INDICATORS OF HYDROLOGIC ALTERATION (IHA) ANALYSIS OF SELECTED STREAMS ON THE ARBUCKLE-SIMPSON AQUIFER, SOUTH CENTRAL OKLAHOMA

By:

Ellen C. Tejan
The Nature Conservancy
2727 E. 21st Street, Suite 102
Tulsa, Oklahoma, 74114

C. Stephen Haase
The Nature Conservancy
Southern United States Conservation Region
632 Catoosa Ridge Road
Rockwood, Tennessee 37854

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404 life Sciences West
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Abstract

Streamflow is a master variable that regulates the ecological integrity of flowing water systems and limits the distribution and abundance of riverine species. Its influence on channel morphology, habitat availability, water temperature, and substrate stability in turn makes it a determinant of other resource values, ranging from local economic values and recreation to ecosystem services. Determining how to develop water resources without adversely affecting other resource values, ranging from local economic values and recreation to ecological values is a central challenge in water management. The first step in this process is to develop an understanding of the natural flow regimes of the streams to be managed, and how those flows affect ecosystem processes. Therefore, the specific objectives of this study were: 1) to characterize the natural flow regime of Arbuckle streams and 2) based on the characterization of the natural flow regime, to identify specific parameters that would be critical to assess the ecological impacts of potential flow regime alteration due to increased water production from the Arbuckle-Simpson Aquifer.

We conducted an Indictors of Hydrologic Alteration (IHA) analysis to quantify patterns in the flow regimes of Arbuckle streams. In general, we found that Arbuckle streams had stable base flows that flowed even in the most extreme drought cycles. The Blue River gage at Blue, OK was the only stream gage that had zero-flow conditions, but these were only during the most extreme droughts (>10 year recurrence interval). These streams had strong seasonal variability with lower base flows in the summer (August through October) and higher base flows in winter (January through June). Gages on springs tended to be quite stable, and did not show seasonal variation. The flows at these sites were most influenced by long-term patterns in precipitation.

Introduction

A central challenge in water management is determining how to develop water resources without affecting other resource values, ranging from local economic values and recreation to ecological values. Water supply is necessary for the economic viability of municipal areas and industry, and yet this economic growth comes at a cost, often unmeasured, for the streams that are harnessed for this purpose and the local residents who rely on these streams for important ecosystem services. These ecosystem services include sport fishing, wildlife habitat, recreation, aesthetics, flood attenuation, groundwater recharge, pollution dilution and soil fertilization (Fitzhugh and Richter 2004). Property values and recreational values such as fishing, camping and kayaking are contingent on the aesthetics and condition of a stream ecosystem, including channel morphology, habitat formation and availability, trophic processing and fish assemblage structure.

Streamflow is considered a master variable that regulates the ecological integrity of flowing water systems and limits the distribution and abundance of riverine species (Poff et al. 1997, Hynes 1970). It is the primary influence on channel morphology, habitat availability, water temperature (Richards et al. 1996, Poff et al. 1997), substrate stability (Doyle et al. 2005, Poff and Ward 1989, Leopold 1994) and food availability (Poff and Allan 1995). Through its influence on habitat and channel morphology, streamflow in turn controls patterns of biodiversity, including the distribution of fishes (Richter et al. 1997, Poff and Allan 1995).

The physical habitat of the river includes channel and floodplain morphology, substrate size and habitat volume, which are primarily influenced by discharge (Poff et al. 1997). Channel and floodplain morphology, (channel dimensions, river bars and riffle pool sequences) are maintained by effective discharge, which corresponds to bankfull stage and bankfull discharges. Bankfull discharges are those flow events that accomplish the most geomorphic work compared to other flows, and can move significant quantities of bed and bank sediment frequently enough to maintain channel morphology (Poff et al. 1997, Leopold 1994, Wolman and Miller 1960, Poff and Ward 1989, Doyle et al. 2005). Discharge also defines the amount and character of habitat available in a stream by determining the size and location of the wetted width, and the current speeds throughout the channel. (Doyle et al. 2005). In some flow regimes, the floodplains themselves may be maintained by higher magnitude floods (Poff et al. 1997). High flows also clean fine sediments from substrate, providing habitat for species living in interstitial spaces (Poff et al. 1997). Playfair's law states that a stream finds an equilibrium between streamflow, sediment supply and slope. Human activity can disrupt the dynamic equilibrium of this balance (Dunne and Leopold 1978, Poff et al. 1997). When one of these variables is altered the stream must find a new balance through changes in channel shape and slope.

Streams and streamflow are dynamic systems, providing a range of conditions and habitats to which biota have adapted over time. Many ecological processes are known to be discharge dependent, such as nutrient cycling, because they depend on current speed or access to certain parts of the channel (Doyle et al. 2005).

Flood events improve habitat and contribute to nutrient cycling (Matzinger and Bass 1995). Moderately high flows transport sediment and nutrients to downstream areas, along with species, resetting the community and providing opportunities for other species to recolonize (Poff et al. 1997). Reisen (1976) observed increased nutrient (nitrogen and phosphorus) concentrations after fall rains, while Matzinger and Bass (1995) observed an increase in course particulate organic matter (CPOM) in periods of high flow, which provide habitat and nutrients for aquatic insects. While floods are important for nutrient transport, Doyle et al. (2005) found that the most important flows for particulate organic matter (POM) transport were only slightly larger than mean daily discharge. They further discovered that the most effective discharge for CPOM transport varied seasonally, depending on size of particle, ease of entrainment, and availability of CPOM.

Streamflow variability, including flood and drought disturbances, play a role in structuring stream communities (Poff and Ward 1989). In response, and stream species have developed a wide range of life history strategies to cope with and exploit these ranges of conditions (Poff et al. 1997, Schlosser 1995). For example, periphyton exploit long periods of low flow for accrual, and sloughing occurs during medium or larger floods (Biggs 1995, Doyle et al. 2005). Reisen (1976) studied periphyton on Honey Creek throughout Turner Falls Park near Davis, Oklahoma. He observed that periphyton communities were dominated by *Myriophyllum* during long periods of base flow conditions in the winter and summer. The *Myriophyllum* stands were set back by periods of high flow in the spring and fall which allowed blooms of *Spirogyra* and *Oedogonium* in the spring, and *Phormidium*, a species associated with travertine deposition, in the fall. Extreme low flow periods on Honey Creek resulted in a disappearance of periphyton (Reisen 1976). Matzinger and Bass (1995) studied seasonal and daily patterns in the drift of aquatic insects in the Blue River near Connerville, Oklahoma. They found a positive correlation between diversity and discharge, and hypothesized that increased high flows dislodged many insects, and the increase in diversity could be due to insects being washed in from upstream. They further observed that turbidity remained high after May floods. Many insects cue on scour and increased turbidity to drift, to seek better habitat and because turbidity provides cover from sight-feeding fish. Doyle et al. (2005) found that macroinvertebrate mobilization spread over a wide range of discharges and was slightly bimodal. This suggests that wide ranges of discharge are effective at mobilizing invertebrates, and that moderate floods are most effective.

Changes in flow regime can strongly influence the assemblage structure of stream fishes. Schlosser (1995) Studied fish assemblages over two years of differing hydrologic patterns. In the low flow year, he observed increased juvenile sunfish and minnows, while the abundance of darters and suckers were not different between years. Recruitment was effected by high flow conditions, affecting the number of juvenile fishes. Species breeding later in the year (minnows and sunfish) fared less well in high flow conditions than species breeding earlier in the year (darters and suckers). The species composition of adults was affected by summer drought conditions, particularly by the immigration species that were more abundant in upstream areas (Schlosser 1995). Poff and Allan (1995) used hydrologic data for least-disturbed streams in the US with long flow records. They compared statistics representing the variability, frequency and predictability of stream flows to functional traits of fish assemblages, and found that habitat generalists were correlated with variable streams while more specialized species occupied streams with more stable streamflow patterns. They further hypothesized that adjustments in hydrologic regime could result in changes in course-scale assemblage structure. By studying fish assemblages and their relationship to flow we can predict how sites' assemblages may change with changes in flow regime due to climate change or diversion (Poff and Allan 1995).

Again, determining how to develop water resources without adversely affecting other resource values, ranging from local economic values and recreation to ecological values is a central challenge in water management. Finding a solution to this difficult question has been the focus of research in the past few decades (Poff and Ward 1989, Poff and Allen 1989, Richter et al. 1996, Poff et al. 1997, Richter et al. 1997, Bunn and Arthington 2002). Richter et al. (1996) identified the following challenges facing river managers: 1) river managers need specificity in flow targets to be met, 2) prescriptions that focus on a few parameters are unlikely to restore all processes and variation, 3) management for one or a few species may result overall harm to the ecosystem and 4) flow relationships may not be transferrable to other systems. Management of stream flow in respect to one or a few species has the notable strength of providing specific flow targets, but using this strategy alone neglects the remainder of the ecosystem, which may require broader variability. Species specific prescriptions also do not provide for the maintenance of stream geomorphology, nutrient transport or food-web support (Richter et al. 1996). That said, river management that focuses solely on flow management is unlikely to succeed, because it may downplay the importance of flow parameters necessary for specific species life histories. Thus, a dual approach is optimal, combining species and flow regime studies, to effectively conserve all parts of the stream ecosystem.

Streams are naturally variable, and the full range of intra in inter-annual variation is necessary to sustain ecosystem function (Poff et al. 1997, Richter et al. 1996). There is a consensus among the scientific community that quantifying and preserving the natural flow regime is an important step in conserving all parts of a stream ecosystem (Poff and Ward 1989, Poff and Allen 1989, Richter et al. 1996, Poff et al. 1997 Richter et al. 1997, Bunn and Arthington 2002). Five components of the flow regime have been identified as critical in sustaining the full native biodiversity and integrity of stream ecosystems: magnitude, frequency, duration, timing or predictability, and rate of change. Incorporating these five flow components into management would be a step forward from management for a single minimum flow or a single species (Poff et al. 1997). The use of a range of variability analysis (RVA) approach 1) allows fast answers, 2) characterizes the whole range of variability of streamflow, and 3) management targets are translatable to a workable set of rules or restoration plan. However, management actions and flow targets should be considered hypotheses, which should be tested and refined through monitoring.

Study Objectives

This study is part of a multi-agency, multi-year assessment of the water resources within the Arbuckle-Simpson Aquifer (OWRB, 2003, 2005, 2007, and 2008). While the goals of the larger study are to assess sustainable yield from the Arbuckle-Simpson Aquifer for long-term water resources decisions, the objective of this study is focused on the potential impacts to flows within streams fed in whole or in part by groundwater discharge. Specific objectives of this study are:

1) to characterize the natural flow regime of and/or recreational flows in the Blue River, Pennington Creek, Honey Creek, Travertine Creek, and Byrds Mill Spring; and

2) based on the characterization of the natural flow regime to identify specific parameters that would be critical to assess the ecological impacts of potential flow regime alteration due to increased water production from the Arbuckle-Simpson Aquifer.

Methods

Study Area

The Arbuckles, located in south central Oklahoma south of the city of Ada, are composed of two areas, the higher relief Arbuckle Mountains (on the Arbuckle Anticline) and the gently rolling Arbuckle Plains (one the Hunton Anticline) which make up 80% of the Arbuckles. These two areas are separated by the Washita River; it is along this river that the greatest relief occurs (Ham 1969).

The geologic province know as Arbuckles is nearly 1000-square-mile inlier of folded and faulted Paleozoic and Precambrian rock, covered on the east, north and west by Permian and Pennsylvanian strata, and on the south by an early cretaceous strata of the Gulf Coastal Plain. They are characterized most generally as outcrops of limestone, and differ from the Ouachita Mountains to the east (Pennsylvanian sandstone and shale) or Wichita Mountains to the west (Cambrian igneous rocks, Ham 1969).

The formations that make up the Arbuckles are, in ascending order: Timbered Hills Group; Arbuckle Group; Simpson Group; Viola Limestone; Sylvan Shale and the Hunton Group. The Timbered Hills Group is made up of sandstone, overlain by a thin trilobitic limestone. The Arbuckle Group is a shallow-water marine deposition made up of partially to wholly dolomitized limestone. The Simpson Group was laid down in a deeper-water environment, containing cleanly washed sand. The upper four formations have basal sandstone overlain by much thicker beds of limestone. Viola Limestone is nearly wholly limestone, with each successive layer laid down as water became shallower. Sylvan Shale was laid down in deepest water of all Mississippian formations. The Hunton Group is the youngest formation, much younger than other groups, and made up of various limestones (Ham 1969).

The Arbuckle and Simpson formations in this area have given rise to a karst landform. Karst hydrologic and orogenic processes and structures include solution processes, underground circulation of water and cave formation (Sweeting 1973). These processes led to the formation the Arbuckle-Simpson Aquifer and caves and springs throughout the area (Figure 1). Area streams get water from two main sources: rainfall and groundwater originating from the aquifer. The Arbuckle-Simpson Aquifer provides part of the municipal water supply for Ada, Sulphur and other towns in the region (OWRB 2003).

Springs are unique aquatic systems (Hubbs 1995) that provide habitat for fishes and invertebrates, including species endemic to the region. The caves and springs in the Arbuckles have unique fauna, including the Oklahoma cave amphipod (*Allocragonyx pellucidus*), an invertebrate known from only four caves, all of which are located in the Arbuckle Plains. Subterranean species are thought to move throughout the aquifer, into which habitat, springs and caves provide a window.

Because of the shallow soils and steep topography in the Arbuckles, the majority of streams are steep with bedrock substrates. Waterfalls, and occasional gravel bars are interspersed by long pools. In areas of deeper soil deposition, the streams can become incised. Riparian forests and grasslands are dependent on stream and associated riparian water tables for nutrient deposition, and access to water (Poff et al. 1997). In the Arbuckles, these consist of burr oak (*Quercus macrocarpa*)/shumard oak (*Q. shumardii*) forest, and seaside alder (*Alnus maritima oklahomensis*)/dull-leaf indigobush (*Amorpha fruticosa*) shrubland (Hoagland 2000). The burr oak/ shumard oak riparian forest association is endemic to south central Oklahoma and the Arbuckles, and occurs on larger stream reaches. Seaside alder is a rare tree found in south central

Oklahoma along the Blue River, Pennington Creek, Mill Creek and other streams throughout the Arbuckle Plains. It grows on the edge of waterways and in monotypic stands on islands with canopies extending over the water to compete for sun light against taller trees (Schrader and Graves 2002). Seaside alder grows on stable portions of the floodplains between bankfull and flood-prone elevations.

Arbuckle streams contain many unique and disjunct species, including several disjunct Ozarkian species: the least darter (*Etheostoma microperca*), redspot chub (*Nocomis asper*) and southern redbelly dace (*Phoxinus erythrogaster*) and the ringed crayfish (*Orconectes neglectus*). The least darter and redspot chub are dependent upon cool spring discharges, and this relationship is being studied in detail by our parent study by Fisher and Seilheimer (IFIM section, this report).

Arbuckle streams are also important from a recreational standpoint. Local residents and tourists use these rivers for leisure fishing, including bass, sunfish and suckers. Trout has been introduced as a winter put-and-take fishery at the Blue River Wildlife Management Area (WMA), operated by the ODWC. The Blue River WMA is also a popular destination for hiking, camping and picnicking.

The Blue River

The Blue River (Figure 2) is the largest stream originating in the Arbuckles. Its headwaters begin in the Hunton Anticline and are fed by springs north of Connerville, Oklahoma. It flows 134 miles south to its confluence with the Red River. It is one of only 42 free-flowing medium sized rivers in the U.S. and the only such river in Oklahoma (Benke 1990).

The Blue River watershed contains four stream types 1) Arbuckle headwaters, 2) Arbuckle medium-sized streams, 3) Woodbine streams and 4) Coastal Plains streams (E. Tejan, unpublished data). The Arbuckle headwaters and medium sized streams provide habitat for numerous spring-dependant species including the disjunct least darter, redspot chub and, southern redbelly dace. These are steep bedrock-dominated streams with step-pool morphology. At the lower end of the Arbuckle formation, on the granite outcropping, the stream becomes very steep with taller waterfalls and deep pools. This area is part of the Blue River WMA, which is managed for hunting, a bass and sunfish fishery in the summer, and a put-and-take trout fishery in the winter. Camping and hiking opportunities are also available. The largest population of seaside alder is on the WMA, along the edges of the Blue River and forming islands.

The Woodbine and Coastal Plain reaches of the Blue River are in deeper soils and are much more incised than those on the Arbuckles. Channels are more trapezoidal in shape, with sandy substrates. These reaches exhibit a fish assemblage more indicative of coastal plains streams, and also host a population of the American eel (*Anguilla rostrata*), a catadromous fish.

Pennington Creek

Pennington Creek originates from Pilot Springs on the Hunton Anticline of the Arbuckles, and flows 41 miles south into the Cumberland Pool of the Tishomingo National Wildlife Refuge (TNWR) to its ultimate confluence with the Washita River just south of the granite outcrop (Figure 3). Pennington Creek has the same stream types as the upper Blue River. Populations of southern redbelly dace and least darter occur in Pennington Creek and its tributaries and springs. There is also a large population of seaside alder on the creek north of Reagan, Oklahoma.

The Tishomingo National Fish Hatchery (TNFH) near Reagan, OK, operated by the U.S. Fish and Wildlife Service, uses water from Pennington Creek for hatchery operations. The hatchery raises sport fish such as paddlefish (*Polyodon spathula*), and also species of conservation concern like the alligator snapping turtle (*Macrochelys temminckii*) and alligator gar (*Atractosteus spatula*). Pennington Creek also flows through Slippery Falls Boy Scout Ranch, and the TNWR. The refuge is managed for the protection of waterfowl habitat on Cumberland Pool, a wetland and sediment trap on Lake Texoma. The Cumberland Pool contains a relatively diverse fish assemblage (Chappell and Fisher 2005).

Honey Creek

Honey Creek is a 13-mile long limestone creek originating on the Arbuckle Anticline, and flows northeast across the Timbered Hills group into the Washita River near Davis, Oklahoma (Reisen 1976). Because of the nature of the limestone upstream, Honey Creek is a travertine-depositing stream, both above and below Bridal Veil Falls, a 77-foot waterfall at the northeast border of the Arbuckle Anticline.

As early as 1868, Turner Falls was known as a popular recreational area, with Bridal Veil Falls as a focal attraction. The City of Davis currently operates Turner Falls State Park as a recreation area for swimming, picnicking and hiking.

Travertine Creek

Travertine Creek originates from Buffalo and Antelope Springs in the Pennsylvanian Vanoss sandstone west of the Hunton Anticline, and flows west 2.5 miles to its confluence with Rock Creek in the Chickasaw National Recreation Area (NRA, Figure 5). Numerous freshwater and mineral springs occur on the park. The mineral springs, once thought to have healing properties, (Becker 2006), are currently reported to discharge 10% of their flow from the early 1900s possibly from a gradual reduction of the hydraulic head within the aquifer. The mineralized springs in the park are believed to get their water from a mix of rocks from the Arbuckle and Simpson groups. The case is different for Antelope and Buffalo springs which derive their freshwater flows from the Arbuckle group in the Arbuckle anticline. Precipitation on the Arbuckle Anticline northeast and east of the park recharges the springs, which respond to rainfall (Hanson and Cates 1994).

The Chickasaw NRA was established in 1902 because of its unique hydrologic setting, including streams, springs and riparian vegetation. The park was established to preserve the freshwater and mineral springs that discharge into Rock Creek and its principle tributary, Travertine Creek (Hanson and Cates 1994). The park is managed today to provide both natural resources and recreation. Thousands of visitors swim and wade in the waters along Rock Creek and Travertine Creek every summer (Becker 2006).

Byrd's Mill Spring

Byrd's Mill Spring is located on the Hunton Anticline just west of Fittstown, OK. It flows into Mill Creek and west 7 miles to its confluence with Clear Boggy Creek near Harden City, OK. This bedrock-bottomed, spring-fed stream provides habitat for populations of southern redbelly dace and seaside alder, and hosts a population of the Oklahoma cave amphipod (Figure 6, Holsinger 1971). The City of Ada relies on discharge from Byrd's Mill Spring for its municipal water supply.

Data Collection and Estimation

Primary data used in this study were obtained from U.S. Geological Survey gaging stations and National Park Service stream monitoring programs. Additional data were estimated so that long-term trends in key flow regime parameters could be determined with increased confidence.

Measured Streamflow Data from Gaging Sites

Data from six USGS gaging stations (Table 1) along the Blue River, Pennington Creek, Honey Creek, and Byrds Mill Spring were analyzed. All stations except at Milburn, OK are currently active. Data collection on the Blue River near Milburn, OK was discontinued in October 1987. The Blue River gage at Connerville, OK and the Pennington Creek gage near Reagan, OK have short and fragmented periods of record (Table 1) that are too brief in total extent (<20 years of data) for reliable statistical analysis. Because of this, the periods of record for these stations have been extended by making use of a hydrograph estimation technique. The period of record for Honey Creek near Turner Falls was also too short for reliable analysis. This record was not extended because an appropriate gaging record for use in the estimation technique did exist.

Byrds Mill Spring flows are extensively modified by a water supply diversion for Ada, Oklahoma. Flow from the Byrds Mill spring head is split between an 18-inch pipe to Ada, and Mill Creek. Prior to 1991, measured flows represented only the water Mill Creek. In 1991 and subsequent years, flow in the 18-inch pipe is also measured, providing a combined flow value more indicative of the actual flow from the spring. Diversion to Ada, Oklahoma increased after 1991 compensate for drier weather. To reduce the impact of these alterations on the hrdrograph, we restricted our analysis of Byrds Mill Spring to water years 1991 to 2001.

Estimated Streamflow Data

Successful characterization and analysis of flow regime parameters using the IHA software is dependent upon the length of the period of record available from gaging stations of interest (Richter et al. 1996). If periods of record are shorter than 15 years, the statistical power and validity of the parameters calculated by the IHA software are reduced.

In the case of Arbuckle-Simpson streams considered in this study, only two gaging stations on the Blue River (Milburn, OK and Blue, OK) had primary periods of record sufficiently long to apply the IHA software without concern over the statistical validity of the results obtained.

To overcome the lack of sufficiently long periods of record for upper Blue River and Pennington Creek, a correlation estimation technique (Richter et al. 1996) was applied to extend the period of record for the Blue River gage at Connerville, OK and the Pennington Creek gage at Reagan, OK. Because of general similarities in hydrograph form and watershed characteristics, the 20-yr-long period of record for the Blue River at Milburn, OK was used as the basis for development of a synthetic hydrograph to extend the period of record at those gages. Evaluation of the synthetic hydrographs suggests that while the overall character of the period of record is reliable, specific details of high-flow events may contain appreciable error. As such, the IHA analysis of the combined periods of record (actual data and estimated data) for Reagan, OK and Connerville, OK focused on the baseflow and low flow portions of the flow regime, where estimation error was less of a factor. Such a situation was well suited for this study, in that the effect of groundwater discharge on streams from the Arbuckle-Simpson Aquifer is greatest during baseflow and low flow events.

The period of record for two gaging stations (Blue River at Connerville, OK and Pennington Creek near Reagan, OK) were extended using simple correlation techniques similar to those first used by Fairchild et al. (1990) to estimate data with the Arbuckles region. Such a correlation technique is also presented by Richter et al. (1996) as an option to extend flow records at sites lacking sufficiently long stream gaging records. In particular, the method has shown acceptable results for gaging stations within the same watershed or for records from gaging stations from nearby streams that have generally similar characteristics (Richter et al. 1996).

Hydrographs for water year 1978 (October 1977 through September 1978) for the three Blue River gaging stations are illustrated in Figure 7. The close correspondence in form between the hydrographs form the Connerville and Milburn gaging stations suggests that application of the simple correlation technique may be appropriate to approximate stream flow data for the Connerville, OK locality using data collected at the Milburn, OK gage. Such an approximation greatly increased the extent of stream flow data for the Connerville, OK locality.

A similar analysis was conducted for the Pennington Creek gage at Reagan, OK and the Blue River gage at Connerville, OK and it was concluded that data from the Connerville gage could be used to approximate data for the Pennington Creek gaging site near Reagan, OK.

Results from application of the correlation technique to estimate data for the Blue River at Connerville, OK and for Pennington Creek near Reagan, OK are illustrated in Figures 8 and 9, respectively. In both cases, data for the time intervals indicated were cross-plotted, and an appropriate function was fit through the resulting data pattern. In both cases, the r^2 value for the resulting function was greater than 0.85. The exponential function illustrated in Figure 7 was used in conjunction with data from the Milburn, OK gage to approximate stream flow values for the Blue River gage at Connerville, OK for water years 1966 through 1976 and 1980 through 1986 (Table 1). Similarly, the logarithmic function illustrated in Figure 8 was used in conjunction with data from the Connerville, OK gaging station to approximate stream flow values for the Pennington Creek gage near Reagan, OK for water years 1966 through 1986 (Table 1).

Water Quality Data

Travertine Creek is a popular recreation site for swimming during the hot summer months, which also coincide with low flow periods. Because bacteria concentrations affect the ability of the public to use the stream for recreation, we examined the relationship between flows and bacterial concentration. We obtained available *Escherichia coli* concentration data from the Chickasaw NRA (Steve Burroughs, personal communication). Data were compared with Oklahoma Water quality criteria (OAC 795) to determine severity of impacts. We used Spearman's Rank Correlation to determine the effect of streamflow and ambient temperature and precipitation on *E. coli* concentrations.

IHA Data Analysis and Ecological Flow Parameters

Indicators of Hydrologic Alteration (IHA) software allows hydrologists and ecologists to create a statistical description of a daily record of stream flow and to measure changes in this description over time. The IHA program calculates a suite of more than 67 ecologically-relevant statistics from a daily hydrologic data series. For example, it calculates the timing and maximum flow of each year's largest flood, then calculates the mean and variance of these values over some decades (Richter et al. 1996, 1997, 1998, Mathews and Richter 2007). If these statistics were changed significantly by, for instance, dam construction or increased consumptive withdrawals, ecologists and water managers could then consider and evaluate whether or not the observed changes are of significance to the downstream ecosystem (Richter et al. 1997). The IHA also includes the Range of Variability Approach (RVA) to support ecologically based management of hydrological systems. This method, described by Richter et al. (1997), helps with the design of adaptive management programs that use the quantified natural variation of a hydrological system as an interim management target. Using the RVA, one can propose a range of variability for each IHA parameter as a management target and quickly calculate how frequently the system has met these goals during the data period.

Parameters evaluated by the IHA software are summarized in Tables 2 and 3. The basic suite of parameters consists of 33 variables that evaluate the magnitude, timing, duration, frequency, and rate of change for high- and low-flow events as wells as for monthly median flow events (Table 2). An additional suite of 34 Ecological Flow Components (EFCs) was recently added to the IHA software (Mathews and Richter 2007). The EFCs are parameters found to typically have direct linkage to many significant ecological and geomorphic processes and characterize small and large floods, high-flow pulses, low-flow periods when the stream is somewhat above to at base flow, and extreme low-flow events when the stream is under drought conditions (Table 3)

An initial step in conducting an IHA analysis is to define the natural range of variability (NRV) characteristic of each of the suite of 67 flow regime parameters summarized in Tables 2 and 3. The specific definition of the natural range of variability is arbitrary, but defining the NRV for each individual flow regime parameter as being between the 25th and 75th percentiles has been found to be useful in ecological flow assessments elsewhere (Richter et al. 1996, 1997). Such a convention has been adopted for use in this study.

Annual median values of the suite of 33 base parameters considered during the IHA analysis were further analyzed to determine if temporal trends exist between the various annual values. Spearman Rank Correlation coefficients (SRC) were calculated for each of the IHA parameters to evaluate temporal trends. Values for the SRCs range from -1.0 to 1.0, and the closer the value is to -1.0 or 1.0, the stronger the temporal correlation (either a negative or positive correlation, respectively).

