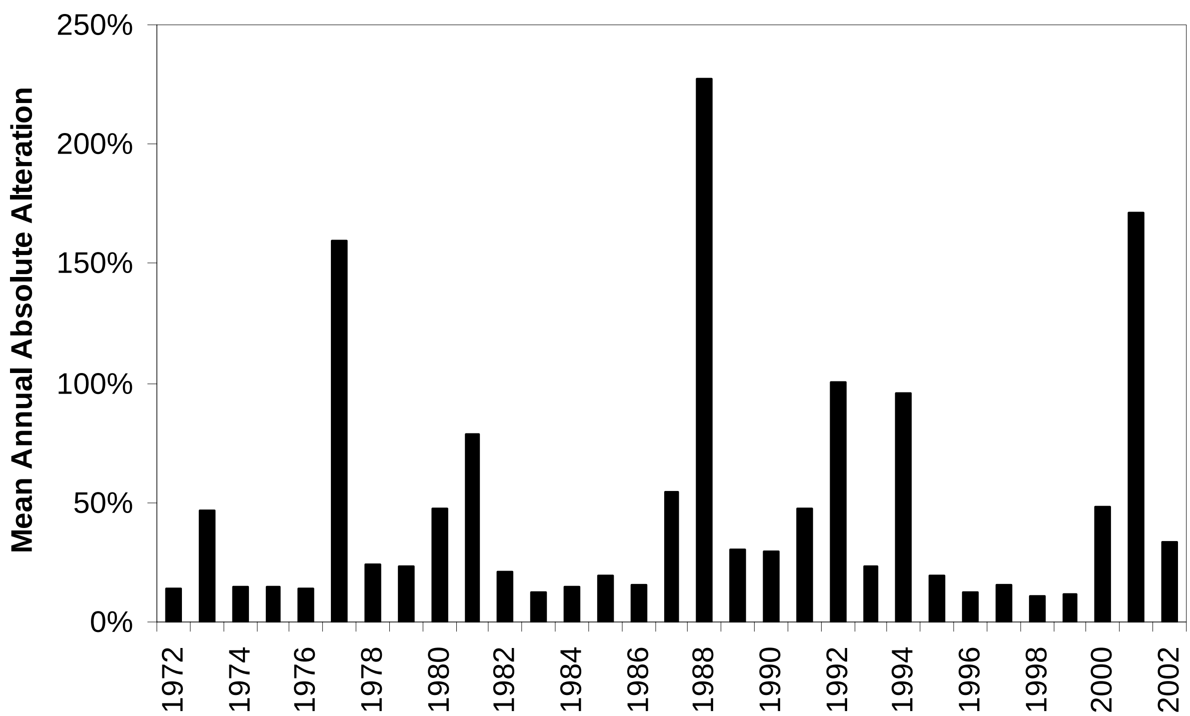


FIGURE 50.—Watershed-averaged mean annual absolute alteration for the Henry's Fork watershed upstream of St. Anthony.