The IHA analysis provides a means of assessing which of the 33 IHA basic parameters is most impacted by flow alteration between the pre- and post-impact periods. The IHA is a summary measure of the change in the statistical distribution between the pre- and post-impact values for each of the individual parameters within the suite of the 33 IHA parameters. The index is defined as (Richter et. al., 1996):

$$\text{IHA} = \frac{(\text{Number of Observed Values - Number of Expected Values})}{\text{Number of Expected Values}}$$

The range of values for each of the 33 IHA parameters in the pre-impact period is divided into three segments typically as follows: upper (values > 75th percentile), middle (values between the 25th and 75th percentile), lower (values < 25th percentile). For each parameter, the number of values for the post-impact period falling into each of the three segments of the range of values is compared to the number falling into the corresponding segment of the value range for the pre-impact period. An Index of Hydrologic Alteration is computed for the upper, middle, and lower segment of the value range for each of the 33 IHA parameters using the equation presented above. Positive values of the index indicate that more post-impact values fall into a particular range segment than would be expected based on the distribution of pre-impact values. For example, if 5 values from the pre-impact data fell in the upper segment of the value range, and 15 values from the post-impact data fell into the upper segment of the range, the Index of Hydrologic Alteration for the upper segment of the value range for the particular parameter under consideration would be (15-5)/5 or 2. Negative values for the index indicate that fewer post-impact values fall into a particular segment that would be expected based on pre-impact distribution.

Results

Blue River

The upstream-most gaging station on the Blue River at Connerville, OK is located on the Hunton Anticline of the Arbuckle Simpson Aquifer (Figure 2). The gage at Milburn, OK is located approximately 6 miles downstream of the Arbuckles and the Precambrian granite on its southern edge. The gage at Blue, OK is located more than 50 miles downstream of the Arbuckles on the gulf coastal plain geology. As such, the Connerville, OK and to a lesser extent the Milburn, OK gages are best positioned to provide information on the surface water flow characteristics of streams associated with the Arbuckle-Simpson Aquifer, while the gaging station at Blue, OK is best positioned to evaluate surface water characteristics of large coastal plains streams, portions of whose watershed integrates areas not underlain by the Arbuckle-Simpson Aquifer.

Gaging Station at Connerville OK

The period of record analyzed for the Blue River at Connerville, OK gage represents a combination of measured and estimated daily flow values (Table 1). The combined period of record analyzed for this locality covers water years 1966 though 1986 and 2004 through 2007.

Summary flow characteristics of the Blue River at Connerville, OK are illustrated by a flow duration curve (Figure 9) and summarized in Table 4. Median monthly flows range from ~40 cubic feet per second (cfs) to ~55 cfs (Figure 10). The NRV (which is defined as the spread of values between the 25th and 75th percentiles) associated with each monthly value is greatest in the period March though June, and least during the period August through October (Figure 10).

The median values and natural ranges of variability for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events are illustrated in Figure 11. The relatively small range of variability for the low-flow events is consistent with groundwater-discharge comprising a significant portion of observed baseflows in the Blue River at this locality.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 12. The 7-day low-flow values range from 33 cfs for events with a 2-year recurrence interval to ~14 cfs for events with a 30-year recurrence interval.

The mean annual number and duration of high-flow (defined as periods when flows were greater than those of the 25th exceedence percentile on the flow duration curve, Table 2) and low-flow (defined as periods when the flows were less than those of the 75th exceedence percentile on the flow duration curve) are illustrated in Figure 13. The median annual number of low-flow events is 6 with a median annual duration of ~5 days for each event. The annual mean number of high-flow pulses is 9 with a median duration for each event being 2 days per event.

No days were recorded during the period of record in which the stream flow dropped to zero cfs at this locality.

To further characterize the natural flow regime during conditions when stream flow is largely supported by groundwater discharge from the Arbuckle-Simpson Aquifer, the EFCs of monthly low flows and extreme low-flow events were examined in detail. The low flow EFC parameter is defined as the median flow values for all stream flows below the median flow value, but greater than those characterized as extreme low flows (Mathews and Richter 2007). As defined, the low flow EFC parameter measures flow values at or near base flow conditions with the channel, and when the flows are not receding from high-flow pulses, and flood events (TNC 2006). Median monthly low flows and their natural range of variability for the Blue River at Connerville, OK are illustrated in Figure 14. The pattern exhibited is generally similar to that for the median monthly flows (Figure 10), though the low-flow values exhibit less overall variability than the monthly median values.

The annual date of the first extreme low-flow event in a given year, along with the mean annual magnitude, duration and frequency of such events are illustrated in Figure 15. Extreme low flows are defined as flows less than those of the 90 exceedance percentile on the flow duration curve (Mathews and Richter 2007, TNC 2006). Typically, such conditions represent flow conditions during prolonged or severe drought conditions. For the Connerville, OK gage, most extreme low-flow events occur in late summer or fall, have mean magnitudes between 25 and 30cfs, mean durations of 8 days or less, and have a wide variation of annual occurrence that range from no events to as many as 16 events per year.

The IHA software computes a base flow metric which is defined as the annual 7-day low flow divided by the mean annual flow for each year of data (Mathews and Richter 2007, TNC 2006). Results for the base flow metric for the Blue River gage at Connerville, OK are illustrated in Figure 16. No clear temporal trend is observed, although the degree of variability in this metric for the 2007 through 2008 period appears to be greater than for the 1966 through 1986 period.

Each of the 33 parameters in the base suite of 33 IHA metrics (Table 2) was evaluated to identify parameters that exhibited a statistically significant temporal trend. Results of this exercise are illustrated in Table 5, and only 3 parameters were found to have significant trends. The date of the 1-day low-flow event occurs later in the year, and the date of the 1-day high-flow event occurs earlier in the year. Additionally, the annual number of hydrograph reversals is increasing with time.

Gaging Station at Milburn OK

The period of record analyzed for the Blue River gage at Milburn, OK represents measured daily flow values (Table 1) collected during water years 1966 though 1986. The period of record for Milburn represents the longest measured record available for a gaging location influenced principally by interaction with the Arbuckle-Simpson Aquifer. As such, it provides the best opportunity to evaluate the flow regime of an Arbuckle-Simpson stream.

Summary flow characteristics of the Blue River at this site are illustrated by a flow duration curve (Figure 17) and summarized in Table 4. Median monthly flows range from ~57cfs to ~100cfs (Figure 18). The NRV associated with each monthly value is greatest in the period March though June, and least during the period August through October.

The annual numbers and durations for low-flow pulses (flow events when the flow magnitude was equal to less than that of the 75th percent exceedence level on the flow duration curve) are illustrated in Figure 19, as well as number of zero-flow days for the site (none were recorded) and the annual numbers and durations for high-flow pulses (flow events when the flow magnitude was equal to or greater than that of the 25th exceedence level on the flow duration curve). The annual number and durations of low-flow events in the Blue River at Milburn, OK exhibit significantly more variability than noted for high-flow pulses, especially with respect to event duration.

The median values and natural ranges of variability for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events are illustrated in Figure 20. Similar to the Blue River gage at Connerville, OK, the relatively small range of variability for the low-flow events is consistent with groundwater-discharge comprising a significant portion of observed baseflows in the Blue River at Milburn, OK locality.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 21. The 7-day low-flow values range from 33 cfs for events with a 2-year recurrence interval to ~17 cfs for events with a 20-year recurrence interval.

The Environmental Flow Components (EFC) parameters calculated by the IHA software (Mathews and Richter, 2007) provide addition characterization of baseflow and low-flow conditions in the Blue River. Monthly medians values and ranges of variability for times of "baseflow" or low flow conditions (flows less than high-flow pulses and greater than extreme low-flow events) are illustrated in figure 22. According to Mathews and Richter (2007) such flow conditions are representative of times when flow in streams is largely support by groundwater discharge into the stream.

Another measure of baseflow variability is the baseflow index (Figure 23). This IHA parameter is defined as the annual 7-day minimum flow divided by the mean annual flow, and exhibits considerable variability for the Blue River at the Milburn site. Although there appears to be a slight decreasing trend with time for the index, statistical analysis indicates that any temporal trends lack statistical significance (Table 5).

Results for the annual number, date, and mean annual magnitude and duration of extreme low-flow EFC parameter for the Blue River gage at the Milburn, OK are illustrated in Figure 24. Such metrics provide a description of low-flow events when flow values are less than or equal to flow magnitude of the 90th exceedence point on the flow duration curve. The annual number of events is variable, ranging from 0 to 16, with 6 or fewer events per year being most typical. The date of the first extreme low-flow event typically falls within the period August to November with rare events falling during the period January to February. Magnitudes of extreme low-flows range between 25 and 30 cfs, with one event have a magnitude of 20 cfs. Such a small cluster of flow magnitudes suggests that the range of 20 to 30 cfs is typical of baseflow groundwater discharge to the Blue River at Milburn, OK. Mean annual durations of extreme low-flows typically vary between 1 and 8 days, with one year having a mean duration of 17 days.

A general picture of flood characteristics for the Blue River at Milburn, OK is provided by the flood frequency plot (Figure 25) and is calculated using annual instantaneous peak flow measurements at the gaging station. Floods with a recurrence interval of 2 years have a magnitude of ~10,000 cfs, while those with a 10-yr recurrence interval have a magnitude of ~30,000 cfs.

Relationships between annual peak flow and mean daily flows measured on the day of occurrence for the instantaneous peak flow are presented in Figure 26. The ratio of instantaneous peak flow to mean daily flow is a measure of the flashiness of the watershed upstream of the gaging station. The apparent increasing trend in the value of this ratio with time suggest that the flooding behavior of the watershed is becoming flashier, suggesting possible land-use change impacts within the watershed. Figure 26 also illustrates the percentage of the peak flow that is due to stormflow, based on hydrograph separation analysis. Essentially all of the peak flow is accounted for by stormflow.

Median values and ranges of variability for the mean annual magnitude and mean annual durations of the high-flow pulse, small flood, and large flood EFC parameters are illustrated in Figures 27. The EFC parameter "high-flow pulse" is defined somewhat differently than the high-flow event parameter contained in the basic suite of IHA parameters (Mathews and Richter 2007), and is a measure of high-flow pulses that remain within the channel of the river and do not access the floodplain. For the Blue River at Milburn, OK, high-flow pulse magnitudes are typically between 150 to 300 cfs and durations of the pulses are relatively short, with a median value of ~3 days. The annual number of high-flow pulses ranges from 3 to 18 (Figure 28a). The high-flow pulses are relatively evenly spread through the period February through November (Figure 28b) with events being slightly more common within the period May through August. Such a distribution suggests that spring and summer thunderstorms likely produce many of the high-flow pulses observed.

Small floods are floods that have a recurrence interval of ~2 years and approximate bankfull or channel-forming discharge flows. The EFC small flood parameter is calculated is mean daily flow values. For the Milburn gage, median values of small floods were ~7,000 cfs (Figure 27). Such a values is less than the value of 10,000 cfs determined from the flood frequency curve for annual peak flows illustrated in Figure 25. Typically, such differences in flood magnitudes are noted between flood magnitude calculations that use peak flows, and similar calculations that use mean daily flows (Dunne and Leopold 1978). Durations for small floods are significantly greater than high-flow pulses, with a median value of ~50 days and almost an order of magnitude variability in range of variability (Figure 27b). Typically 1 small flood occurs during a year, though there is one example of two occurring in the same water year (Figure 29a). All but three small floods occur during period April through June (Figure 29b). Three events occurred during the period October through November.

Large floods are those with a recurrence interval of ~10 years and represent significant high-water events. Median magnitudes for large floods are approximately 15,000 cfs. Their median durations are similar to those of small floods (~50 days) but exhibit significantly less variability (Figure 27). During the 20-yr period of record, only two large floods occurred (Figure 30a), and both occurred during October (Figure 30b).

The evaluation to identify statistically significant temporal trends within the base suite of IHA parameters was also conducted for data from the Milburn OK locality (Table 5). In this case, no significant temporal trends for any of the 33 base parameters were detected.

Gaging Station at Blue OK

The period of record analyzed for the Blue River gage at Blue, OK represents measured daily flow values (Table 1) collected during water years 1937 through 2007.

Summary flow characteristics of the Blue River at this site are illustrated by a flow duration curve (Figure 31) and summarized in Table 4. Data provided on the website (http://waterdata.usgs.gov/ok/nwis/dv/?site_no=07332500&referred_module=sw) for this gaging location indicates that flow data after ~1980 may be impacted by flow regulation within the watershed. Because of this, the data were stratified into two periods (1937-1978) and (1984-2007) to evaluate potential flow regime changes associated with such impacts.

Median monthly flows range from ~45cfs to ~200cfs (Figure 32). For most months, median monthly flows in the period 1984 through 2007 are consistently higher than the corresponding values for the earlier period. Note also that the flow duration curve for the 1984-2007 period typical lies slightly above the curve for the 1936-1978 period (Figure 31). These trends for the flow duration curves and for monthly median flow values are representative of climatic variation. The post alteration period, from 1984 to 2007, lies entirely within wet years (Figure 33). The NRV associated with each monthly value is greatest in the period January through June, and least during the period August through October (Figure 32).

The median values and natural ranges of variability for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events for the two time periods at the Blue River gage at Blue, OK are illustrated in Figure 34. Similar to the Blue River gaging site upstream at Connerville OK, the relatively small range of variability for the low-flow events is consistent with groundwater-discharge comprising a significant portion of observed base flows in the Blue River at this locality, even though it is well downstream from the outcrop area of the Arbuckle-Simpson Aquifer (Figure 2).

The annual numbers and durations for low-flow pulses (flow events when the flow magnitude was equal to less than that of the 75th percent exceedance level on the flow duration curve) are illustrated in Figure 35 along with the number of zero-flow days for the site (none were recorded) and the annual numbers and durations for high-flow pulses (flow events when the flow magnitude was equal to or greater than that of the 25th exceedance level on the flow duration curve). For both periods of record, the median annual number of low-flow events is 4 to 5 with a median annual duration of between 7 to 10 days for each event. The annual mean number of high-flow pulses is 11 to 13 with a median duration for each event being 2 to days per event. No days were recorded during the period of record in which the stream flow dropped to zero cfs at this locality.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 36. For both periods of record evaluated, the frequency curves are generally similar, with the 7-day low-flow values ranging from ~25 cfs for events with a 2-year recurrence interval to ~1 cfs for events with a 20-year recurrence interval.

Flood frequency curves for the two periods are illustrated in Figure 37. Flooding behavior is very similar for both periods of records and the flood frequency curves are generally similar. The peak flow magnitude of a flood event with a 2-year recurrence interval is ~9,000 cfs, and ~25,000 cfs for an event with a 10-year recurrence interval.

Relationships between annual peak flow and mean daily flows measured on the day of occurrence for the instantaneous peak flow at the Blue, OK gage are presented in Figure 38. The ratio of instantaneous peak flow to mean daily flow is a measure of the "flashiness" of the watershed upstream of the gaging station. The apparently increasing trend in the value of this ratio with time suggests that the flooding behavior of the watershed is become flashier, a change that may suggest land-use change impacts within the watershed and a similar change to that noted for the upstream gaging station at Milburn, OK. Figure 38 also illustrates the percentage of the peak flow that is due to stormflow based on hydrograph separation analysis.

The each of the 33 parameter in the base suite of 33 IHA metrics (Table 2) was evaluated to identify parameters that exhibited a statistically significant temporal trend. Results of this exercise are illustrated in Table 5. For the 1937-1978 period, only 3 parameters were found to have significant trends at the Blue, OK gage. The date of the 1-day low-flow event is occurring later in the year, and the date of the 1-day high-flow event is occurring earlier in the year. Additionally, the annual base flow index exhibits an increasing trend with time. For the period potentially impacted by flow diversion, however eight parameters exhibit temporal trends. The monthly median flows for the four months in the period May through August all exhibited decreasing trends with time, as do the magnitudes of the 1-, 3-, and 7-day low flow events. Additionally, the mean annual duration of low-flow events exhibits an increasing trend with time.

Changes between pre- and post-impact periods such as those discussed in the preceding paragraph are consistent with those associated with off-stream diversion of water during the summer growing season. Examination of only the magnitudes of monthly median values, and magnitudes of the NRV for flow regime parameters (e.g., Figures 32 and 34) may not detect potentially significant changes. Both changes in magnitude for stratified sampling periods, and temporal trends must be evaluated to characterize flow regime changes resulting from changes in water management practices.

Index of Hydrologic Alteration values were calculated for each of the 33 core parameters by comparing the two stratified periods of record to each other. The 1937-1978 period was used as the pre-impact periods, and the 1984-2007 periods was assumed to be the period impacted by flow diversion. Results are illustrated in Figure 39. Magnitudes of IHA values for the 33 core flow regime parameters are illustrated ranked from highest (most altered) to lowest (least altered) in Figure 40 and the parameters contributing ~5% or more to the total hydrologic alteration index calculated for the Blue River gage at Blue, OK are given in Table 6.

Results of the IHA calculations illustrated in Figures 38 and 40 can be used to assess the magnitude of flow regime alteration that has been experienced by a river upstream of a gaging locality. The calculations can also be used to identify which aspects of the flow regime have been most altered. In the case of the Blue River at Blue, OK, no clear pattern of flow alteration principally involving one or more grouping of IHA parameters is discernable. Such a situation differs significantly from alteration patterns frequently associated with flood control or hydropower dam operations (Richter et al. 1996, Richter et al. 1997, Mathews and Richter 2007), but may be typical of alteration patterns associated with diverse water diversion impacts throughout a watershed.

<u>Pennington Creek</u>

The Pennington Creek gage near Reagan, OK is located close to the edge of the outcrop area of the Arbuckle-Simpson Aquifer (Figure 3). In the case of the Reagan, OK station, the impact of groundwater discharge from the aquifer on low-flow events in Pennington Creek watershed can be evaluated.

The period of record analyzed for the Pennington Creek gage near Reagan, OK represents a combination of measured and estimated daily flow values (Table 1). The combined period of record analyzed for this locality covers water years 1966 though 1986 and 2004 through 2007.

Summary flow characteristics of Pennington Creek at this site are illustrated by a flow duration curve (Figure 41) and summarized in Table 4. Median monthly flows range from ~20 cfs to ~48 cfs. The NRV associated with each monthly value is greatest in the period March though June, and least during the period August through October (Figure 42).

The median values and NRV for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events are illustrated in Figures 43. The relatively small range of variability for the low-flow events is consistent with groundwater-discharge comprising a significant portion of observed base flows in Pennington Creek at this locality.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 44. The 7-day low-flow values range from ~14 cfs for events with a 2-year recurrence interval to ~7 cfs for events with a 20-year recurrence interval.

The mean annual number and duration of high-flow (defined as periods when flows were greater than those of the 25[th] exceedence percentile on the flow duration curve, Table 2) and low-flow (defined as periods when the flows were less than those of the 75[th] exceedence percentile on the flow duration curve) are illustrated in Figure 45. The median annual number of low-flow events is 4 with a median annual duration of ~6 days for each event. The annual mean number of high-flow pulses is 9 with a median duration for each event being ~2.5 days per event. No days were recorded during the period of record in which the stream flow dropped to zero cfs at this locality.

To further characterize the natural flow regime during conditions when stream flow in Pennington Creek is largely supported by groundwater discharge from the Arbuckle-Simpson Aquifer, the EFCs of monthly low flows and extreme low-flow events were examined in detail. As defined by Mathews and Richter (2007), the low flow EFC parameter measures flow values at or near base flow conditions with the channel, and when the flows are not receding from high-flow pulses and flood events (TNC 2006). Median monthly low flows and their NRV for the Pennington Creek near Reagan, OK are illustrated in Figure 46. The pattern exhibited is generally similar to that for the median monthly flows (Figure 41), though the low-flow values exhibit less overall variability than the monthly median.

The annual date of the first extreme low-flow event in a given year, along with the mean annual magnitude, duration and frequency of such events are illustrated in Figures 47. Extreme low flows are defined as flows less than those of the 90th percentile exceedance on the flow duration curve (Mathews and Richter 2007, TNC 2006). Typically, such conditions represent flow conditions during prolonged or severe drought conditions. For the Pennington Creek gage near Reagan, OK most extreme low-flow events occur in late summer or fall, have mean magnitudes between 11 and 13 cfs, and mean durations of 8 days or less, and have a wide variation of annual occurrence that range from no events to as many as 16 events per year.

The IHA software computes a base flow metric which is defined as the annual 7-day low flow divided by the mean annual flow for each year of data (Mathews and Richter 2007, TNC 2006). Results for the base flow metric for the Reagan, OK gage on Pennington Creek are illustrated in Figure 48. The baseflow index does not exhibit a distinct temporal trend.

Each of the base suite of 33 IHA metrics (Table 2) was evaluated to identify parameters that exhibited a statistically significant temporal trend. Results of this exercise are illustrated in Table 5, and only 2 parameters were found to have significant trends. The annual number of hydrograph reversals is increasing and the mean annual hydrograph fall rate is decreasing with time.

Honey Creek

The gaging station on Honey Creek at Turner Falls, OK is located on the Arbuckle Anticline of the Arbuckle-Simpson Aquifer (Figure 4). The period of record for the Turner Falls, OK gage is short and represents measured daily flow values (Table 1) collected during water years 2005 through 2007. Because of the short period of record, the full suite of IHA analyses was not completed at this locality as the statistical methods involved require a minimum of 20 years of data to have adequate statistical power for meaningful interpretation. A flow duration curve, and monthly mean flows were the only parameters evaluated in order to provide a summary look at Honey Creek stream flow at the site.

General flow characteristics for the Honey Creek gage at Turner Falls, OK are illustrated by a flow duration curve (Figure 49) and summarized in Table 4. Median monthly flows range from ~3 cfs to ~21 cfs. The NRV associated with each monthly value is greatest in November and the period May through July, and least in September and March (Figure 50). It must be noted, however, that the period of record for Honey Creek at Turner Falls, OK site is too short for such conclusions to be little more than very general inferences about the flow regime at this locality.

Byrds Mill Spring

Byrds Mill is a major spring that occurs within the Hunton Anticline of the Arbuckle-Simpson Aquifer near the town of Fittstown, OK and groundwater from the aquifer constitute a major component of the spring flow. This spring also provides water for the city of Ada, Oklahoma, and its hydrograph represents a highly altered system. Prior to 1991, stream gage data represents only flow in Mill Creek, and excludes water diverted to Ada. After 1991, however, both water in the stream and water diverted to Ada via an 18-inch pipe are represented in the gage data, which combined provide a hydrograph more representative of Byrds Mill Spring discharge. Because of a dry period, Ada began using more water in 2001. Therefore, the period of record we analyzed for Byrds Mill Spring represents combined daily flow values collected during water years 1991 through 2001. This period of record, however, is too short for a robust analysis of the hydrology of Byrds Mill Spring and results should be interpreted with caution.

Summary flow characteristics of the Byrds Mill Spring are illustrated by a flow duration curve (Figure 51) and summarized in Table 4. Median monthly flows range from ~17 cfs to ~23 cfs. The median monthly flow was highest in January through June and lower from August through December (Figure 52).

The median values and natural ranges of variability for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events are illustrated in Figure 53. The relatively small range of variability for both the high- and low-flow events is consistent with groundwater-discharge that is predominantly diffuse flow in character.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 54. The 7-day low-flow values range from ~14 cfs for events with a 2-year recurrence interval to 8.5 cfs for events with a 10-year recurrence interval.

To further evaluate the response of Byrds Mill Spring during low flow conditions, the EFCs of monthly low flows and extreme low-flow events were examined in detail. As defined by Mathews and Richter (2007), the low flow EFC parameter measures flow values at or near base flow conditions with the channel, and when the flows are not receding from high-flow pulses, and flood events (TNC 2006). Median month low flows and their NRV for Byrd's Mill Spring are illustrated in Figure 55. The pattern exhibited is generally similar to that for the median monthly flows (Figure 51), though the low-flow values exhibit less overall variability than the monthly median.

The annual date of the first extreme low-flow event in a given year, along with the mean annual magnitude, duration and frequency of such events are illustrated in Figure 56. Extreme low flows are defined as flows less than those of the 90 exceedence percentile on the flow duration curve (Mathews and Richter 2007, TNC 2006). Typically such conditions represent flow conditions during prolonged or severe drought conditions. For Byrds Mill Spring extreme low-flow events can occue as early as April, but the preponderance of events occur in the fall, have mean magnitudes from 13 to 14 cfs, mean durations of typically 5 days or less, and have a wide variation of annual occurrence that range from no events to as many as 10 events per year. Byrds Mill Spring does not usually have any zero-flow days.

The IHA software computes a base flow metric which is defined as the annual 7-day low flow divided by the mean annual flow for each year of data (Mathews and Richter 2007, TNC 2006). Results for the base flow metric for the Byrds Mill Spring gage near Fittstown, OK are illustrated in Figure 57. The baseflow index shows a significant declining trend in the correlation coefficient. This may indicate that less of the streamflow in Mill Creek is from baseflow.

The each of the 33 parameters in the base suite of 33 IHA metrics (Table 2) was evaluated to identify parameters that exhibited a statistically significant temporal trend. Sixteen parameters were found to have statistically significant trends (Table 5). Of interest because of their potential implication for water supply issues are the decreases in fall (August, September, October and November) monthly median flows, the decreasing magnitudes of low-flow events (1- 3- 7- 3- and 90-day), the decreasing baseflow index, and the decreasing November and April low flows. The small flood duration is also decreasing, while the number of extreme low flows and the Small flood rise rate are both increasing.

Travertine Creek

Water Quality

Because Travertine Creek is a popular swimming area, water quality should allow primary body contact beneficial uses during the recreation season (May 1 – September 30). *E. coli* concentrations, an indicator of bacterial loading, are monitored by the Chickasaw NRA at 11 sites on the park, 4 of which had enough data for analysis. Three of these sites are on Travertine Creek: Bear Falls, Little Niagara, and Panther Falls. The fourth site, Black Sulphur Springs, is on Rock Creek (Steve Burroughs personal communication, Figure 5). The primary body contact beneficial use is considered not attained if the geometric mean of 5 samples exceeds 126 colonies/100 mL or any single sample exceeds 406 colonies/100 mL (ODEQ 2004).

E. coli concentrations at Black Sulfur Springs were most closely correlated to discharge at Rock Creek (0.508). This was the only strong correlation between any of the environmental variables and *E. coli* concentrations. The inverse correlation between *E. coli* at Little Niagara and discharge at Antelope springs (-0.485) was the closest of any environmental variables at that site (Table 7). *E. coli* concentrations at Panther Falls was weakly inversely correlated to the number of days since a rain event greater than 0.5 inches (-0.332, Table 7). These observations were echoed by the flow duration comparisons. Little Niagara was the only site that showed any pattern with discharge (Figure 58). All of the exceedences at this site occurred when flow durations were greater than about 40%, and flows were less than 3.3 cfs. Bear Falls and Panther Falls showed no relationship between flow and *E. coli* concentrations. The examination of flow duration on Rock Creek and *E. coli* concentrations at Black Sulphur Springs showed that concentrations exceed TMDL limits much of the time, and that the highest concentrations occurred during periods of high flow (Figure 59).

Antelope Spring gage at Sulphur, OK

The period of record analyzed for the Antelope Spring gage at Sulphur, OK represents measured daily flow values (Table 1) collected during water years 1986 through 1989 and 2002 through 2006.
Summary flow characteristics of Antelope Spring at this site are illustrated by a flow duration curve (Figure 60) and summarized in Table 4. Median monthly flows range from 2 cfs to 4 cfs. The NRV (which is defined as the spread of values between the 25th and 75th percentiles) associated with each monthly value is greatest in the period January through June, and least during the period August through October (Figure 61).

The median values and natural ranges of variability for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events are illustrated in Figure 62. The relatively small range of variability for both the high- and low-flow events is consistent with groundwater-discharge that is predominantly diffuse flow in character.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 63. The 7-day low-flow values range from 1 cfs for events with a 2-year recurrence interval to ~0.1 cfs for events with a 10-year recurrence interval.

The mean annual number and duration of high-flow (defined as periods when flows were greater than those of the 25th exceedence percentile on the flow duration curve (Table 2) and low-flow (defined as periods when the flows were less than those of the 75th exceedence percentile on the flow duration curve) are illustrated in Figure 64. The median annual number of low-flow events is 0 with a median annual duration of 5 days for each event. The annual mean number of high-flow pulses is 3 with a median duration for each event being 11 days per event. No days were recorded during the period of record in which the stream flow dropped to zero cfs at this locality.

The EFCs of monthly low flows and extreme low-flow events were examined in detail. The low flow EFC parameter is defined as the median flow values for all stream flows below the median flow value, but greater than those characterized as extreme low flows. As defined, the low flow EFC parameter measures flow values at or near base flow conditions with the channel, and when the flows are not receding from high-flow pulses, and flood events. Median monthly low flows and their NRV for the Antelope Spring at Sulphur, OK are illustrated in Figure 65. The pattern exhibited is general similar to that for the median monthly flows (Figure 61), though the low-flow values exhibit less overall variability than the monthly median.

The annual date of the first extreme low-flow event in a given year, along with the mean annual magnitude, duration and frequency of such events are illustrated in Figure 66. Extreme low flows are defined as flows less than those of the 90 exceedence percentile on the flow duration curve. Typically, such conditions represent flow conditions during prolonged or severe drought conditions. For Antelope Spring, most extreme low-flow events occur in late summer or fall, have mean magnitudes between 5 and 9 cfs, and mean durations of 10 days or less, and have a variation of annual occurrence that range from no events to as many as 3 events per year.

The IHA software computes a base flow metric which is defined as the annual 7-day low flow divided by the mean annual flow for each year of data (Mathews and Richter 2007, TNC 2006). Results for the base flow metric for the Antelope Spring gage near Sulphur, OK are illustrated in Figure 67. No clear temporal trend is observed, although the degree of variability in this metric for the 2002 through 2007 period appears to be significantly less than for the 1986 through 1989 period.

Rock Creek Gage at Sulphur, OK

The period of record analyzed for the Rock Creek gage at Sulphur, OK represents measured daily flow values (Table 1) collected during water years 1990 through 2006.

Summary flow characteristics of Rock Creek at this site are illustrated by a flow duration curve (Figure 68) and summarized in Table 4. Median monthly flows range from 9 cfs to 32 cfs. The NRV (which is defined as the spread of values between the 25th and 75th percentiles) associated with each monthly value is greatest in the period January through May, and least during the period July through October (Figure 69).

The median values and natural ranges of variability for 1-, 3-, 7-, 30-, and 90-day high- and low-flow events are illustrated in Figure 70. The relatively small range of variability for the low-flow events is consistent with groundwater-discharge comprising a portion of observed baseflows in Rock Creek at this locality.

The recurrence frequencies for 7-day low-flow events are illustrated in Figure 71. The 7-day low-flow values range from 7 cfs for events with a 2-year recurrence interval to ~3 cfs for events with a 10-year recurrence interval.

The mean annual number and duration of high-flow (defined as periods when flows were greater than those of the 25th exceedence percentile on the flow duration curve (Table 2) and low-flow (defined as periods when the flows were less than those of the 75th exceedence percentile on the flow duration curve) are illustrated in Figure 72. The median annual number of low-flow events is 6 with a median annual duration of 6 days for each event. The annual mean number of high-flow pulses is 11 with a median duration for each event being 3 days per event. No days were recorded during the period of record in which the stream flow dropped to zero cfs at this locality.

The EFCs of monthly low flows and extreme low-flow events were examined in detail. The low flow EFC parameter is defined as the median flow values for all stream flows below the median flow value, but greater than those characterized as extreme low flows (Mathews and Richter 2007). As defined, the low flow EFC parameter measures flow values at or near base flow conditions with the channel, and when the flows are not receding from high-flow pulses, and flood events. Median monthly low flows and their natural range of variability for the Rock Creek at Sulphur, OK are illustrated in Figure 73. The pattern exhibited is general similar to that for the median monthly flows (Figure 58), though the low-flow values exhibit less overall variability than the monthly median.

The annual date of the first extreme low-flow event in a given year, along with the mean annual magnitude, duration and frequency of such events are illustrated in Figure 74. Extreme low flows are defined as flows less than those of the 90th percentile exceedance on the flow duration curve. Typically, such conditions represent flow conditions during prolonged or severe drought conditions. For the Rock Creek locality, most extreme low-flow events occur in late summer or fall, have mean magnitudes between 3 and 5 cfs, and mean durations of 9 days or less, and have a variation of annual occurrence that range from no events to as many as 3 events per year.

The IHA software computes a base flow metric which is defined as the annual 7-day low flow divided by the mean annual flow for each year of data (Mathews and Richter 2007, TNC 2006). Results for the base flow metric for Rock Creek at the Sulphur, OK locality are illustrated in Figure 75. No clear temporal trend was observed, although the degree of variability in this metric for the 2007 through 2008 period appears to be greater than for the 1966 through 1986 period.

Each of the 33 parameters in the base suite of 33 IHA metrics (Table 2) was evaluated to identify parameters that exhibited a statistically significant temporal trend. Results of this exercise are illustrated in Table 5, and 15 parameters were found to have significant trends. Median flows from March through September, and December were all declining. The magnitude of 9-day minimum flows, and 30-day and 90-day maximum flow were also declining. The annual number of low flows, the number of hydrograph reversals and the hydrograph rise fall rate were increasing. The annual hydrograph rise rate was decreasing. In essence, overall streamflow was decreasing and flood events were becoming more flashy. These trends were likely the result of variation in weather patterns.

Discussion

Natural Flow Regimes

Streamflow patterns in Arbuckle-Simpson streams could be generalized into 3 broad categories: Hunton Anticline streams, perennial streams, and springs. This generalization is meant only to facilitate the discussion of our findings, and was based on broad, subjective similarities of our results.

Hunton Anticline streams, which included the Blue River at Connerville, Pennington Creek near Reagan, Ok, Blue River at Milburne, OK and Rock Creek at Sulphur, OK, derive their flows from springs and precipitation, and had stable base flows, as evidenced by the small ranges of variability in low flow events. These streams never went dry, even in the most extreme droughts. Base flows were highest in the winter (January through June) and lowest in the summer (August through October).

One could use the Milburne, OK gage to gain in particular to gain a better understanding of the hydrology of Hunton anticline streams in general. While specific details may differ, the general patterns and characteristics such as dates of occurrence, variability in number of annual high- and low-flow events and duration of events should be similar. Thus, even though sufficient flow record may be lacking for a specific stream, analysis of the flow record for the Blue River at Milburn can be used to establish expected patterns for various components of the flow regime. Such patterns can serve as the basis development of water management practices that will maintain the general nature and character of the flow regime. Specifically, in the case the analysis for the Blue River at Milburn OK, the consistency of baseflow magnitudes during low-flow events of various durations and frequencies, the variability in annual number and duration of extreme low-flow events, the lack of zero-flow days, and the variability of the monthly baseflow magnitudes are characteristics of the flow regime that can guide development of water management practices for the Arbuckle-Simpson systems. While additional studies may be required for sites lacking adequate data, the general character and patterns of variability can be inferred from the existing record at the Milburn OK site. Data from the Blue River at the Milburn gaging station can also be used in conjunction with the Environmental Flow Components calculated by the IHA software to define general ranges of variability and patterns for critical ecological flow components that are representative streams influenced by groundwater discharge from the Arbuckle-Simpson aquifer. Such information provides a basic framework for establishing water management policies that will maintain critical variability and patterns in streams throughout the Arbuckle-Simpson outcrop area.

Perennial streams, such as the Blue River at Blue, Oklahoma, at first glance may appear very similar to Hunton Anticline streams, but these streams were more weakly influenced by groundwater. While they also had stable base flows, during extreme drought events these streams ceased to flow. One could argue that Rock Creek might fit into this category because its low flow events had a small discharge relative to watershed size and base flows. However, it did retain flow even in the harshest droughts, so was considered with the Hunton group.

The spring group included Antelope Spring and Byrd's Mill Spring which derived their flow entirely from groundwater and had low variability. Springs had moderate seasonality in monthly median and monthly low flows. There was also little variability in EFC low flows or high flows, and low or high flow statistics. Hanson and Cates (1994) observed that variation in Antelope Springs discharges were correlated with long-term weather patterns. Our characterization of this group, however, is based on the Antelope Spring and Byrds Mill Spring IHAs. Antelope Spring had a short period of record (7 years), which had a long break in collection in the middle of the record (Table 1), however, it was not highly modified. The entirety of Byrd's Mill Spring's period of record has been affected by diversions, and the most reliable period or record, from was only 10 years long. To better understand spring flows on the Hunton Anticline, we would need to model a longer period of unaltered flow for Byrds Mill spring and a longer continuous dataset from Antelope Spring. As more flow data is collected for these springs, we would be able to better describe these gages.

Honey Creek was not assigned to any group. With only 3 years of data, there was not enough information to describe the natural flow regime. We identified some seasonality of flow, with a wet winter season and summer low flows. But we need more data to better understand the flow regime, especially high and low flow patterns. Because this stream originated on the Arbuckle Anticline, we did not attempt to extend the gage or group it with the Hunton streams, as the relationship in flow patterns between these gages was unclear.

Water Quality

The retention of primary body contact beneficial uses is important on the Chickasaw NRA. Becker (2006) observed that since 2001, E. coli bacteria counts exceeded the regulatory standard (ODEQ 2004) on the streams during periods of high and use after rainfall events, and during periods of extended drought. In our examination of the E. coli and its relationship to streamflow, we found only weak, yet still significant relationships between streamflow and bacterial concentrations, indicating that there were additional factors in play. At Black Sulfur Springs, we observed exceedances at all flows, though they increased during high flows. This indicated instream as well as runoff related sources. This was consistent with Becker's (2006) findings that bacteria in Rock Creek were from cattle and untreated sewage, and that the highest potential sources of bacteria were land use and sewer overflows. Coliform concentrations at Bear falls and Panther Falls showed no relation to flow, while Little Niagara showed a weak negative relationship to flow at Antelope springs. This was also consistent with the findings of Becker (2006). She found that Travertine Creek bacteria were from sewage, cattle and horses. Swimmers and waders also seemed to be an intermittent source of bacteria in Travertine Creek during low-flow conditions. Other factors influenced coliform concentrations in these streams. The pathways of these and other contaminants need to be studied further to better understand these effects.

Flow Alteration and Water Management Considerations

The Blue River at Blue, OK had a number of upstream diversions, so the period of record was stratified to allow examination of pre-and post alteration flow patterns. Most flow statistics (flow duration curve, monthly median flows, high flow statistics) showed more water in the post-diversion period. This could have been due to the unusual climate cycle of 30 wet years (Table 23) that spans the post alteration period. Flow alteration analysis revealed significant alterations of median flows, and low flow statistics during the summer months, despite these being wet years. This was likely due to diversion of surface water upstream. These alterations could become more severe during naturally dry years, and should be monitored to determine the true degree of alteration and its impact on the stream including habitat condition and water quality.

Recall that extreme low flows act as disturbances in a stream ecosystem, affecting nutrient cycling, and fish assemblage structure through crowding or induction of physiological stress. Poff and Allan (1995) observed that habitat generalists are correlated with variable streams while more specialized species occupied streams with more stable streamflow patterns. Perennial streams would have been more likely to host species tolerant of variable conditions, whereas Hunton anticline streams are more likely to have specialist biota that need stable conditions. Poff and Allen (1995) and Poff and Ward (1989) hypothesized that adjustments in hydrologic regime could result in changes in course-scale assemblage structure. If such an extreme alteration were to occur on a Hunton steam it could shift the evolutionary tendencies of the river away from species adapted to stable flows, to those species that favor a more variable stream type.

In order to protect the social, economic and ecological values that streams provide, water management should include the protection of the full suite of variability in the natural flow regime. Because proposed diversions in the Arbuckles focus on groundwater withdrawal, base flows and small floods are most likely to be impacted. 7Q2 is currently used as a management goal for stream discharge, but protection at this flow level is not likely to protect base flows important for ecosystem function. In our study, 7Q2 roughly coincided with low flow events (specifically 1-day, 3-day, and 7-day annual low flows) which represented annual drought conditions and disturbance events. Management for this index may increase the frequency of occurrence and duration of these conditions and detrimentally impact stream ecosystem function.

To ensure proper ecosystem function and retention of associated ecosystem values, one might consider managing to maintain the monthly median EFC low flow events. Retention of these flow levels may ensure the protection of recruitment and growth conditions, and habitat availability for fish and macroinvertebrate communities. Hunton Anticline and perennial streams could be managed in two seasons: winter and summer. Because springs do not have a strong seasonal component, they can be effectively managed using annual indices. Managing for base flows alone, however, may not ensure the maintenance of channel structure and sediment composition. These components are maintained by effective discharge, which is equivalent to a 1.5-year flood event (Table 4). Reduction of base flows may also reduce the magnitude of these smaller flood events, in turn reducing their ability to maintain the channel. Habitat quantity and condition, stream stability and riparian vegetation maintenance depend on these flows.

This study examined the least altered flow regimes and existing alterations and trends on streams in the Arbuckle Simpson Aquifer. While we have provided some insight on how flows relate to ecosystem services, there is still much work to be done. Continued monitoring of streamflow across a variety of climactic conditions, especially at those site on the Arbuckles themselves are needed. In addition, a more detailed understanding of the type of ecosystem services provided by the stream and their economic values is needed. An understanding of the important life history components of key indicator species are needed, though this question is being answered for some of the most important species in the IFIM study. With the answers to these questions, we can begin to understand the true benefits and costs to society by water development practices.

Literature Cited

Becker, C.J. 2006. Water quality and possible sources of nitrogen and bacteria to Rock and Travertine Creeks, Chickasaw National Recreation Area, Oklahoma, 2004. U.S. Geological Survey Scientific Investigations Report 2005-5279, 23 p.

Benke, A.C. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society 9:77-88.

Biggs, B.J.F. 1995. The contribution of flood disturbance, catchment geology and land use to the habitat template of periphyton in stream ecosystems. Freshwater Biology 33:419-438.

Bunn, S.E. and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30: 492-507.

Steve Burroughs, personal communication

Chappell, W.S., and W.L. Fisher. 2005. Fish assemblage and aquatic habitat relationships at the Tishomingo National Wildlife Refuge, Oklahoma. Proceedings of the Oklahoma Academy of Science 85:19-31.

Doyle, M.W., E.H. Stanley, D.L. Strayer, R.B. Jacobsen and J.C. Schmidt. 2005. Effective discharge analysis of ecological processes in streams. Water Resources Research 41, W11411 doi:10.1029/2005WR004222.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W. H. Freeman and Co., New York, NY. 818p.

Fairchild, R.D., R.L. Hanson and R. E. Davis. 1990. Hydrology of the Arbuckle Mountains area, south central Oklahoma. Oklahoma Geological Survey Circular 91. Oklahoma Geological Survey. 112p.

Fitzhugh, T. and B. Richter. 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. BioScience 54: 741-754.

Ham, W.E. 1969. Regional geology of the Arbuckle Mountains, Oklahoma. Oklahoma Geological Survey Guide Book 17. 52p.

Hanson, R.L., and S.W. Cates. 1994. Hydrogeology of the Chickasaw National Recreation Area, Murray County, Oklahoma. Water Resources Investigations Report 94-4102. U.S. Geological Survey. 88p.

Hoagland, B. 2000. The vegetation of Oklahoma: a classification for landscape mapping and conservation planning. Southwestern Naturalist 45: 385-420.

Holsinger, J.R. 1971. A new species of the subterranean amphipod genus *Allocrangonyx* (Gammaridae), with a re-description of the genus and remarks on its zoogeography. International Journal of Speleology 3:317-331, PLS 1-7.

Hubbs, C. 1995. Springs and spring runs as unique aquatic systems. Copeia 1995:989-991.

Hynes, H.B.N. 1970. The ecology of running waters. University of Toronto Press, Toronto. 555p.

Leopold, L.B. 1994. A view of the river. Harvard University Press, Cambridge, MA. 298 p.

Mathews, R. and B.D. Richter. 2007. Application of the Indicators of Hydrologic Alteration Software in environmental flow setting. Journal of the American Water Resources Association 43:1400-1413.

Oklahoma Department of Environmental Quality. 2004. The State of Oklahoma water quality assessment: integrated report. Oklahoma City, Oklahoma. 69p.

Matzinger, M.A. and D. Bass. 1995. Downstream drift of aquatic insects in the Blue River of south-central Oklahoma. Proceeding of the Oklahoma Academy of Sciences 75:13-19.

Oklahoma Water Resources Board (OWRB). 2003. The Arbuckle-Simpson hydrology study: management and protection of an Oklahoma water resource. Fact Sheet. Oklahoma Water Resources Board, Oklahoma City, Oklahoma.

Oklahoma Water Resources Board (OWRB). 2005. Arbuckle-Simpson hydrology study: annual report federal fiscal year 2005. Oklahoma Water Resources Board, Oklahoma City, Oklahoma.

Oklahoma Water Resources Board (OWRB). 2007. Arbuckle-Simpson hydrology study: annual report federal fiscal year 2006. Oklahoma Water Resources Board, Oklahoma City, Oklahoma.

Oklahoma Water Resources Board (OWRB). 2008. Arbuckle-Simpson hydrology study: 2007 annual report. Oklahoma Water Resources Board, Oklahoma City, Oklahoma.

Poff, N.L. and J.D. Allan. 1995. Functional organization of stream fish assemblages in relation to hydrologic variability. Ecology 76:606-627.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47: 769-784.

Poff, N.L. and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46: 1805-1818.

Reisen, W.K. 1976. The ecology of Honey Creek: temporal patterns of the travertine periphyton and selected physico- chemical parameters, and *Myriophyllum* community productivity. Proceedings of the Oklahoma Academy of Sciences 56:69-74.

Richards, C., L.B. Johnson and G.E. Host. 1996. Landscape scale influences on stream habitats and biota. Canadian Journal of Fisheries and Aquatic Sciences 53:259-311.

Richter, B. D., J.V. Baumgartner, J. Powell and D. P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163-1174.

Richter, B. D., J.V. Baumgartner, R. Wigington and D. P. Braun. 1997. How much water does a river need? Freshwater Biology 37:231-249.

Richter, B. D., J.V. Baumgartner, D.P. Braun and J. Powell. 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research and Management 14:329-340.

Schlosser, I.J. 1985. Flow regime, juvenile abundance, and the assemblage structure of stream fishes. Ecology 66:1484-1490.

Schrader J.A. and W.R. Graves. 2002. Infraspecific systematics of *Alnus maritima* (Betulaceae) from three widely disjunct provenances. Castanea 67:380-401.

Sweeting, M.M. 1973. Karst landforms. Comumbia University Press, New York, NY.

The Nature Conservancy. 2006. Indicators of Hydrologic Alteration version 7: user's manual. The Nature Conservancy, Arlington, VA. 70p.

Wolman, M.G. and J.P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68:54-74.

Table 1. Period of record for USGS gaging stations used in this study.

Gage Station Name	Station ID	Water Body	Drainage Area (mi^2)	Measured Period of Record*	Estimated Period of Record
Connerville, OK	07332390	Blue River	162	1977-1979, 2004-2007	1966-1976, 1980-1986
Milburne OK	07332400	Blue River	230	1966-1986**	n/a
Blue OK	07332500	Blue River	476	1937-2007	n/s
Reagan OK	07331300	Pennington Creek	66	2004-2007	1966-1986
Turners Falls OK	07329780	Honey Creek	16	2005-2007	n/a
Fittstown OK	07334200	Byrds Mill Spring	n/a	1991-2001	n/a
Sulphur, OK	07329849	Antelope Spring	n/a	1986-1989, 2002-2006	n/a
Sulphur, OK	07329852	Rock Creek	44.1	1990-2006	n/a

* Water year covers the period October 1 to September 30.

** Period of record is incomplete for the year indicated

Table 2. Description of the suite of 33 basic IHA flow regime parameters. Adapted from The Nature Conservancy (2006).

IHA Parameter Group	**Hydrologic Parameters**	**Ecosystem Influences**
1. Magnitude of monthly water conditions	Mean or median value for each calendar month *Subtotal 12 parameters*	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year *Subtotal 12 parameters*	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments

Table 2 continued. Description of the suite of 33 basic IHA flow regime parameters. Adapted from The Nature Conservancy (2006).

3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum *Subtotal 2 parameters*	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) *Subtotal 4 parameters*	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals *Subtotal 3 parameters* **Grand total 33 parameters**	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

Table 3. Description of the suite of 44 Ecological Flow Components. Adapted from The Nature Conservancy (2006).

EFC Type	**Hydrologic Parameters**	**Ecosystem Influences**
1. Monthly low flows	Mean or median values of low flows during each calendar month *Subtotal 12 parameters*	• Provide adequate habitat for aquatic organisms • Maintain suitable water temperatures, dissolved oxygen, and water chemistry • Maintain water table levels in floodplain, soil moisture for plants • Provide drinking water for terrestrial animals • Keep fish and amphibian eggs suspended • Enable fish to move to feeding and spawning areas • Support hyporheic organisms (living in saturated sediments)
2. Extreme low flows	Frequency of extreme low flows during each water year or season Mean or median values of extreme low flow event: • Duration (days) • Peak flow (minimum flow during event) • Timing (Julian date of peak flow) *Subtotal 4 parameters*	• Enable recruitment of certain floodplain plant species • Purge invasive, introduced species from aquatic and riparian communities • Concentrate prey into limited areas to benefit predators
3. High flow pulses	Frequency of high flow pulses during each water year or season Mean or median values of high flow pulse event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters*	• Shape physical character of river channel, including pools, riffles • Determine size of streambed substrates (sand, gravel, cobble) • Prevent riparian vegetation from encroaching into channel • Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants • Aerate eggs in spawning gravels, prevent siltation • Maintain suitable salinity conditions in estuaries

Table 3 continued. Description of the suite of 44 Ecological Flow Components. Adapted from The Nature Conservancy (2006).

4. Small floods	Frequency of small floods during each water year or season Mean or median values of small flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters*	Applies to small and large floods: • Provide migration and spawning cues for fish • Trigger new phase in life cycle (i.e insects) • Enable fish to spawn in floodplain, provide nursery area for juvenile fish • Provide new feeding opportunities for fish, waterfowl • Recharge floodplain water table • Maintain diversity in floodplain forest types through prolonged inundation (i.e. different plant species have different tolerances) • Control distribution and abundance of plants on floodplain • Deposit nutrients on floodplain
5. Large floods	Frequency of large floods during each water year or season Mean or median values of large flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal 6 parameters* **Grand total 34 parameters**	Applies to small and large floods: • Maintain balance of species in aquatic and riparian communities • Create sites for recruitment of colonizing plants • Shape physical habitats of floodplain • Deposit gravel and cobbles in spawning areas • Flush organis materials (food) and woody debris (habitat structures) into channel • Purge invasive, introduced species from aquatic and riparian communities • Disburse seeds and fruits of riparian plants • Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes) • Provide plant seedlings with prolonged access to soil moisture

Table 4. Selected moderate and low-flow indices for stream gages in the Arbuckles.

Variable	Blue River at Connerville, OK	Blue River at Milburne, OK	Blue River at Blue, OK (Pre-alteration)	Blue River at Blue, OK (Post-alteration)	Pennington Creek near Reagan, OK	Byrds Mill Spring near Fittstown, OK	Honey Creek at Turner Falls, OK	Rock Creek near Sulphur, OK	Antelope Spring at Sulphur, OK
Watershed Area (sq.mi.)	162	203	476	476	65.7	n/a	16.4	44.1	n/a
Mean daily flow (cfs)	88.0	142.0	293	351	39.0	19.9	22.0	17	2.34
<u>Monthly median flows (cfs):</u>									
October	42	43	48	43	21	18	6	14	1.8
November	39	50	53.5	90.5	21	17.5	21	17	2.4
December	38	57	70	124	25	19	9	16	3.6
January	40	75	81.5	156	30	21	10	21	4.3
February	48	72.5	110	167.5	30	21	8	25.5	3.8
March	55	82	107	170	31	22	9	32	3.4
April	65	99.5	135.5	163	36	23	8	32	3.3
May	64	101	157	201	38	23	13	28	3.2
June	56	89.5	117.3	149.5	34	22	5	21	2.7
July	47	58	64.5	74	25	19	3	12	2.1
August	42	43	41	46	22	17	4	9	1.9
September	37	39	39.5	46.5	20	17	3	9.25	1.9
<u>Monthly Median low flows (cfs):</u>									
October	41.5	41.5	42	42	21	18	-	10	1.8
November	37	45	53	56	21	17.75	-	13	2.625
December	35.5	51.5	58	82.75	24	18.5	-	13	3.55
January	34	68	76	97	26	20	-	18.5	0.76
February	41	66.75	74.5	122.5	27	21	-	17	1.1
March	57	61	81.5	111	26	22	-	23.25	2.4
April	56.75	73	87	112.3	30	21.5	-	22.5	3
May	59.5	69	99	102.5	29	20	-	22	3.2
June	49	68	85	106.5	28	20	-	16.5	2.4
July	46.25	58	60.25	70	24	18	-	10.85	2.7
August	41.5	44.5	38.5	48.5	22	17	-	9	2.45
September	37.5	39	38.75	43.25	20	17.5	-	9.15	2.3

Table 4 continued. Selected moderate and low-flow indices for stream gages in the Arbuckles.

Variable	Blue River at Connerville, OK	Blue River at Milburne, OK	Blue River at Blue, OK (Pre-alteration)	Blue River at Blue, OK (Post-alteration)	Pennington Creek near Reagan, OK	Byrds Mill Spring near Fittstown, OK	Honey Creek at Turner Falls, OK	Rock Creek near Sulphur, OK	Antelope Spring at Sulphur, OK
Median annual Minimum flow events (cfs):									
1-day	32	31	20.5	19	14	13	-	5.1	0.55
3-day	32	31	23.67	23	14	13.3	-	6.5	0.5867
7-day	32	31.43	25.29	25.29	14	14	-	6.5	0.5943
30-day	34	37.03	29.85	32.43	17	14.43	-	8.22	0.6693
90-day	36	43.54	37.86	46.07	18	16.31	-	9.637	0.5473
Extreme low flow events							-		
Median magnitude (cfs)	31.5	29	19.25	19	12	14	-	4.3	0.06
Median duration (days)	2.5	3.25	3	4.5	3.5	2.5	-	4.75	21.5
Median Julian day	14	290.5	243	243	344.8	252.3	-	253.5	36.5
Median number per year	2.5	0	1.5	0	3	1	-	0	0
Low flow recurrences (daily means, cfs)									
7-day low flow (2-year recurrence interval)	33	32	24	25	15.0	14.5	-	7	1.1
7 day low flow (10-year recurrence interval)	21	21	2	2	8.0	8.5	-	3	0.1
Flood recurrences (daily means, cfs)									
1.5 year	1,037	2,440	4,953	6,000	377	27	-	783	4
2 year	2,478	4,220	7,150	7,280	506	27	-	1010	6
10 year	6,599	14,000	15,500	19,140	1101	31	-	2280	11
30 year	-	-	22,500	25,940	-	-	-	-	-

Table 5. IHA parameters for gaging stations on the Blue river that exhibit statistically significant increasing (+ve SRC value) or decreasing (-ve SRC value) trends.