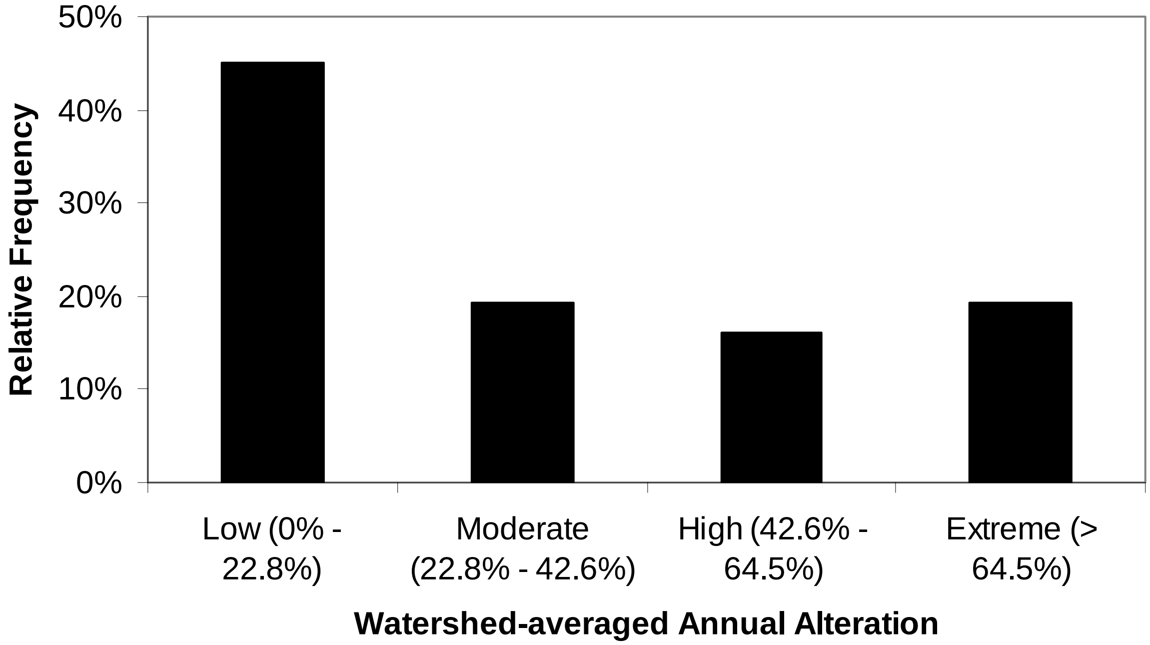


FIGURE 51.—Relative frequency distribution of watershed-averaged annual alteration values for water years 1972-2002.

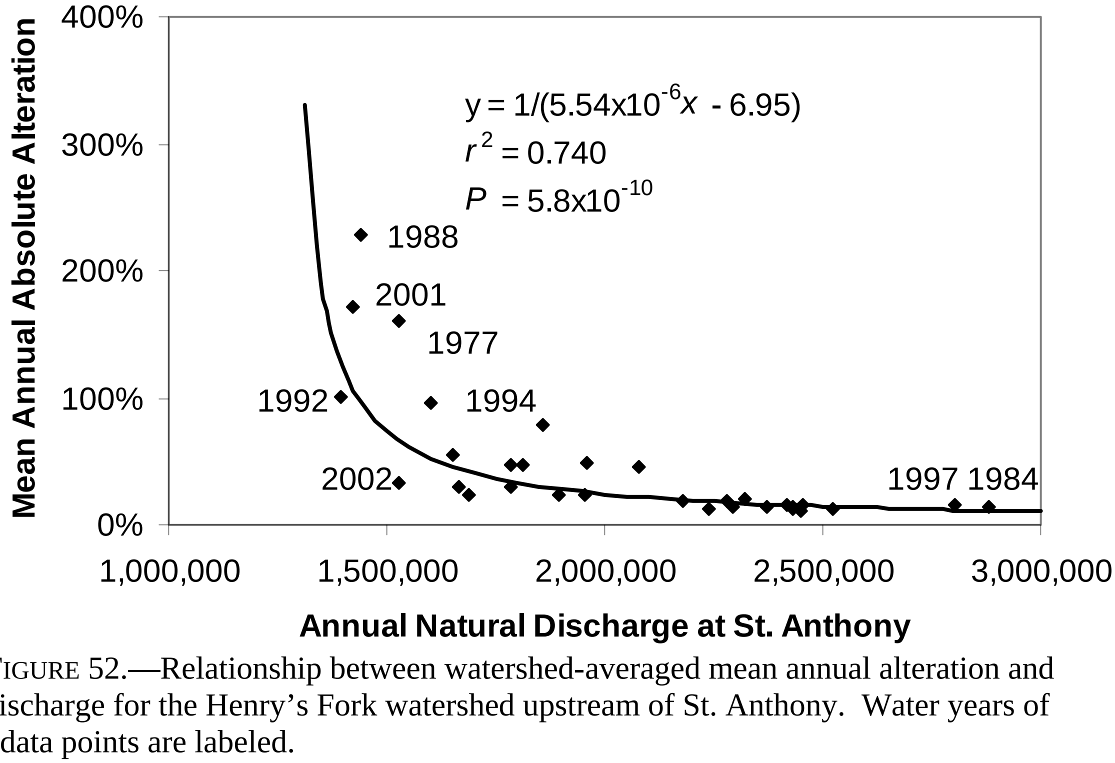


FIGURE 52.—Relationship between watershed-averaged mean annual alteration and annual discharge for the Henry's Fork watershed upstream of St. Anthony. Water years of extreme data points are labeled.