Station	IHA parameter	Correlation coefficient	p-value
Blue River at Connerville, OK	Date of annual 1-day minimum flow	0.5348	0.0134
	Date of annual 1 day maximum	-0.4130	0.0640
	Annual number of hydrograph reversals	.4535	0.040
Blue River at Milburne, OK	None detected		
Blue River at Blue, OK (pre)	Baseflow index	0.4051	0.012
	Date of annual 1-day minimum flow	-.02903	0.077
	Date of annual 1 day minimum	0.2818	0.087
Blue River at Blue, OK (post)	May median flows	-0.4081	0.084
	June median flows	-0.4544	0.052
	July median flows	-0.4855	0.037
	August median flows	0.5213	0.024
	Magnitude of 1-day minimum flow	0.4855	0.037
	Magnitude of 3-day minimum flow	-0.4081	0.084
	Magnitude of 7-day minimum flow	-0.3921	0.097
	Annual mean duration of low-flow events	0.4569	0.050
Pennington Creek near Reagan, OK	Annual mean hydrograph fall rate	-0.3693	0.099
	Annual number of hydrograph reversals	0.4127	0.063
Byrd's Mills Spring near Fittstown, OK	October median flows	-0.6672	0.025
	November median flows	-0.7142	0.010
	June median flows	-0.6659	0.025
	August median flows	-0.7362	0.020
	September median flows	-0.6901	0.025
	1-day minimum	-0.8991	0.001
	3-day minimum	-0.9142	0.001
	7-day minimum	-0.916	0.001
	30-day minimum	-0.92	0.001
	90-day minimum	-0.8416	0.001
	Baseflow index	-0.8775	0.001
	November low flow	-0.7379	0.025
	April low flow	-0.8273	0.050
	Extreme low frequency	0.665	0.025
	Small flood duration	-0.7762	0.050
	Small flood rise rate	0.8002	0.050
Rock Creek near Sulphur, OK	March median flows	-0.5604	0.0401
	April median flows	-0.5875	0.0303
	May median flows	-0.7591	0.0025
	June median flows	-0.8009	0.0009
	July median flows	-0.6777	0.0095
	August median flows	-0.5485	0.0439
	Magnitude of 90-day minimum flow	-0.6703	0.0108
	Annual mean hydrograph rise rate	-0.6101	0.0225
	Annual mean hydrograph fall rate	0.6948	0.0073
	Annual number of reversals	0.8776	0.0000

Table 6. IHA parameters accounting for ~5% or more of the total hydrologic alteration observed between the "pre" and the "post" time periods for the Blue River gage at Blue, OK.

IHA parameter	Percentage of Total Alteration
Annual mean high-flow pulse duration	5.73
Annual mean hydrograph fall rate	5.32
Annual mean low-flow pulse duration	5.29
Annual 90-day maximum flow magnitude	5.28
January median flow magnitude	5.10
Base flow index	5.04
October median flow magnitude	4.94
Total HA	**35.26**

Table 7. Spearman's Rank Correlation coefficients between *Escherichia coli*, discharge and rainfall patterns.

Variable	Black Sulphur Springs	Little Niagara	Bear Falls	Panther Falls
Daily high temperature	-0.241	-0.044	0.033	0.002
Daily low temperature	-0.136	-0.103	-0.065	0.030
Precipitation	0.278	0.242	0.089	0.165
Julian Day	-0.227	-0.167	0.010	-0.332
Days since last rain	-0.240	-0.127	-0.195	-0.049
Days since rain> .5 inches	-0.392	0.059	-0.021	-0.202
Days since rain > 1 inches	-0.243	0.291	0.097	-0.115
Discharge at Antelope Springs	-	-0.485	-0.152	-0.069
Discharge at Rock Creek	0.508	-	-	-

Figure 1. Studied streams and springs in the Arbuckles.

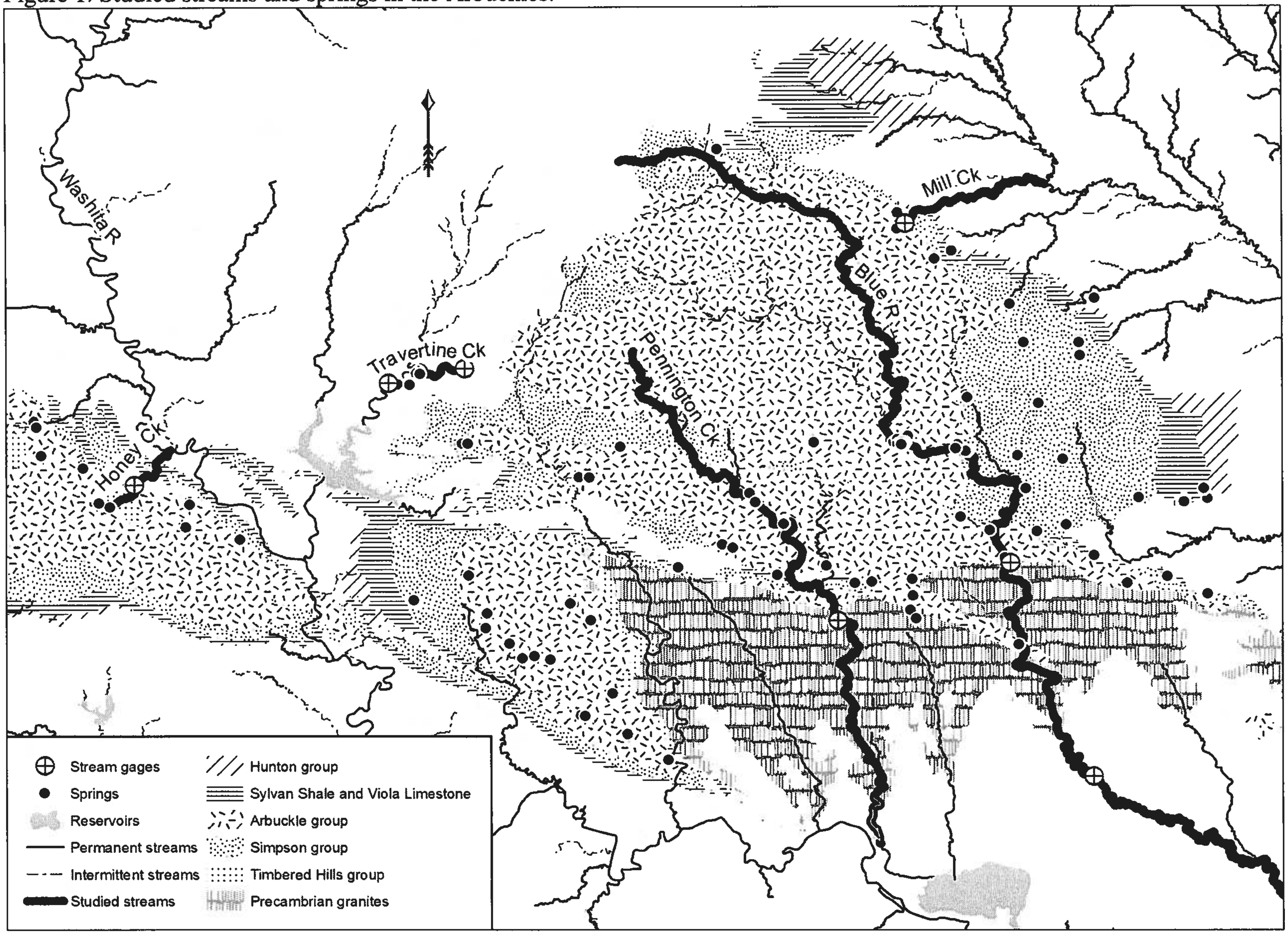


Figure 2. The Blue River.

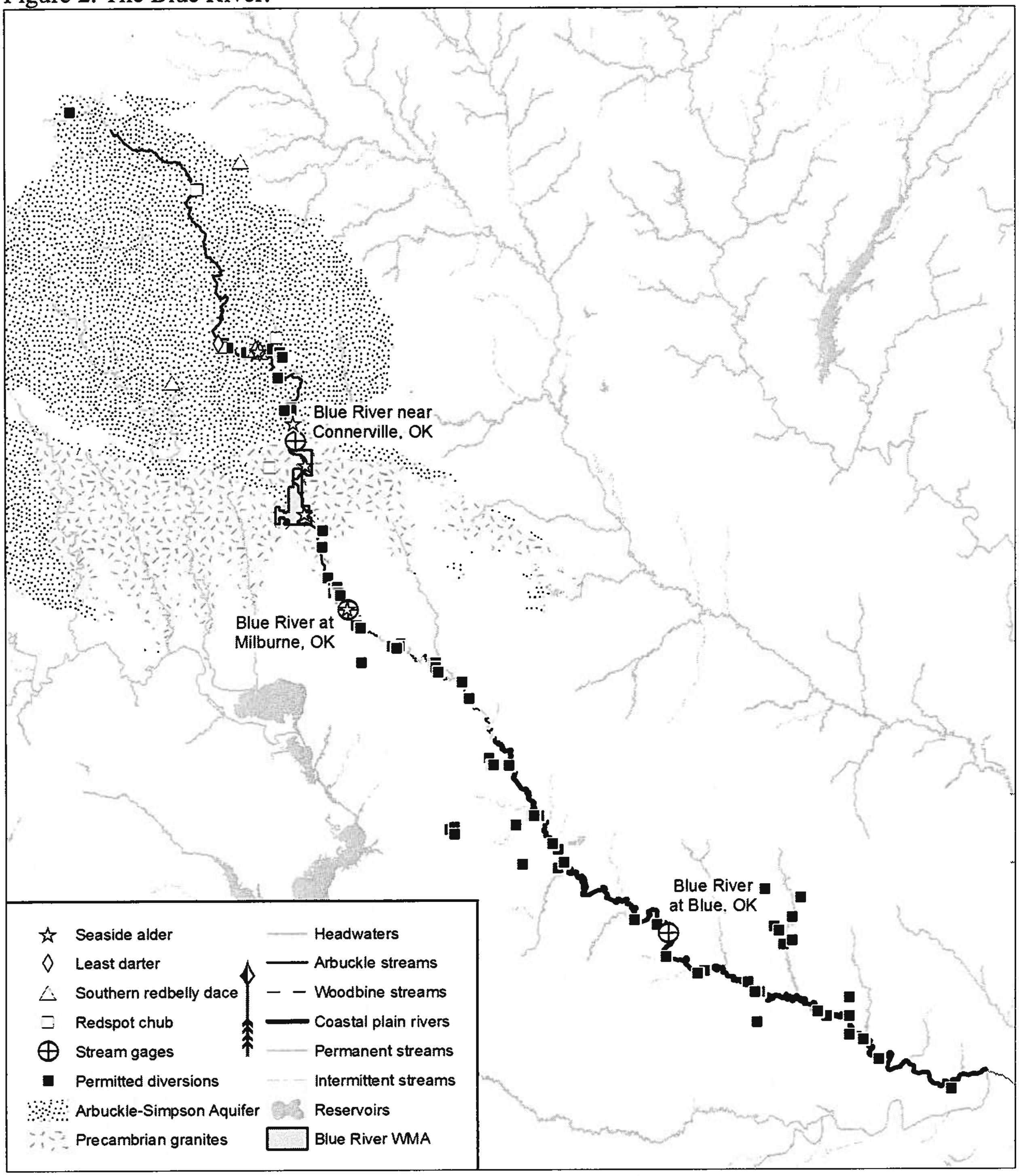


Figure 3. Pennington Creek.

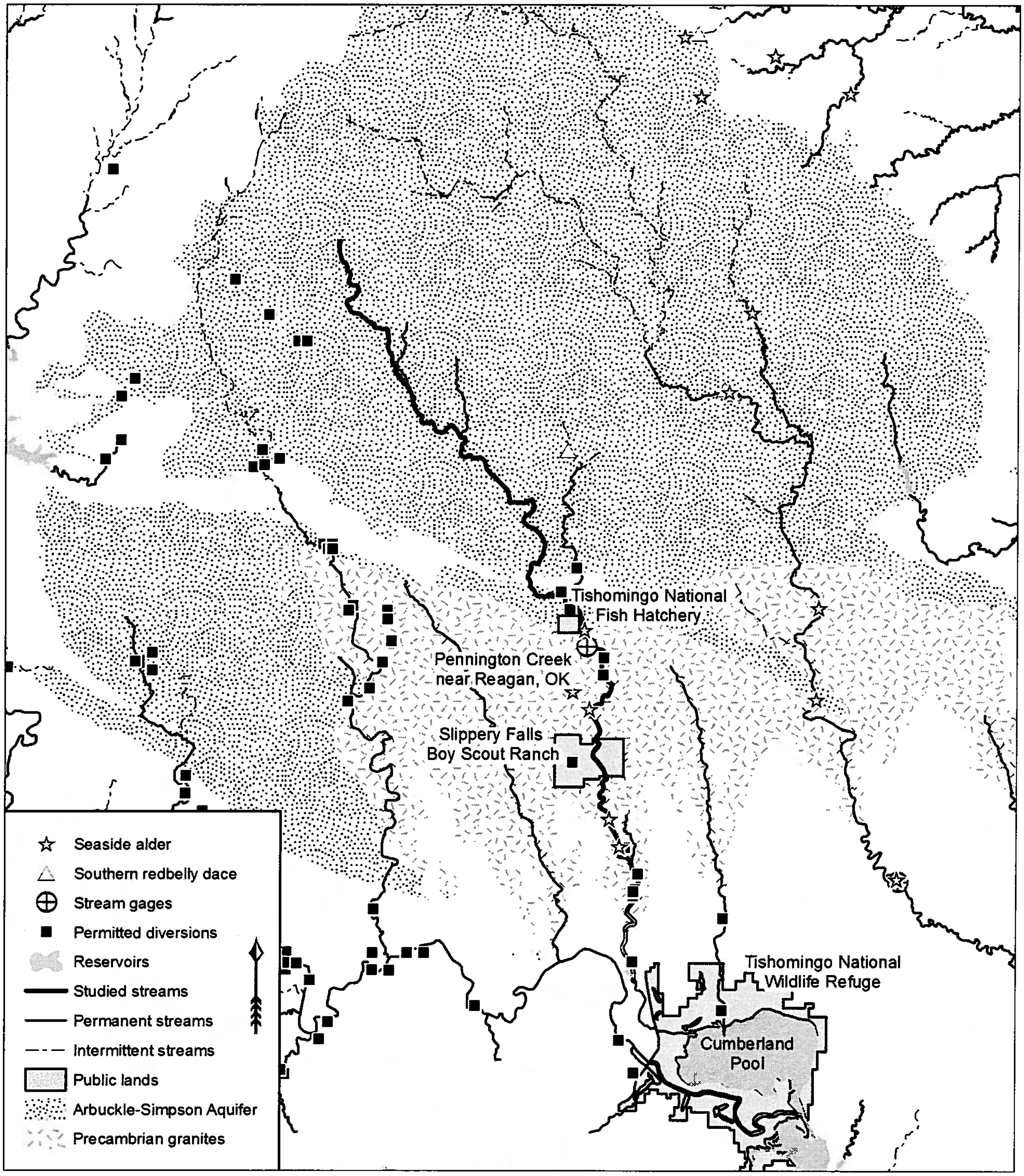


Figure 4. Honey Creek at Turner Falls State Park.

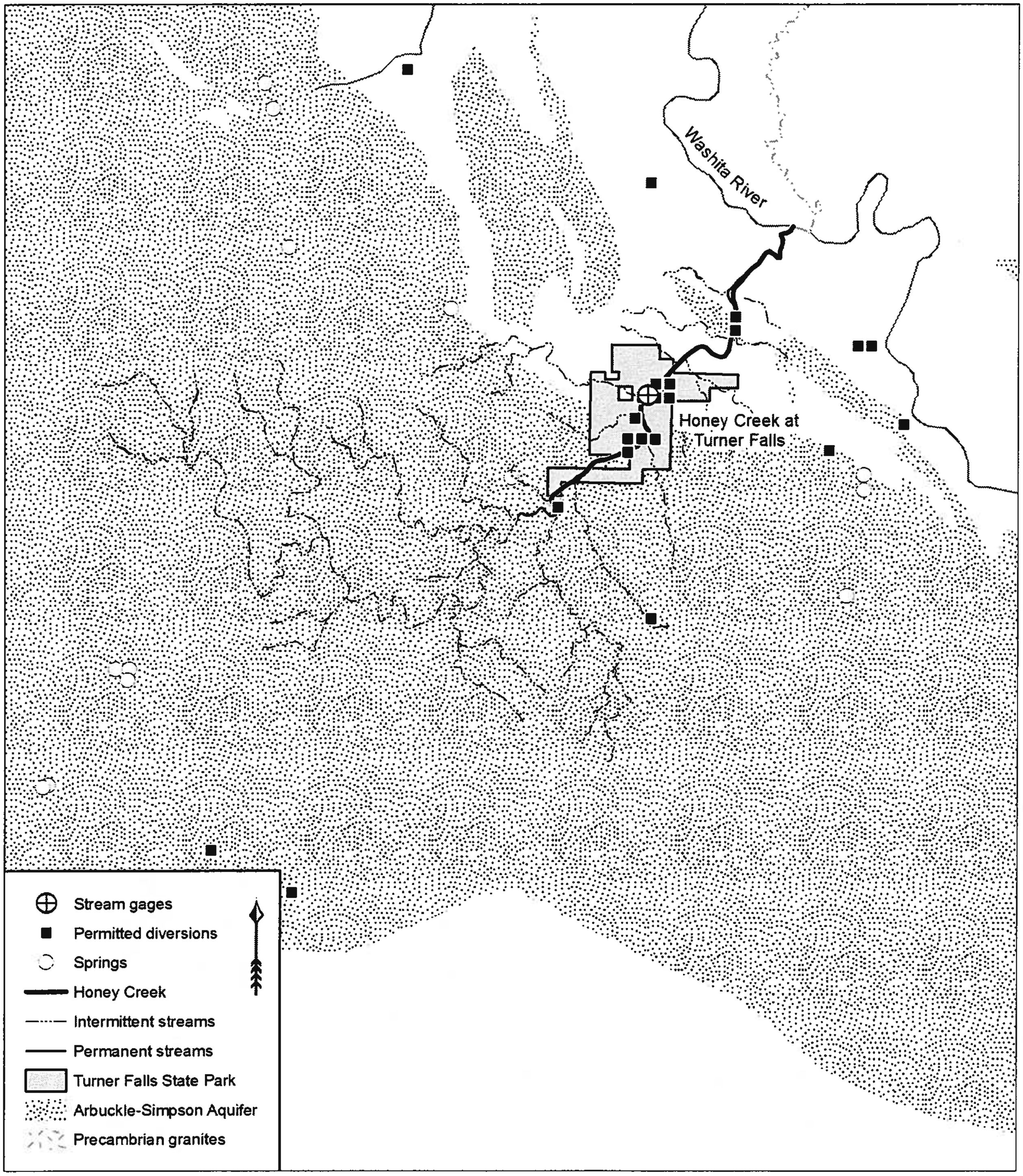


Figure 5. Travertine Creek on the Chickasaw National Recreation Area.

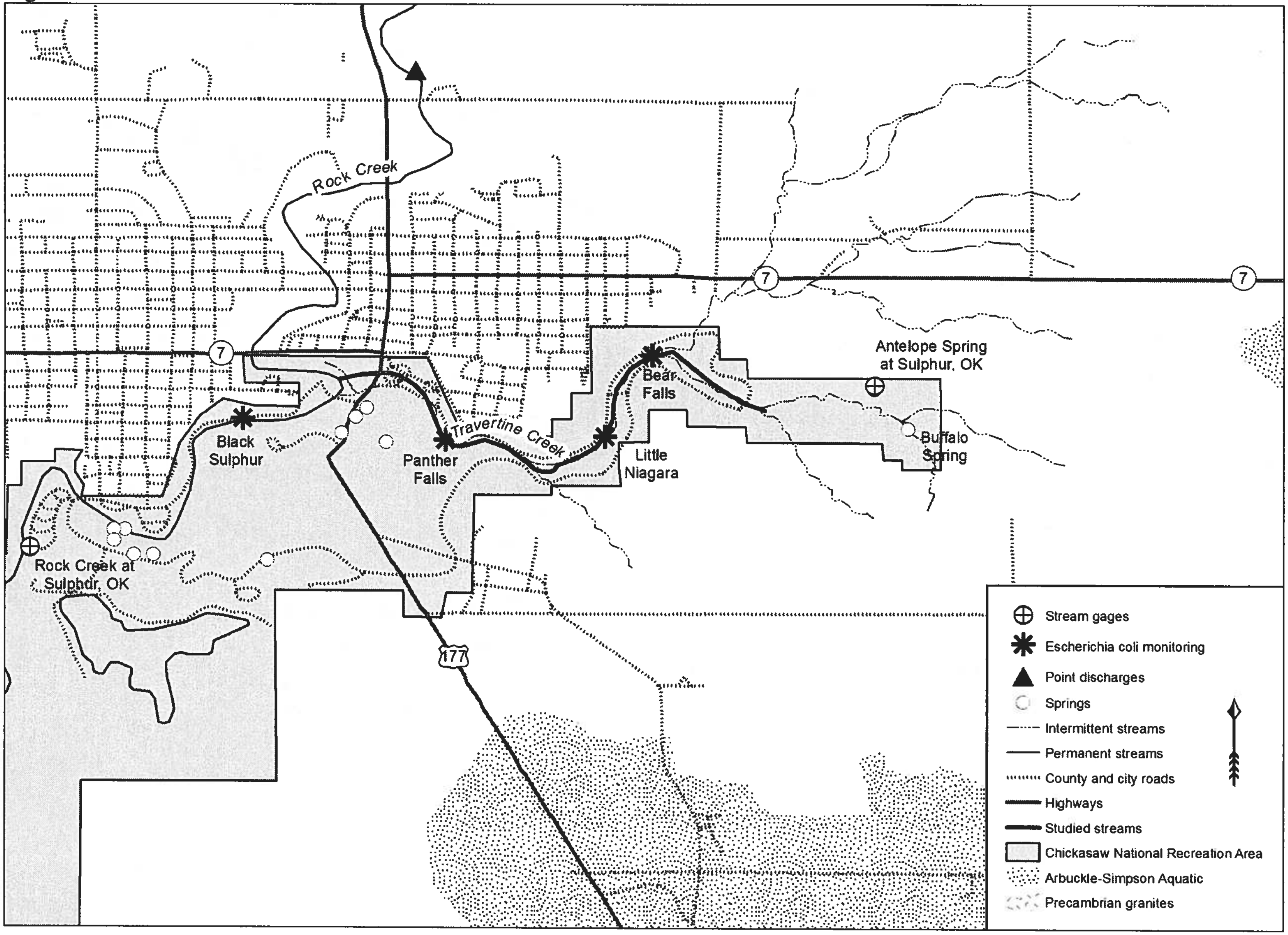


Figure 6. Byrd's Mill Spring.

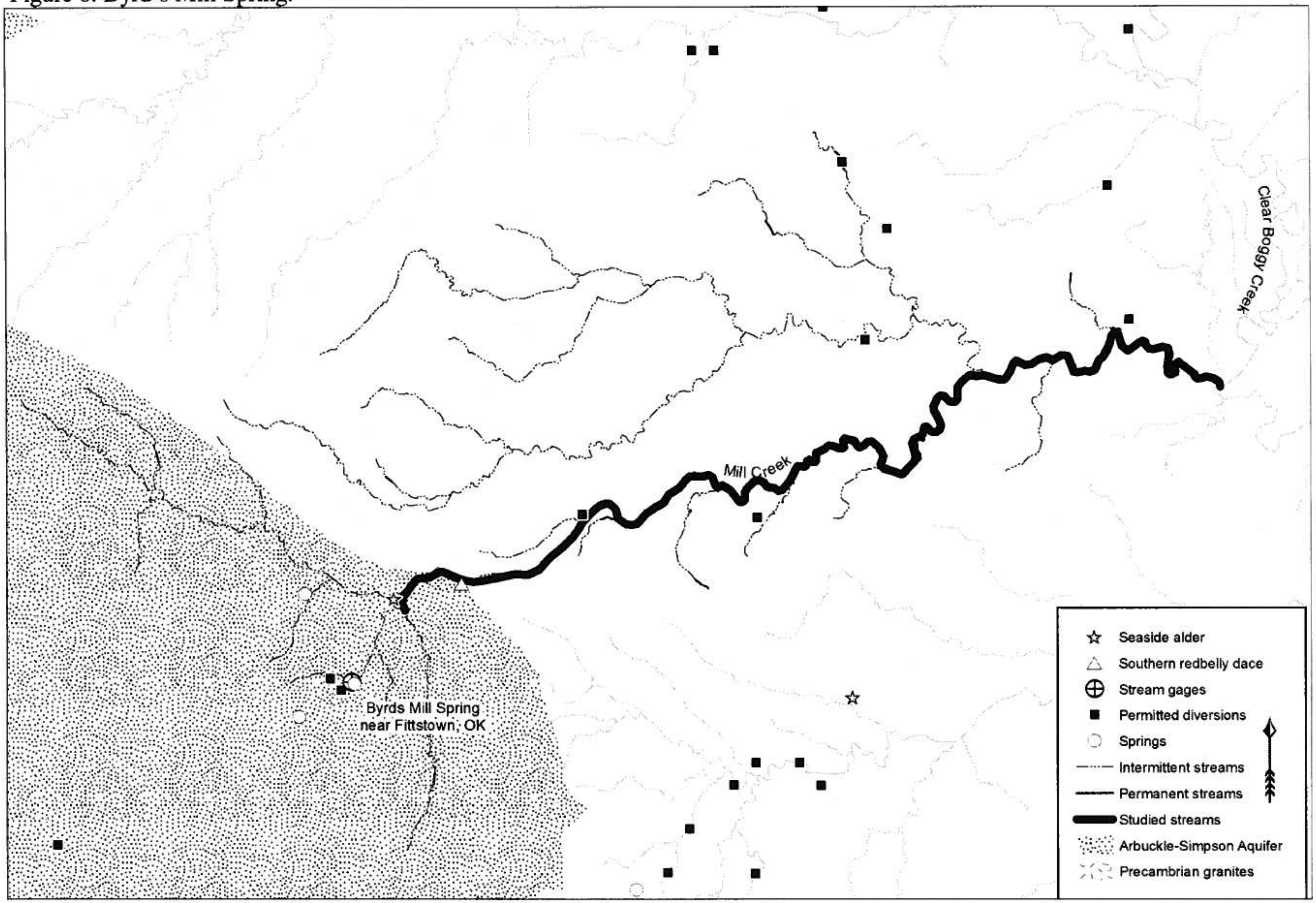


Figure 7. Annual hydrographs for water year 1978 illustrating generally similar character of hydrographs from three gaging stations on the Blue River.

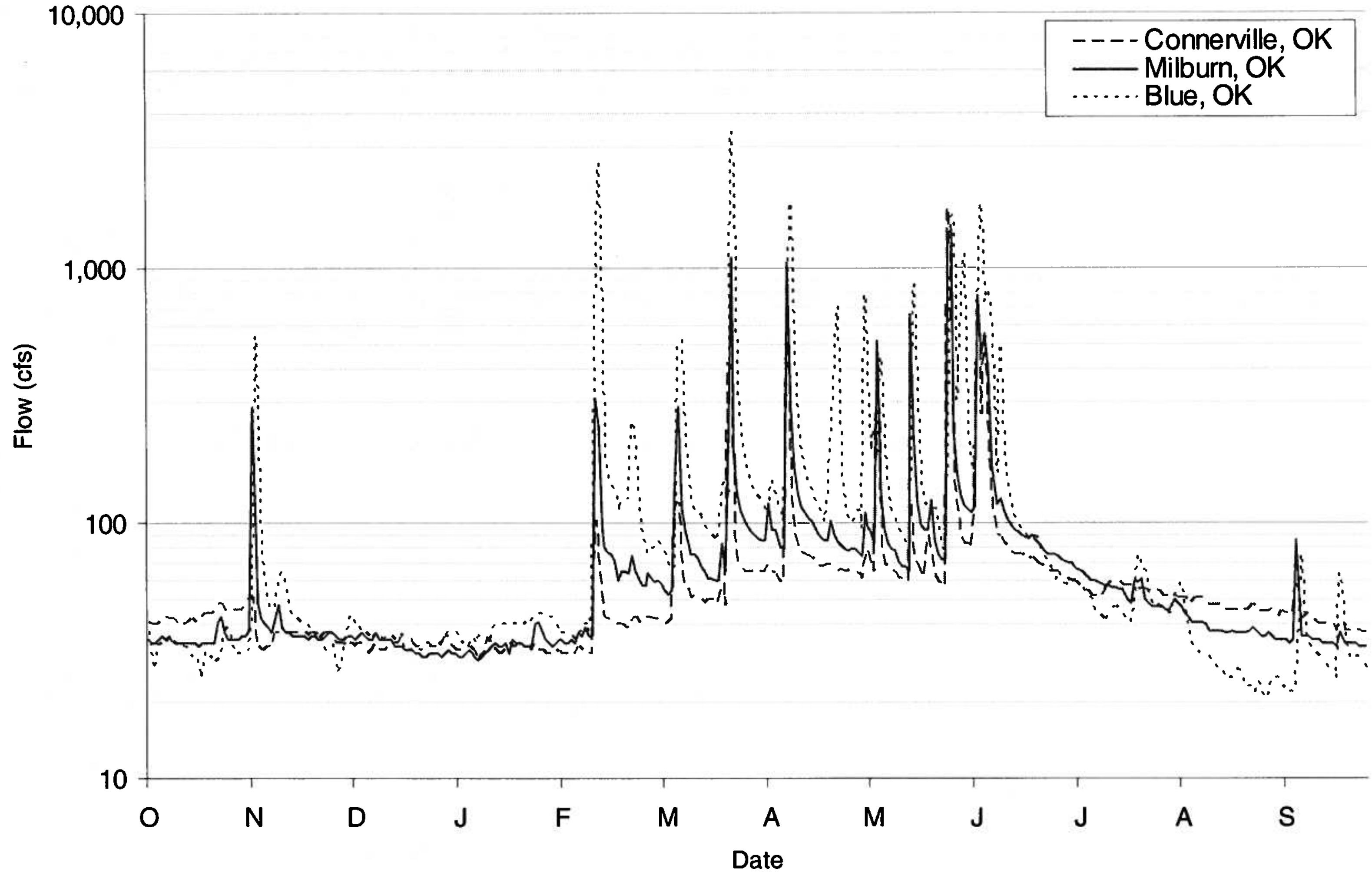
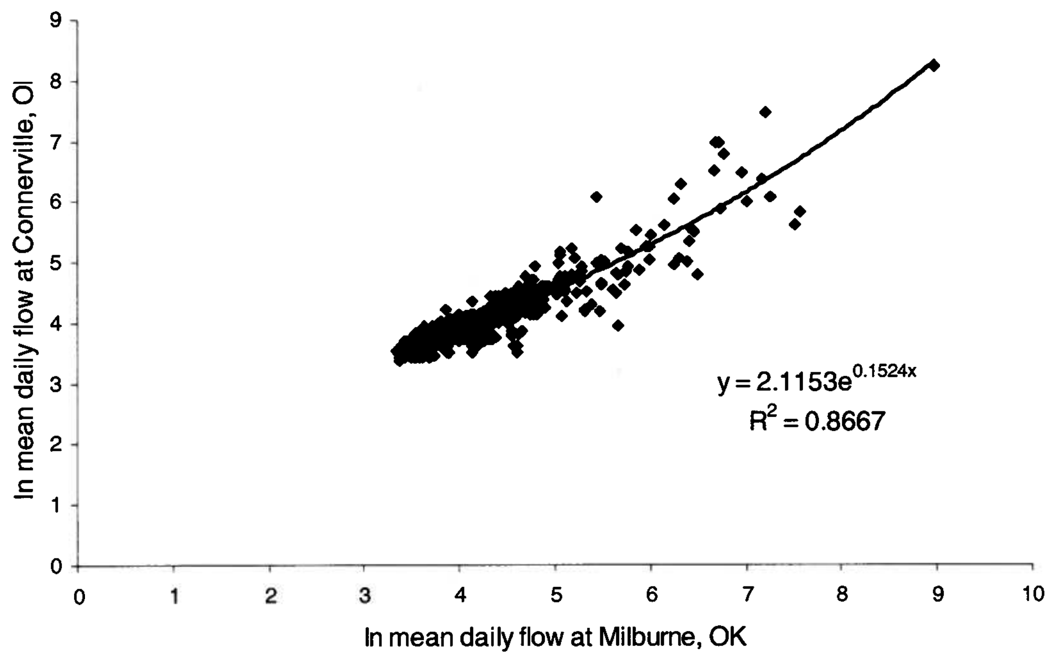


Figure 8. Correlation graphs used to develop estimation relations between mean daily flows for a) the Blue River at Connerville, OK using the Blue River gage at Milburn, OK and b) Pennington Creek at Reagan, OK using the Blue River gage at Milburn.

a)



b)

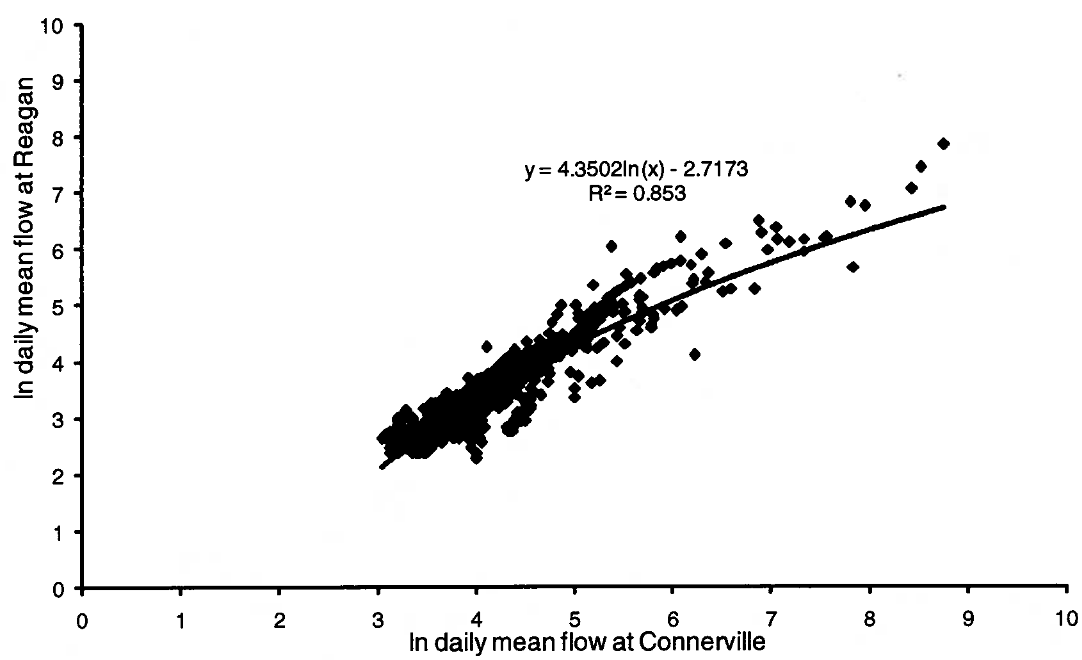


Figure 9. Flow duration curve for mean daily flows for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

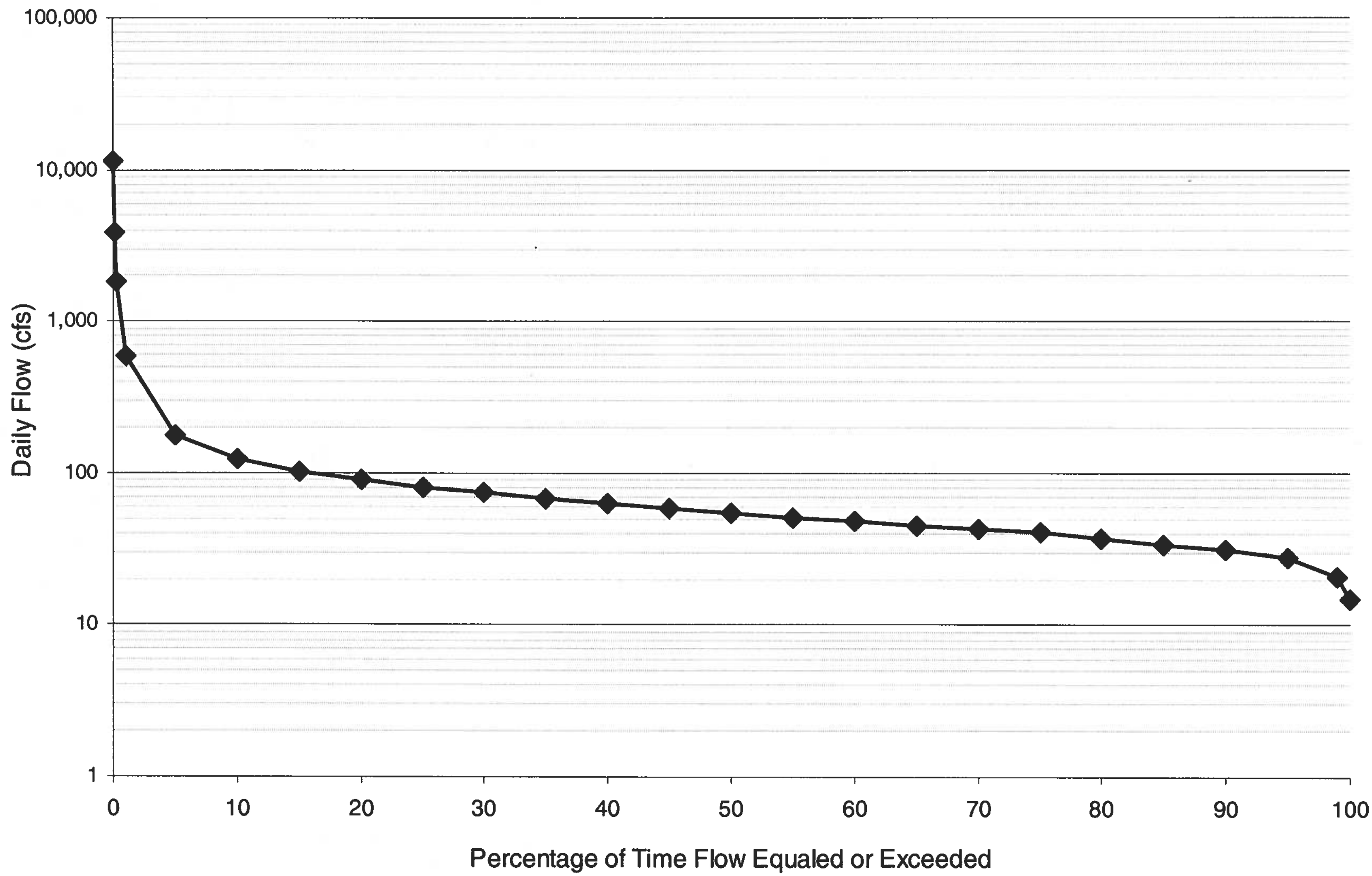


Figure 10. Median, 25th and 75th percentile values for mean monthly flows for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

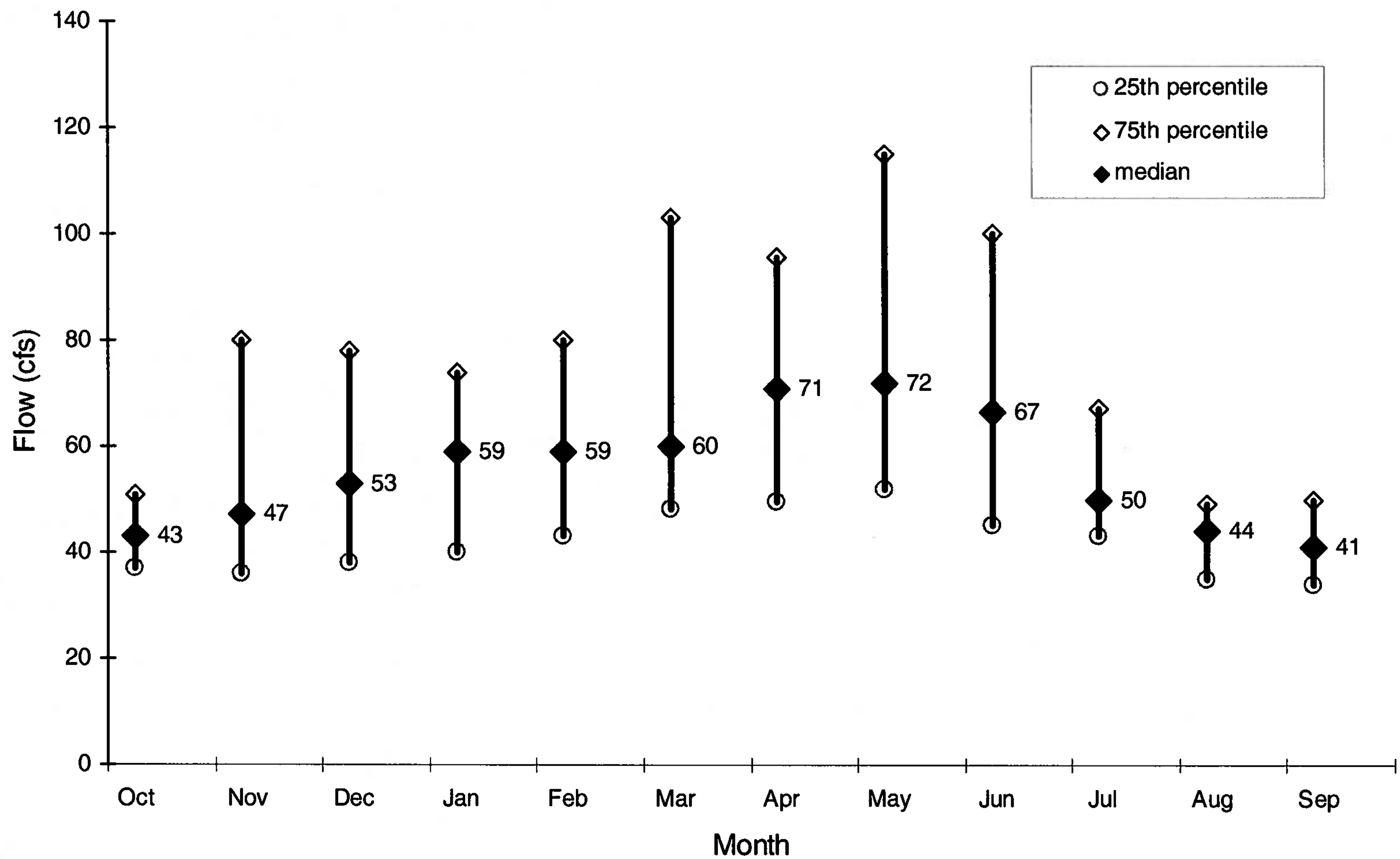
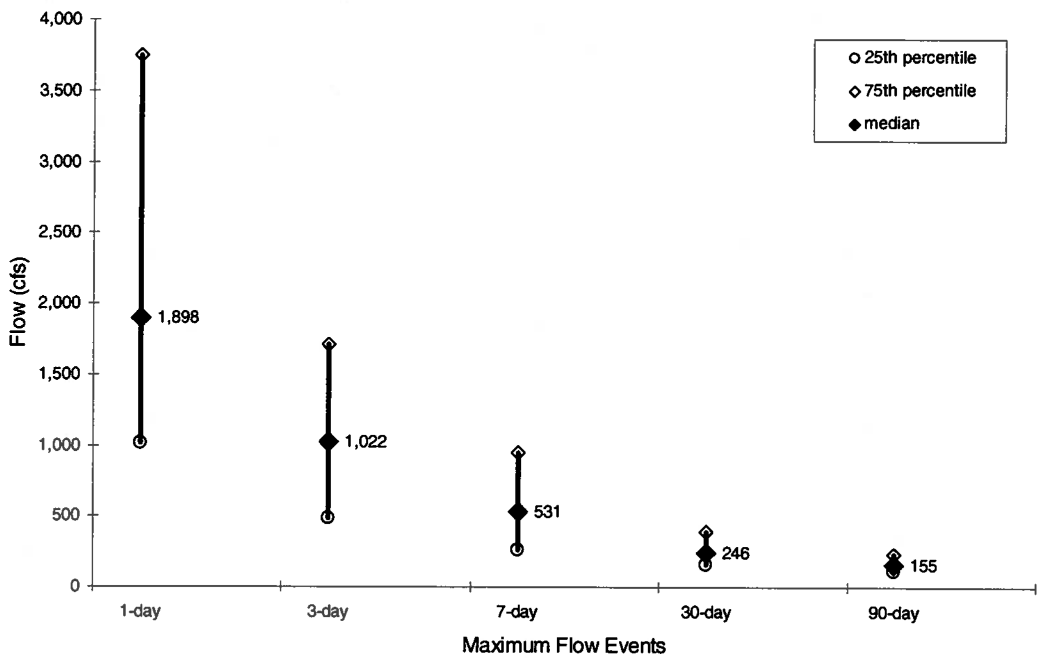


Figure 11. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-d maximum annual flows (a) and minimum flows (b) for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

a)



b)

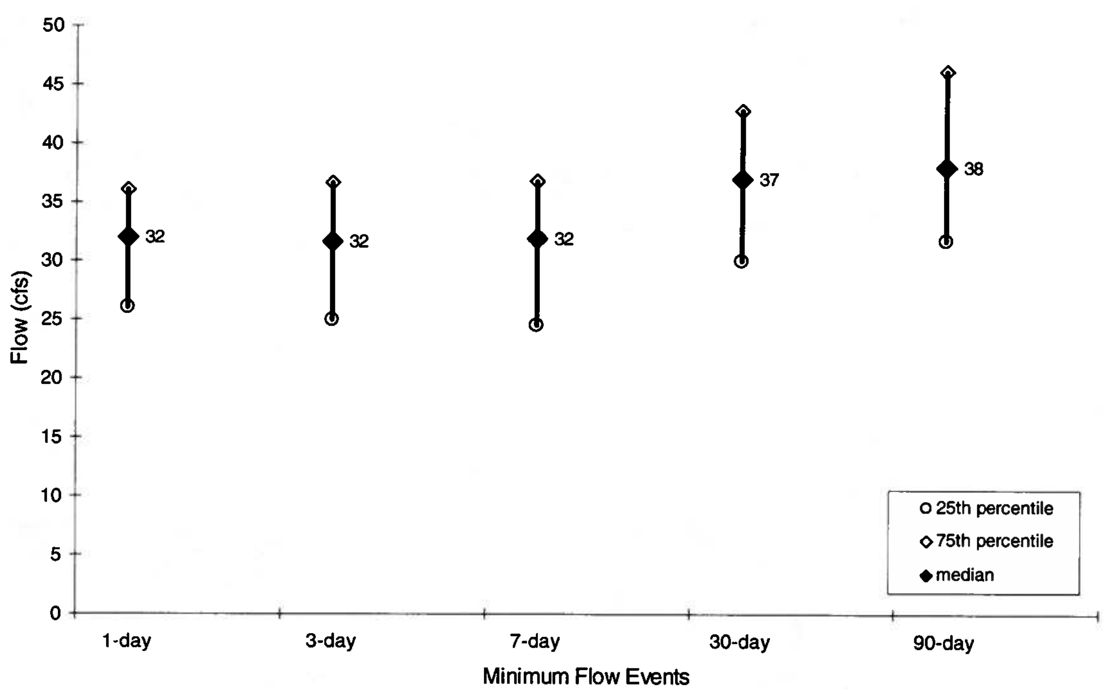


Figure 12. 7-day low flow recurrence interval for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

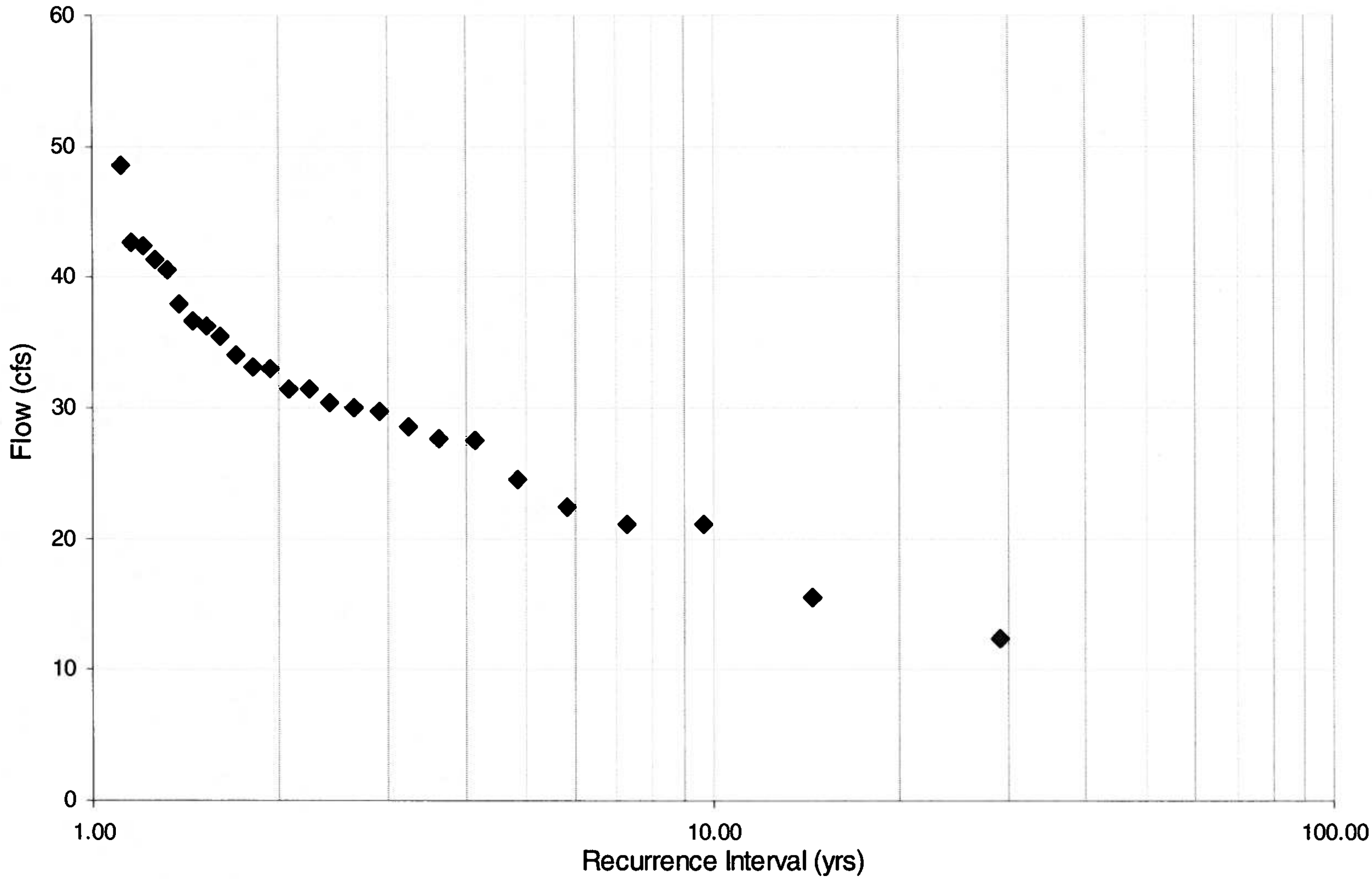


Figure 13. Median, 25th and 75th percentile values of annual occurrence frequency and duration of low- and high-flow pulses for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

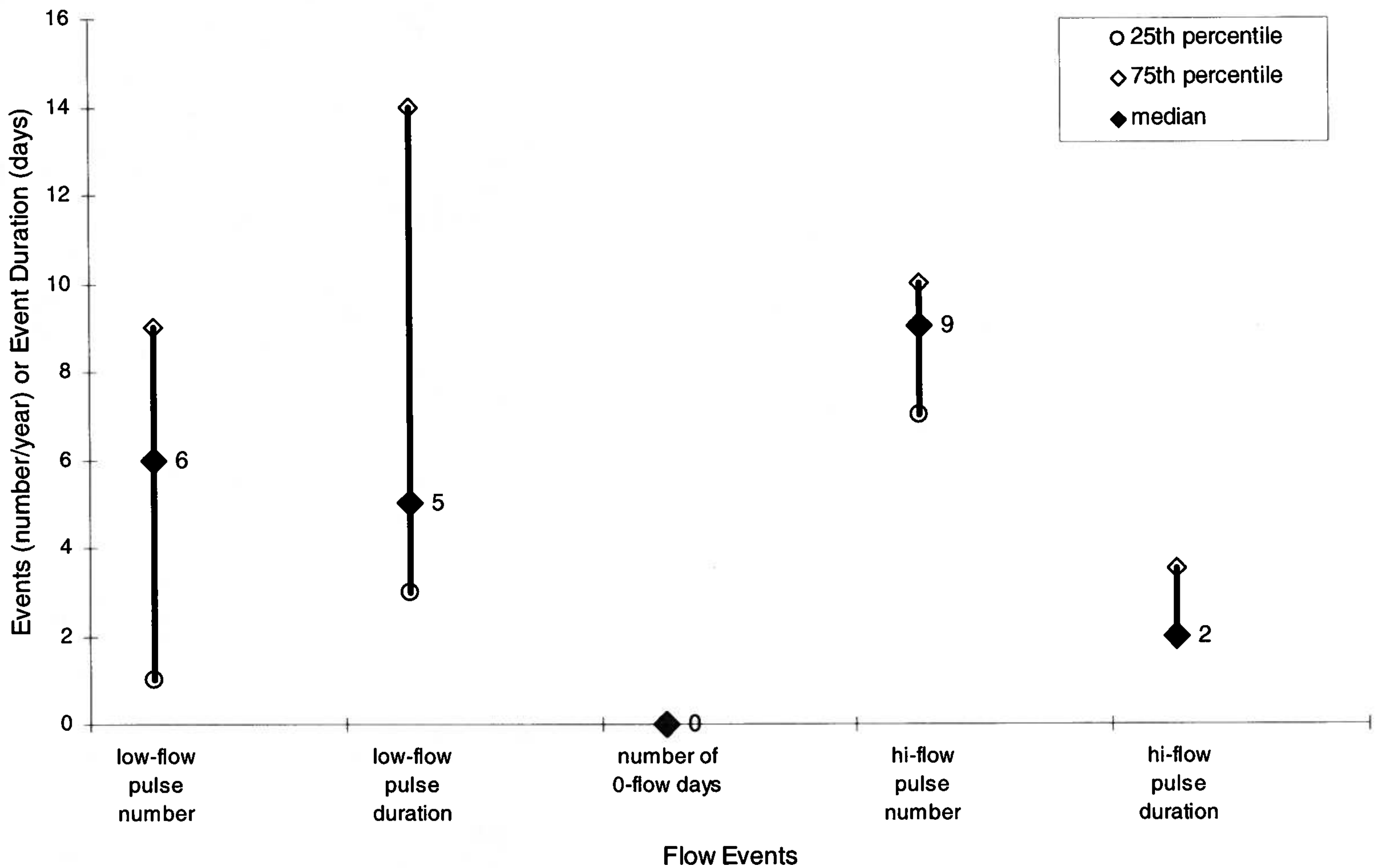


Figure 14.Median, 25th and 75th percentile monthly low flows for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

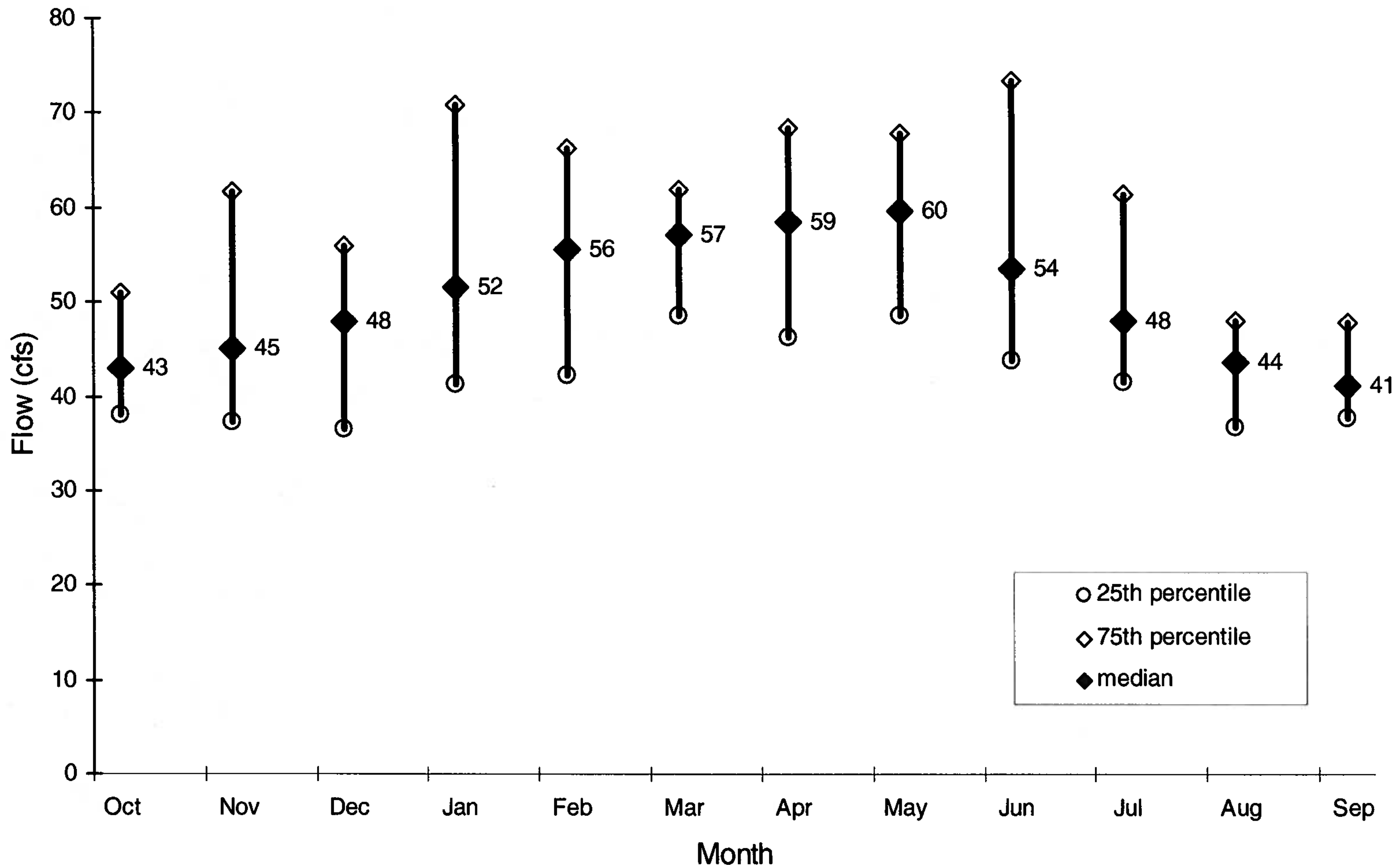


Figure 15. Extreme low flow event information for the Blue River gage at Connerville, OK. The period of record includes estimated and measured flow values. a) date of occurrence for the first event, b) annual mean magnitude c) annual mean duration and d) annual mean frequency.