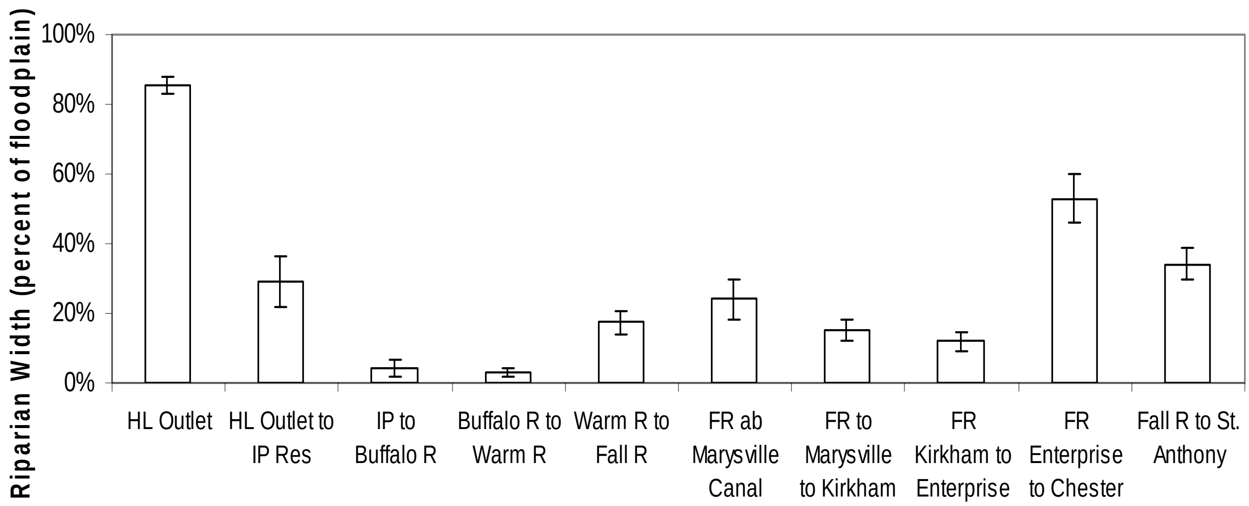
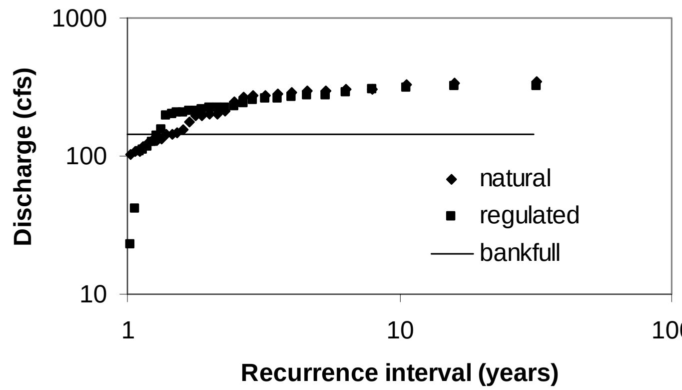
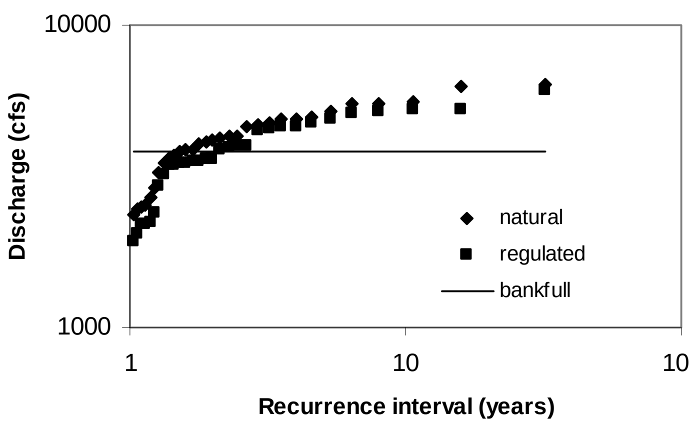


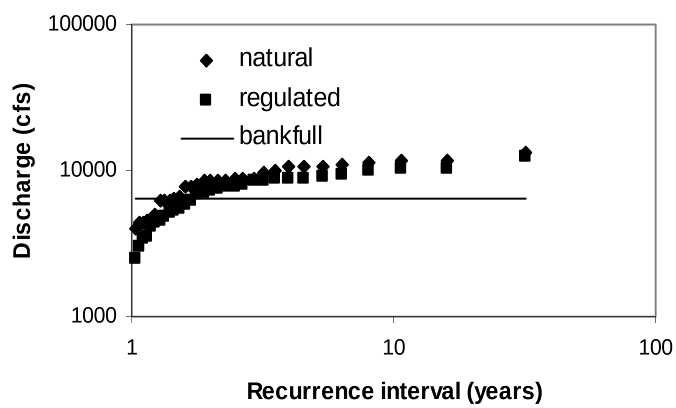
FIGURE 53.—Mean riparian area width plus or minus standard error for all reaches.



a. Henry's Lake Outlet



b. Fall River at Chester



c. Henry's Fork at St. Anthony

FIGURE 54.—Flood (one-day maximum discharge) frequency plots for Henry's Lake Outlet (a), Fall River near Chester (b), and Henry's Fork at St. Anthony (c).