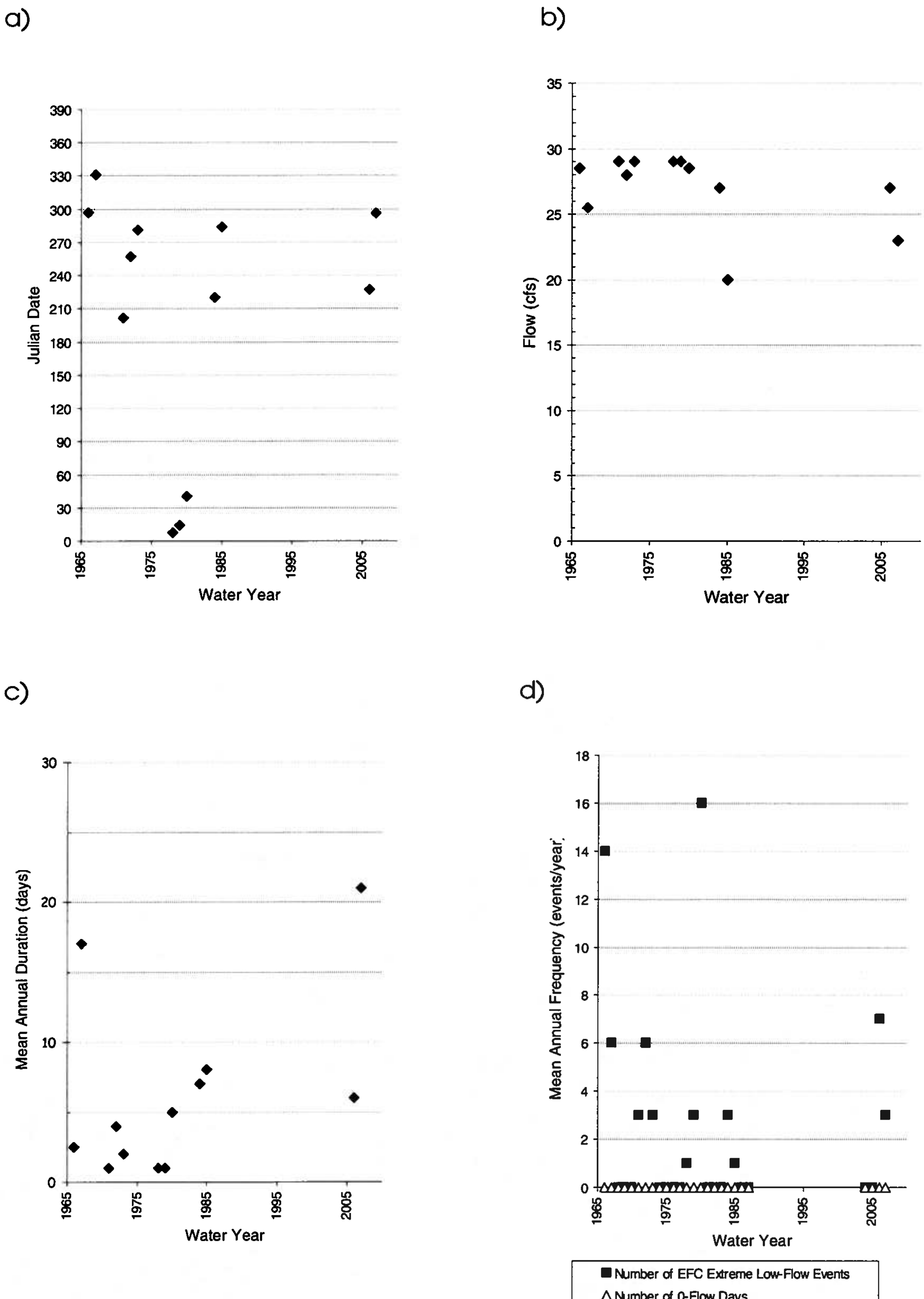


Figure 16. Median annual base flow index for the Blue River gage at Connerville, OK. The combined period of record including estimated and measured flow values from water years 1966 through 2007.

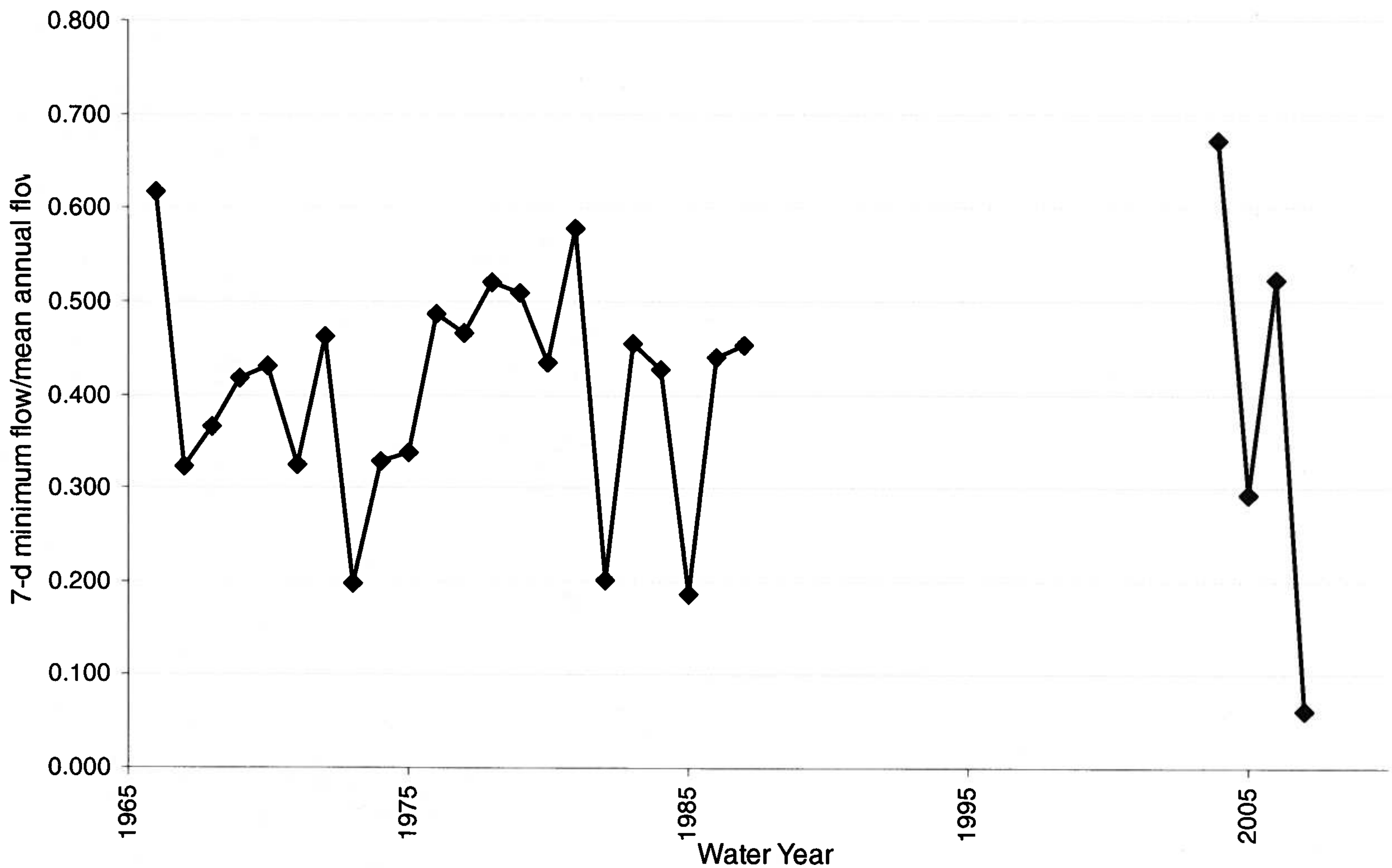


Figure 17. Flow duration curve for mean daily flows for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

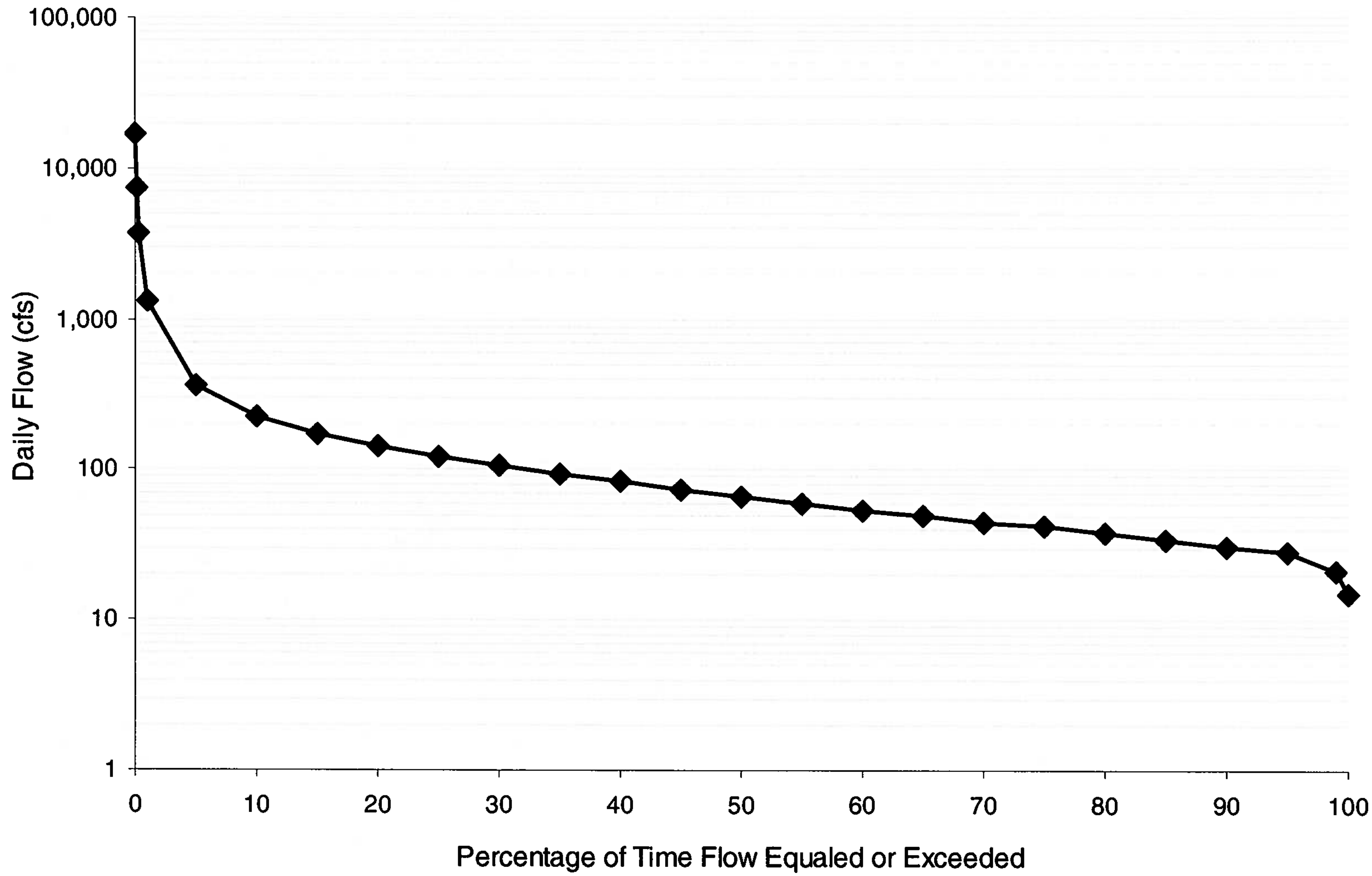


Figure 18. Median, 25th and 75th percentile values for mean monthly flows for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

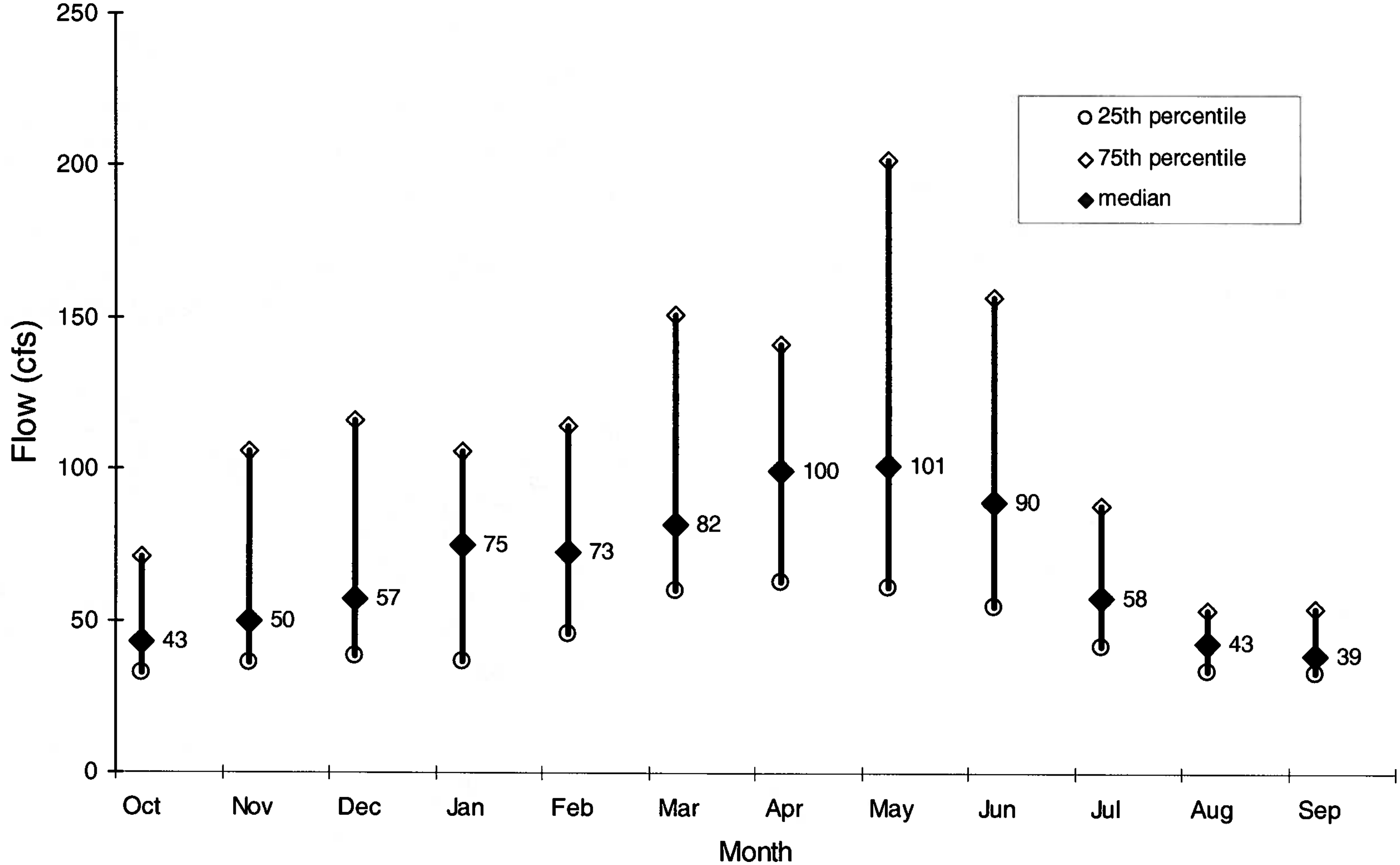


Figure 19. Median, 25th and 75th percentile values of annual occurrence frequency and duration of low- and high-flow pulses for the Blue River gage at Milburne, OK using measured data for water years 1966-1986.

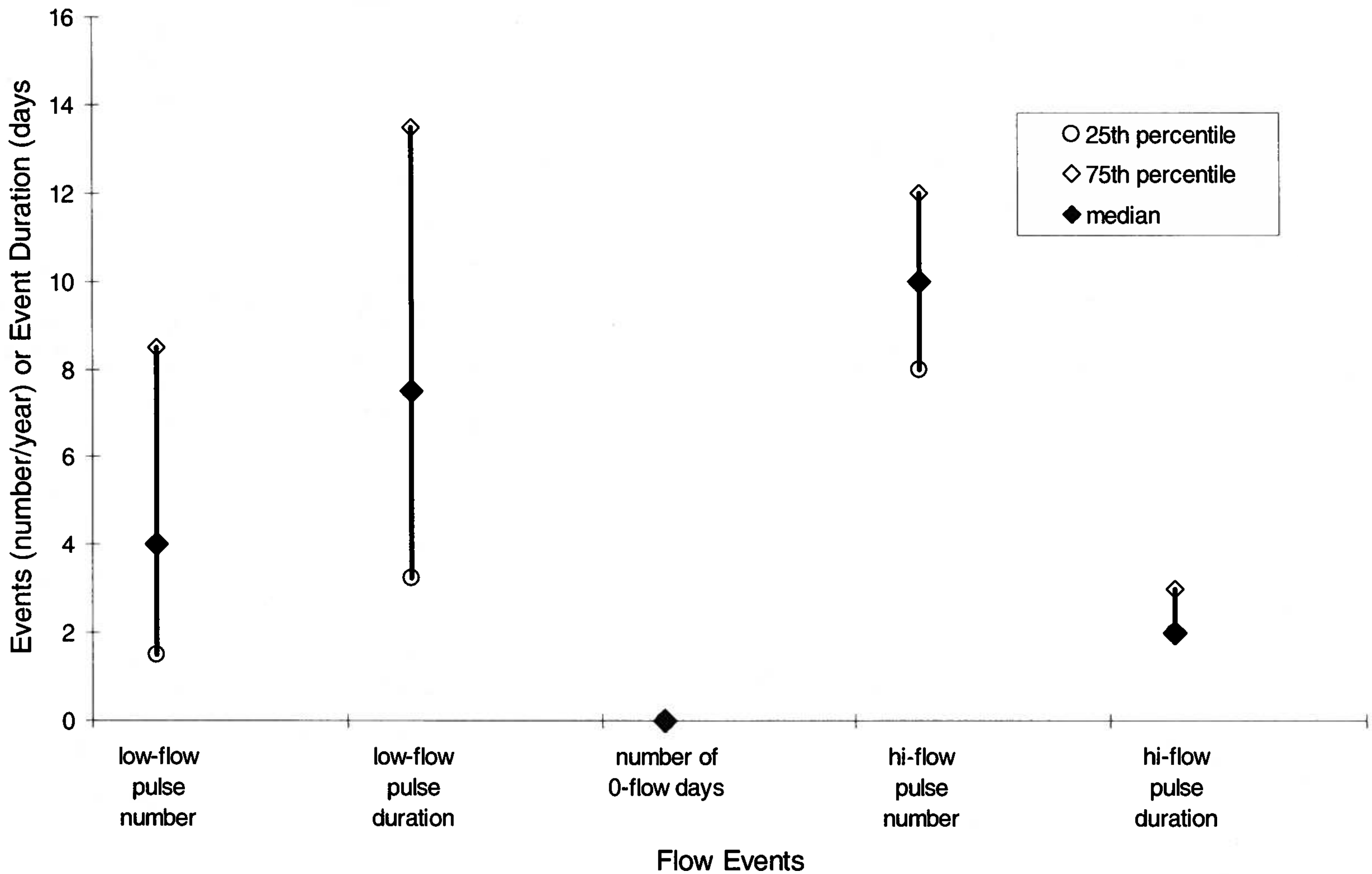
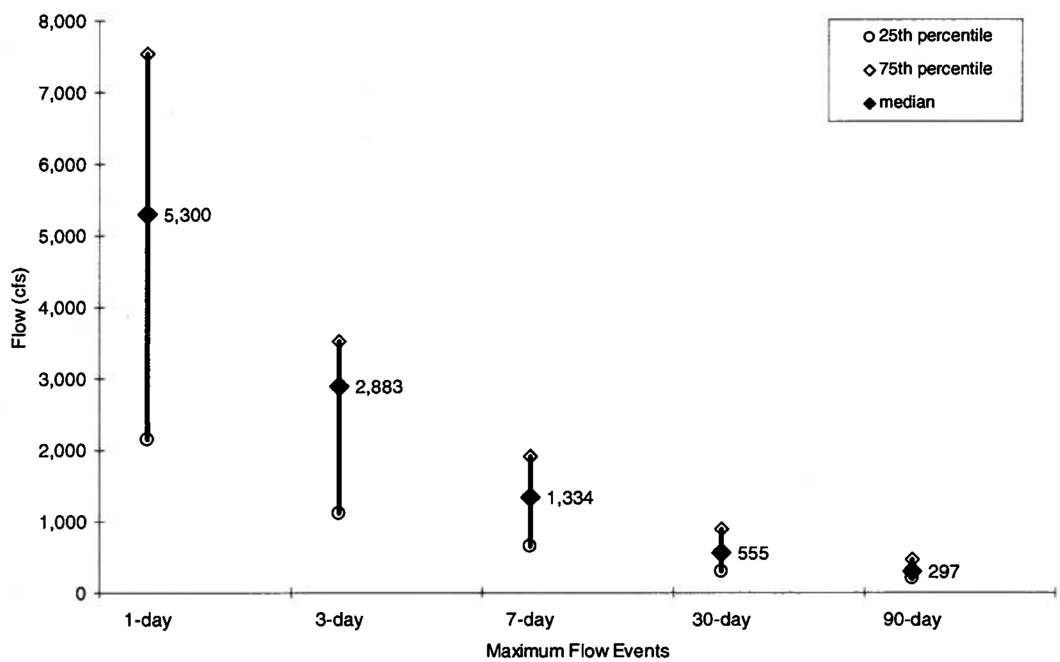


Figure 20. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-d a) maximum annual flows and b) minimum annual flows for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

a)



b)

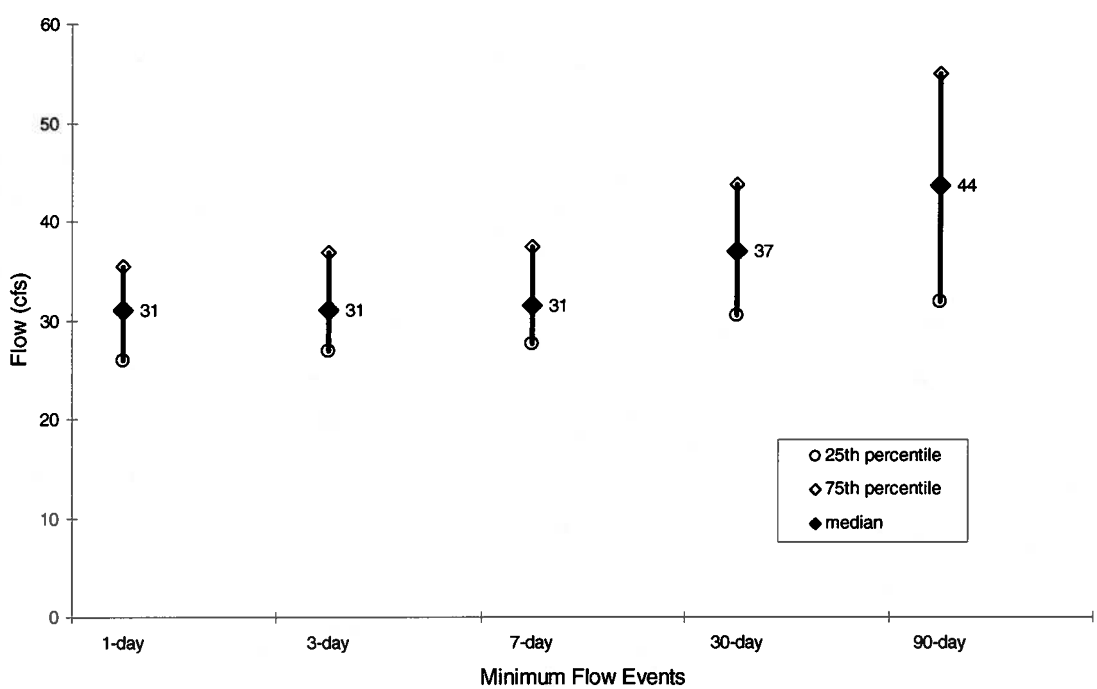


Figure 21. 7-day low flow recurrence interval for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

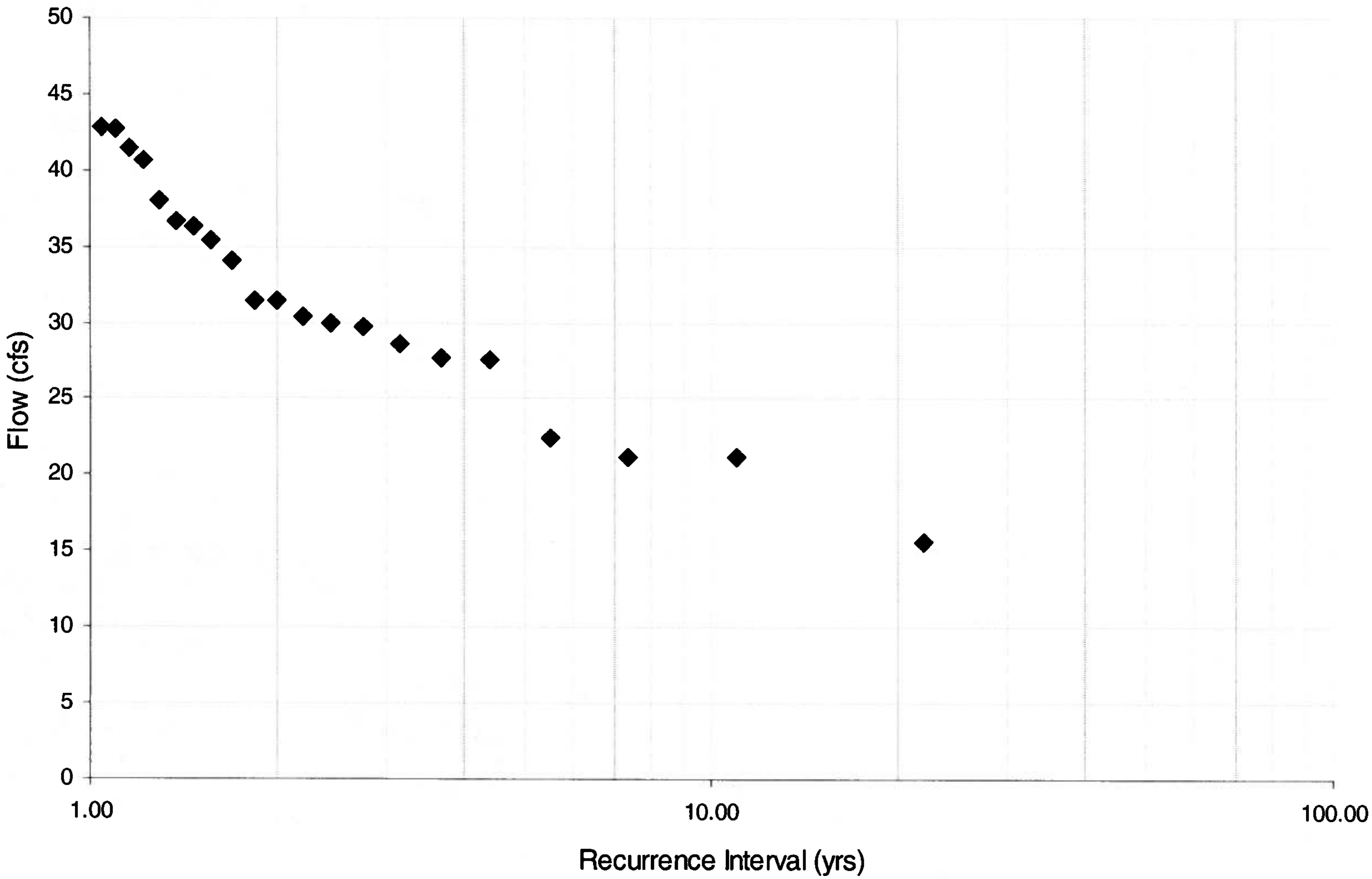


Figure 22. Median, 25th and 75th percentile monthly low flows for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

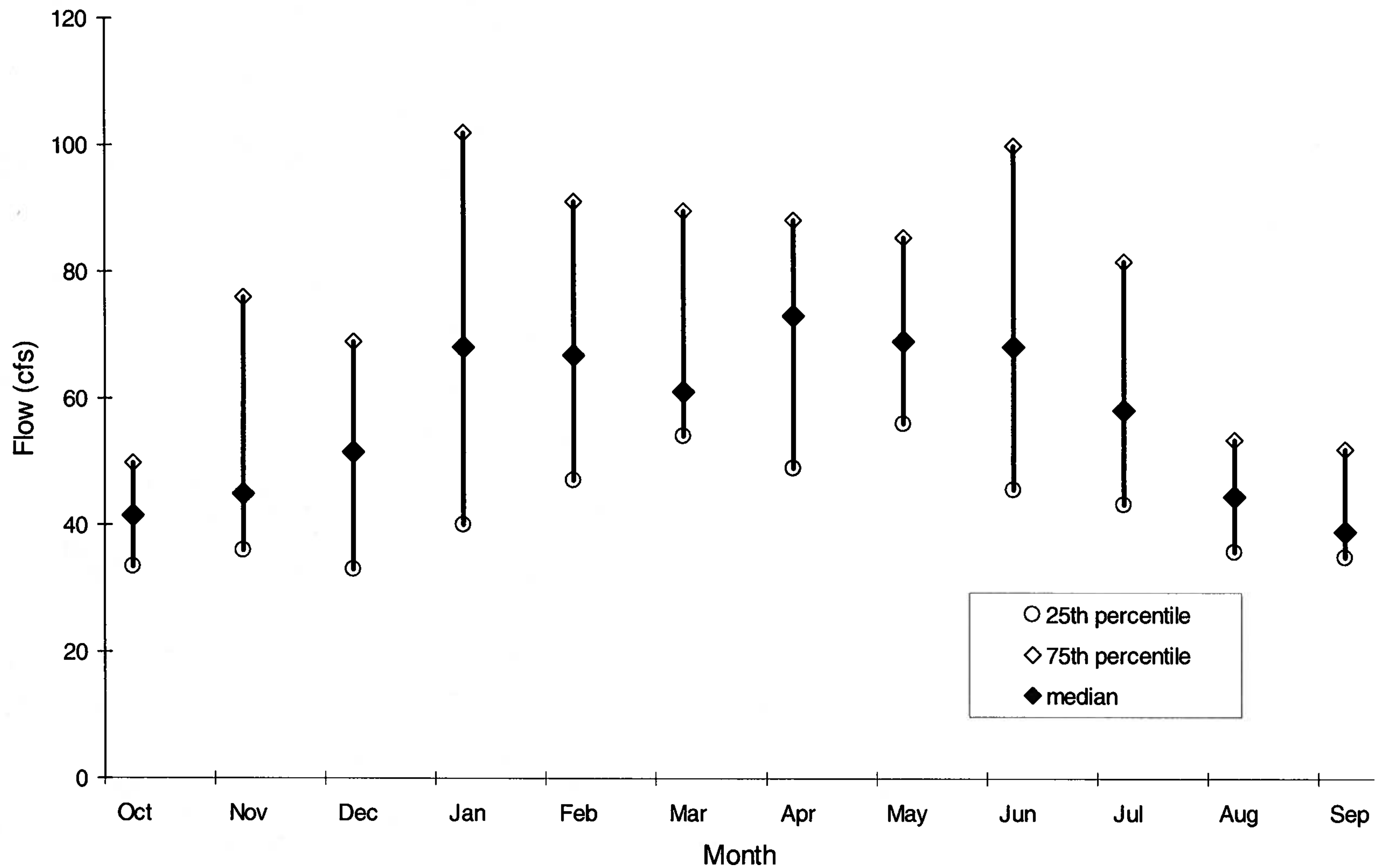


Figure 23. Median annual base flow index for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

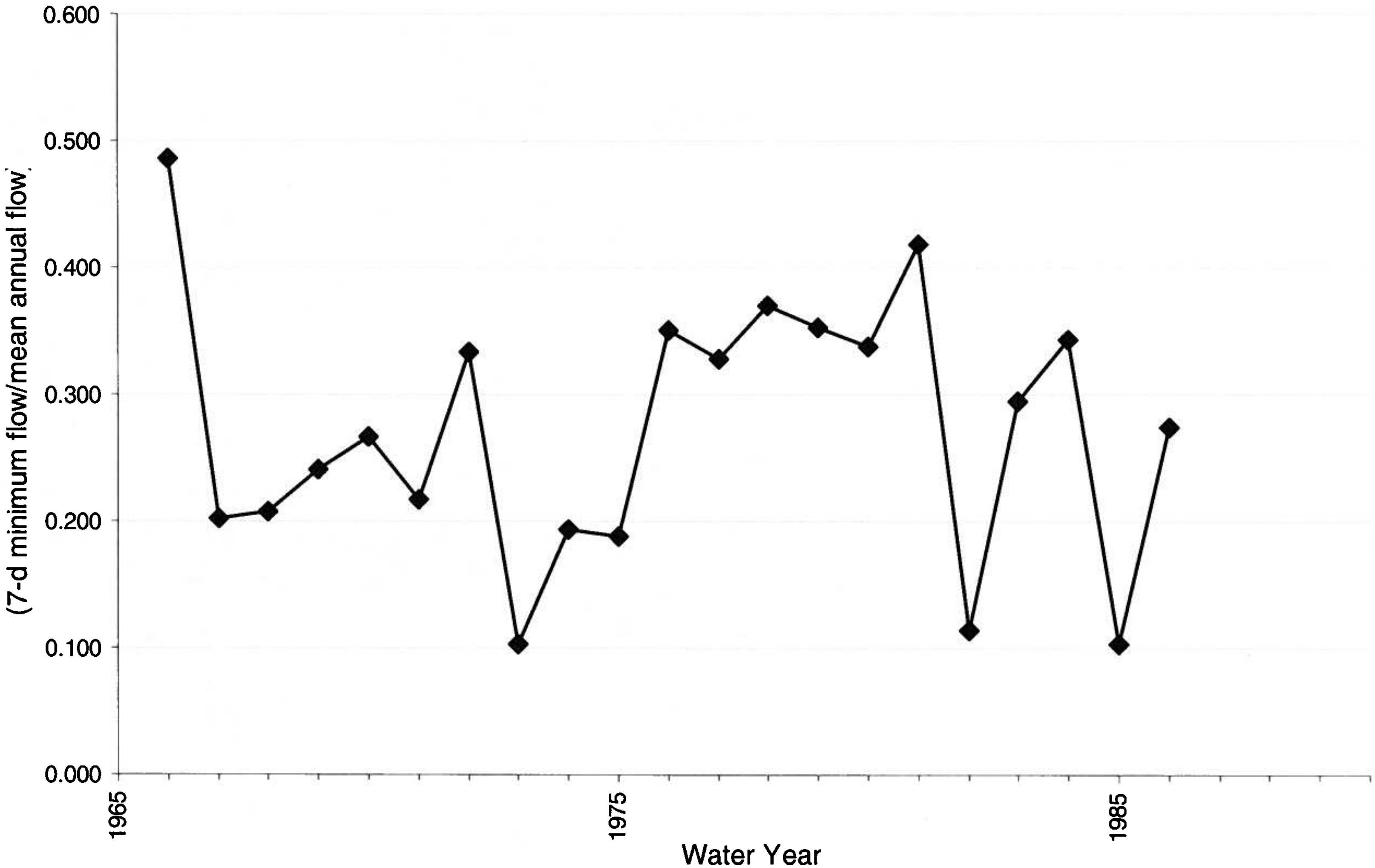
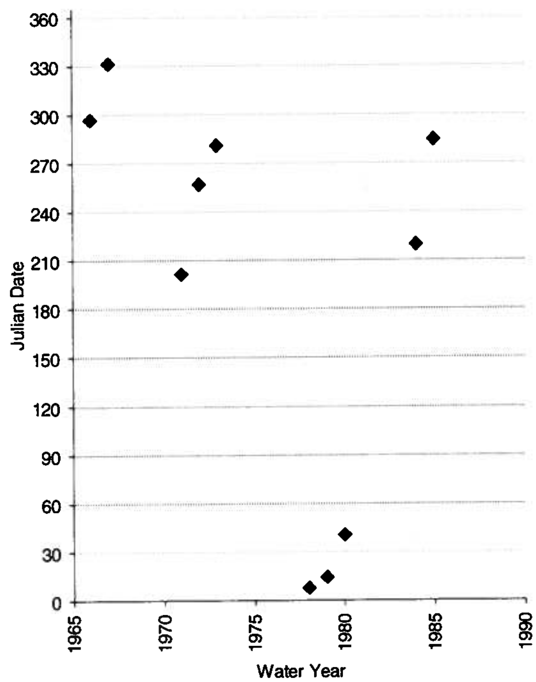
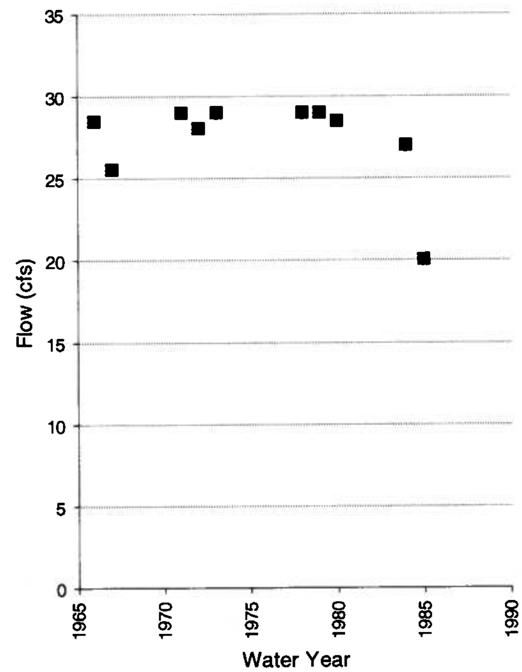


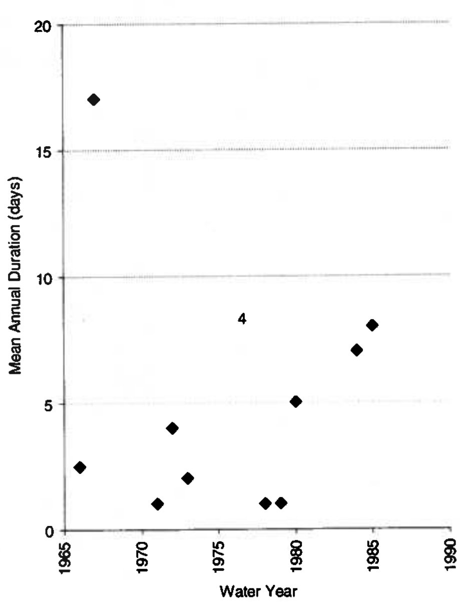
Figure 24. Extreme low flow event information for the Blue River gage at Milburn, OK using measured data for water years 1966-1986: a) date of occurrence for the first event, b) annual mean magnitude c) annual mean duration and d) annual mean frequency.

a) b)





c) d)



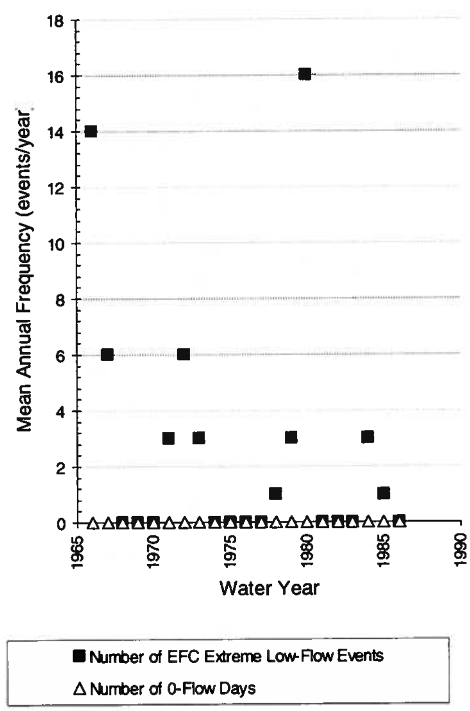


Figure 25. Annual instantaneous peak flow recurrence interval for the for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

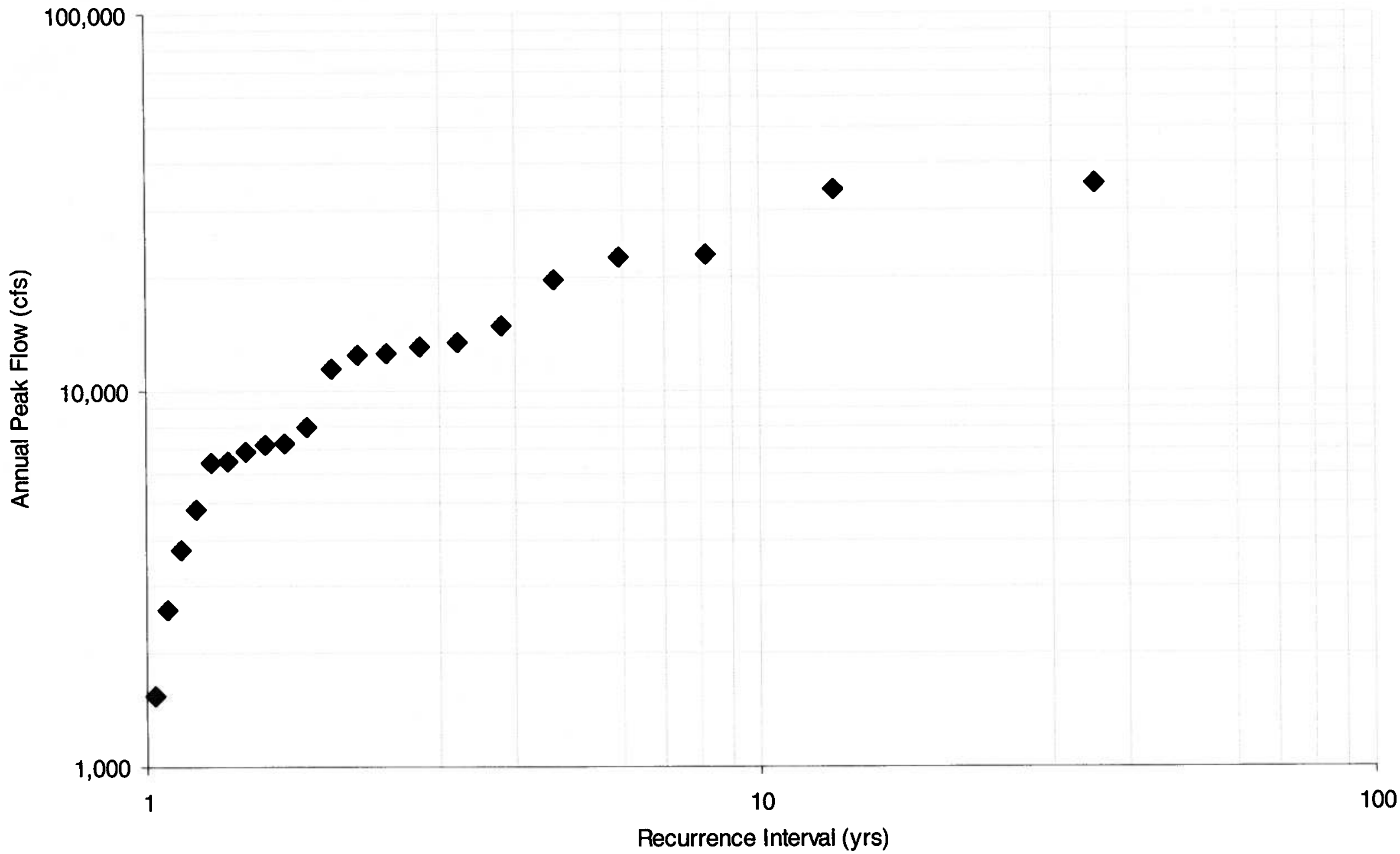


Figure 26. Percentage of annual instantaneous peak flow due to stormflow and ratio of annual instantaneous peak flow to mean daily flow recorded for that day on which peak flow was measured for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

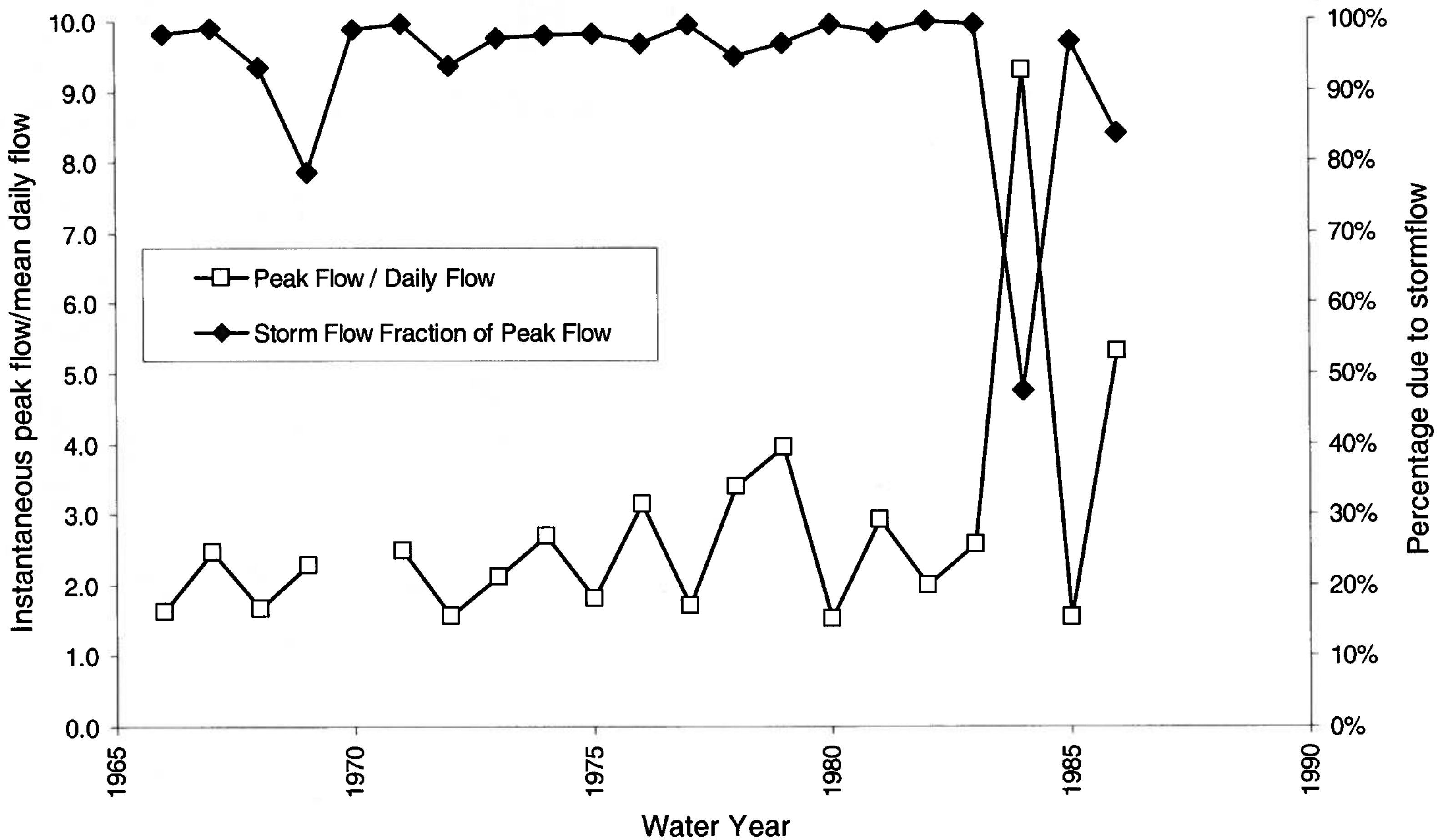
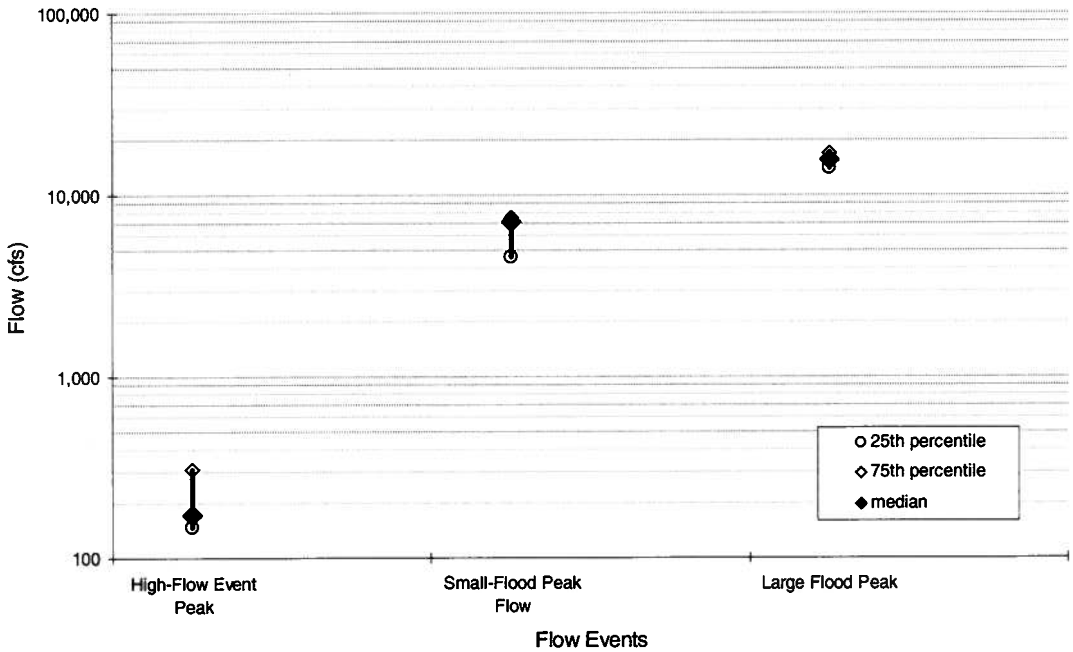


Figure 27. Median, 25th and 75th percentile flow a) magnitudes and b) durations for high-flow events and floods for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

a)



b)

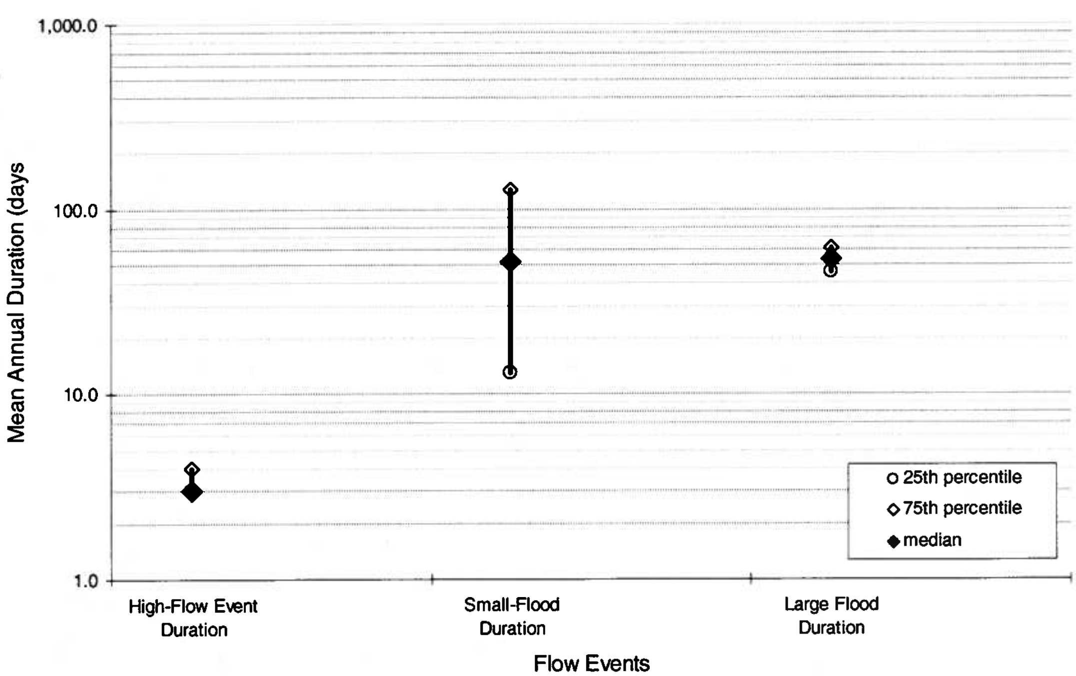
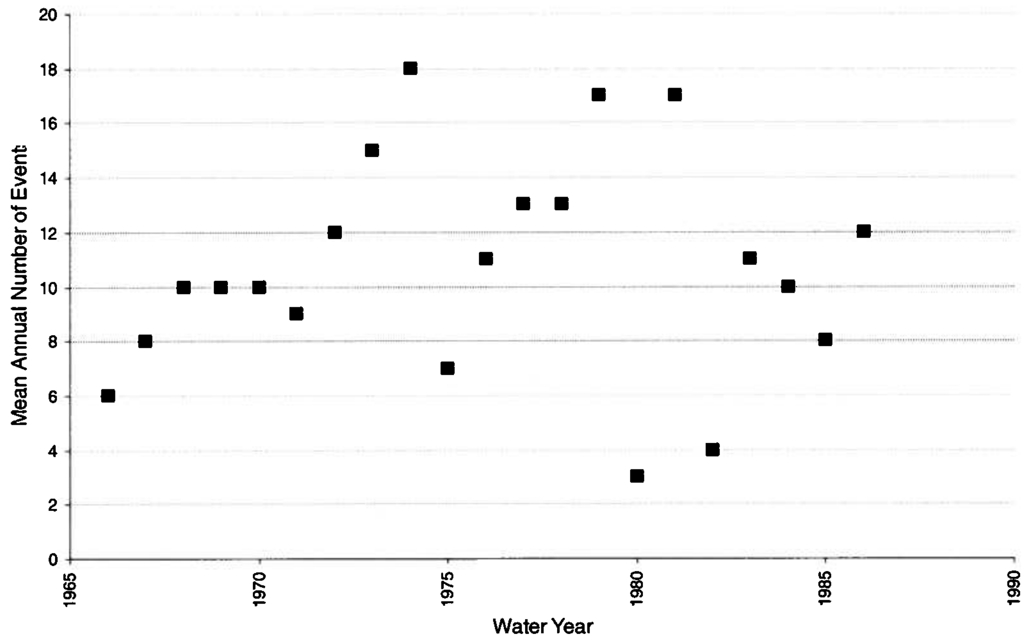


Figure 28. a) Annual frequency and b)date of the first high-flow pulses for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

a)



b)

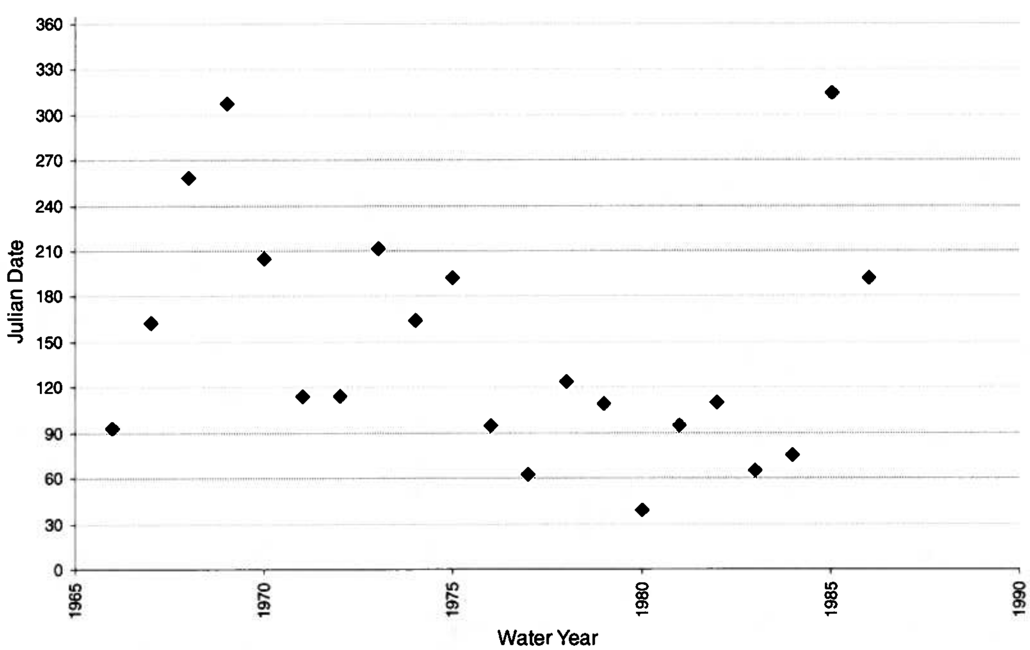
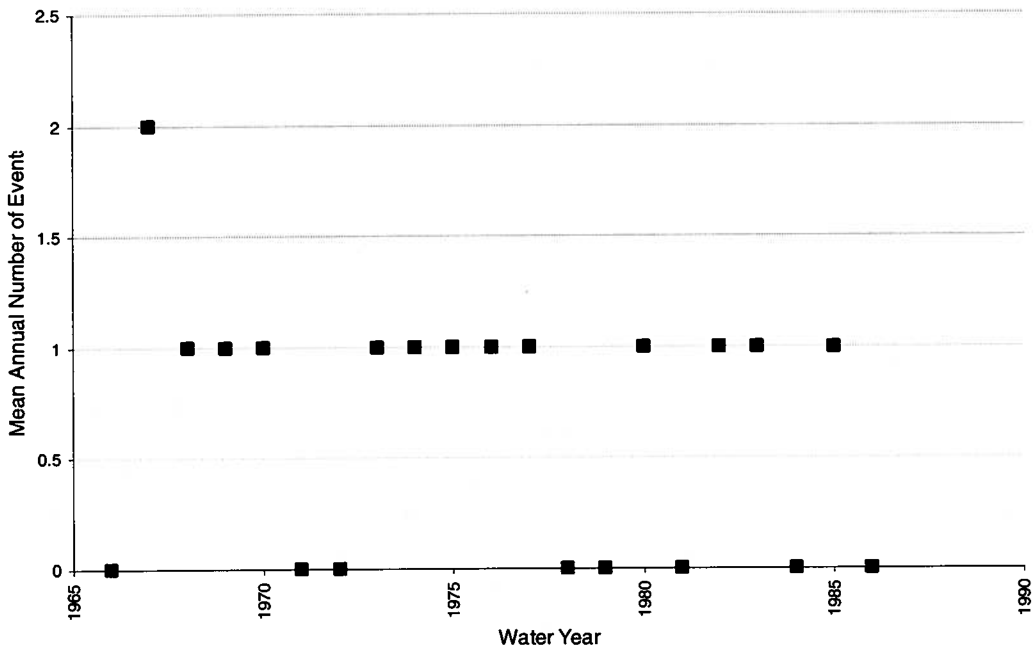


Figure 29. a) Annual frequency and b) date of the first small flood for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

a)



b)

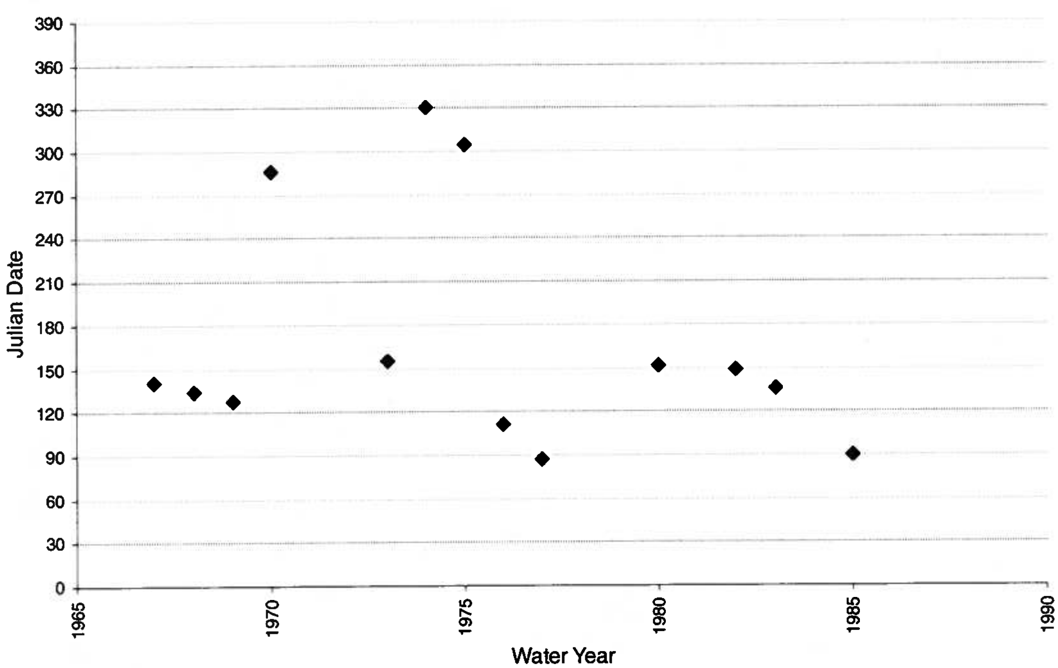
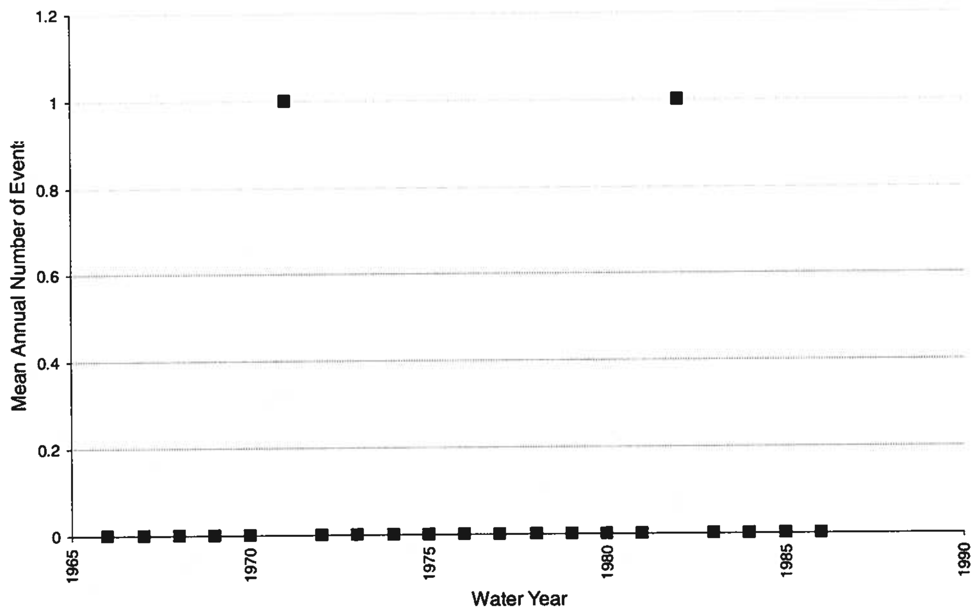


Figure 30. a) Annual frequency and b) date of large floods for the Blue River gage at Milburn, OK using measured data for water years 1966-1986.

a)



b)

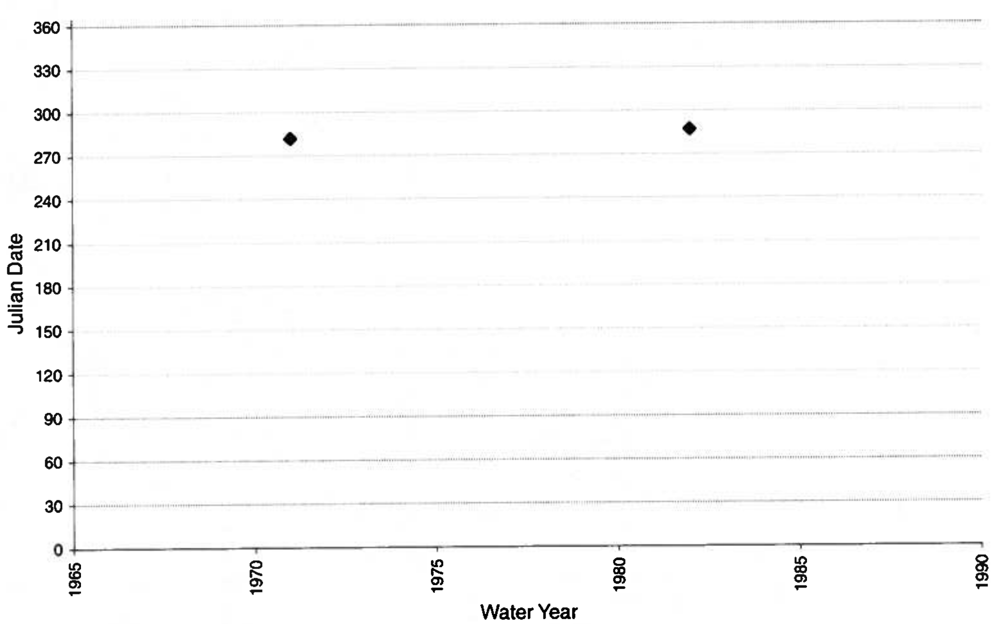


Figure 31. Flow duration curve for mean daily flows for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

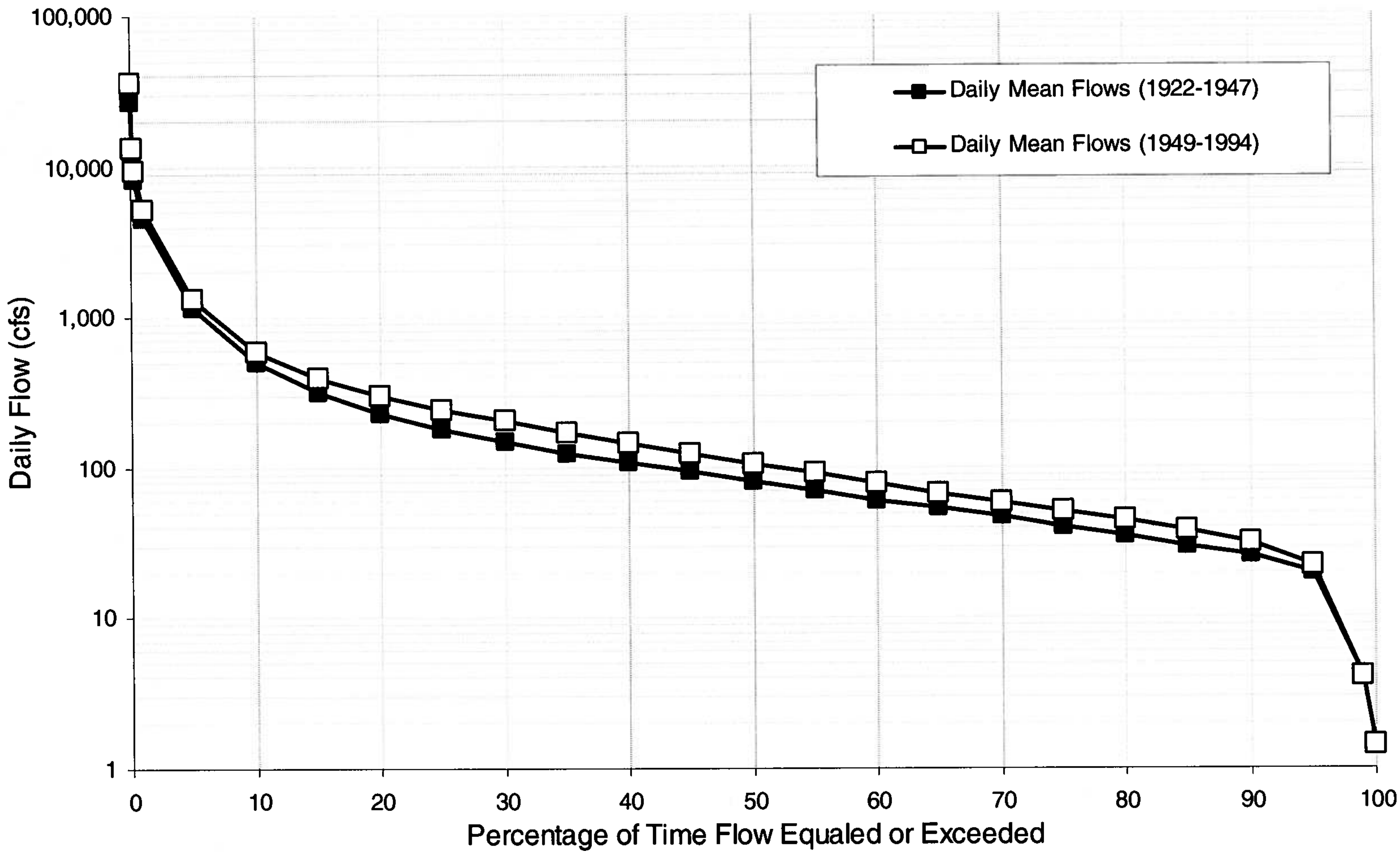


Figure 32. Median, 25th and 75th percentile values for mean monthly flows for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

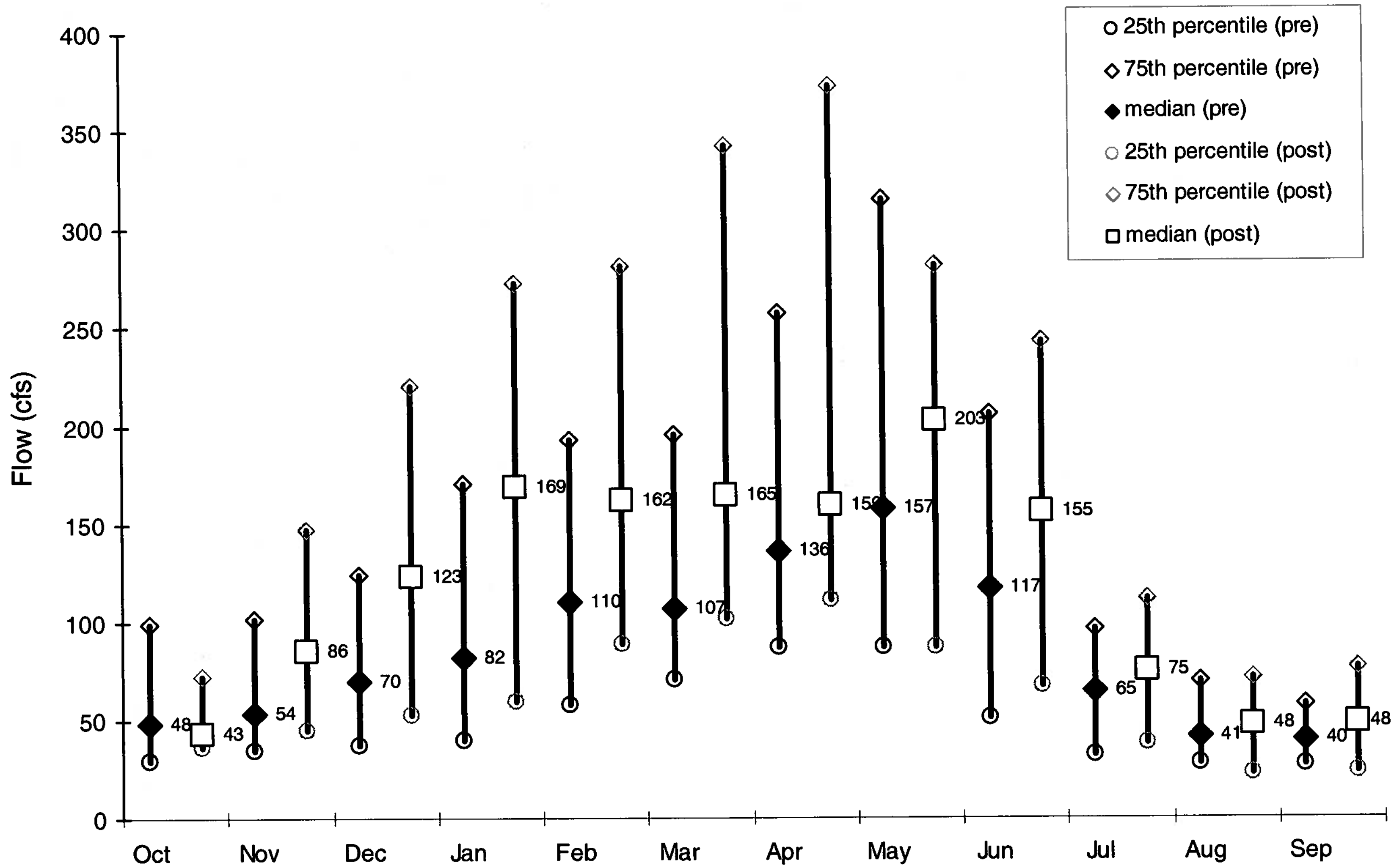


Figure 33. Annual precipitation history with 5-year tendencies. Courtesy of Oklahoma Climatological Survey.

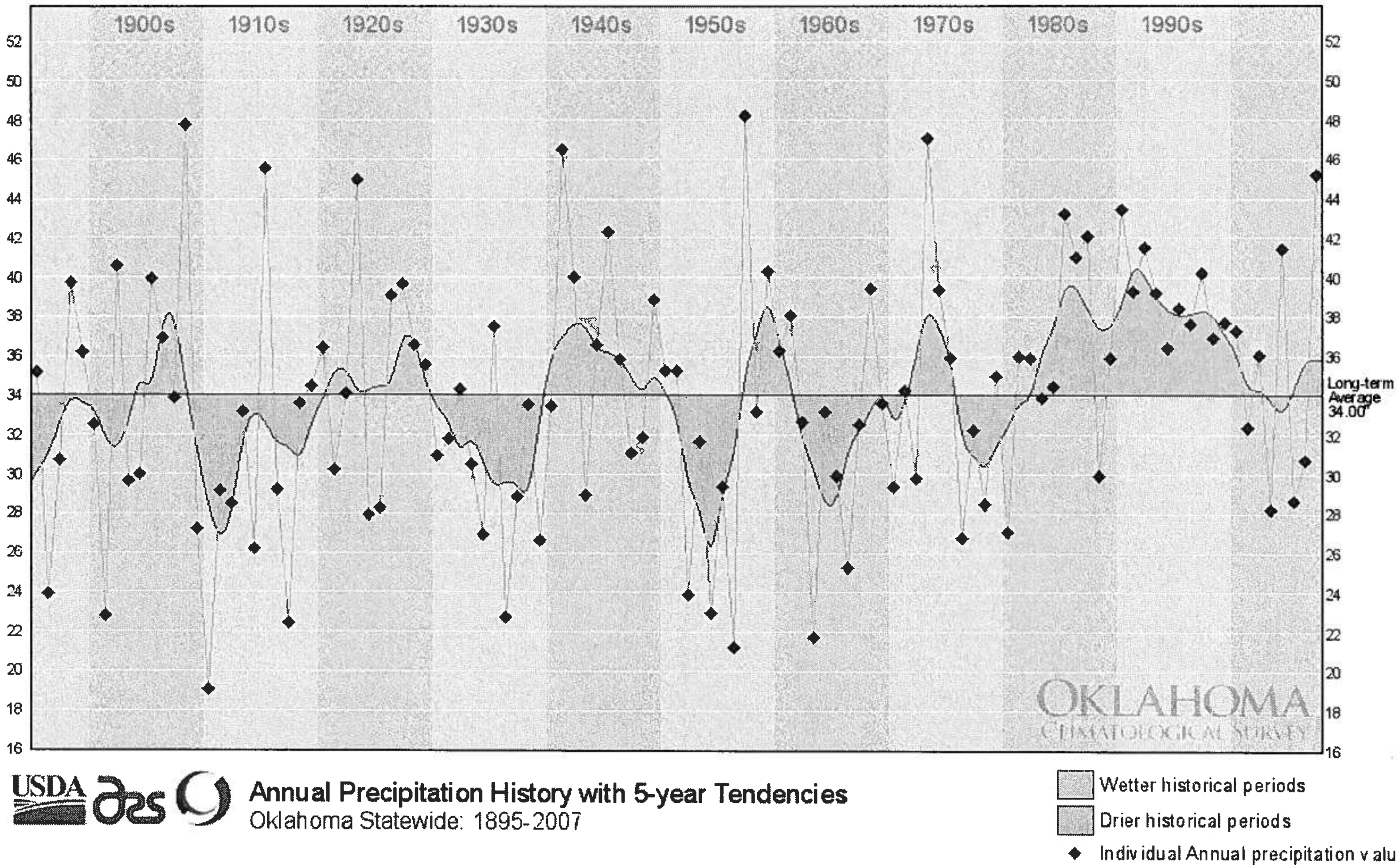
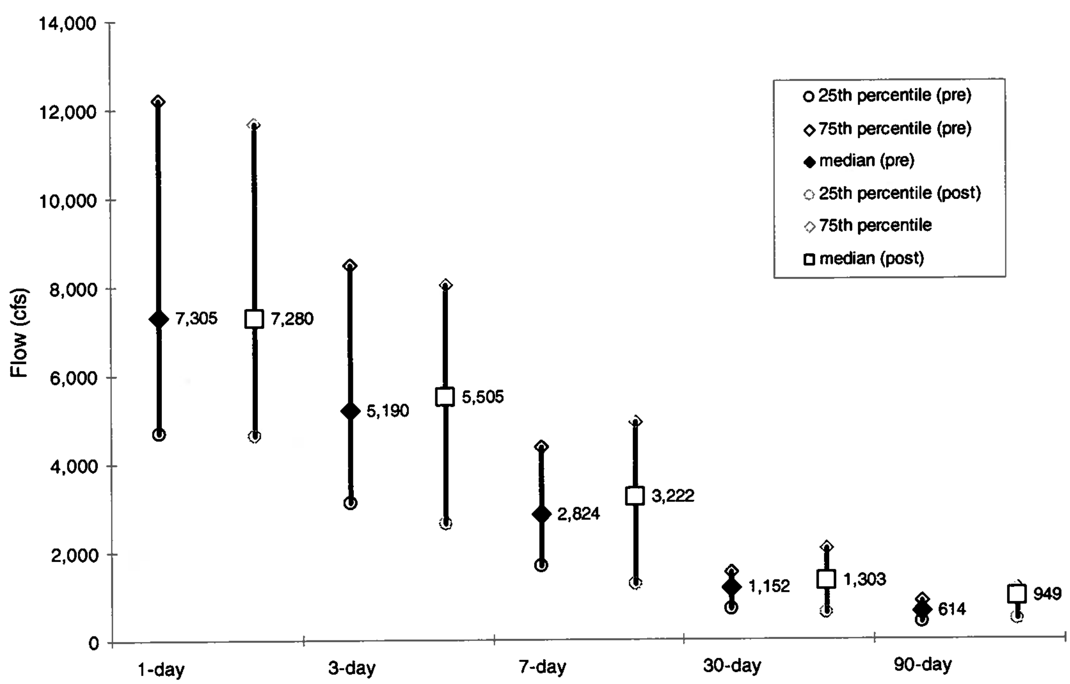


Figure 34. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-d annual a) maximum flows and b) minimum flows for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

a)



b)

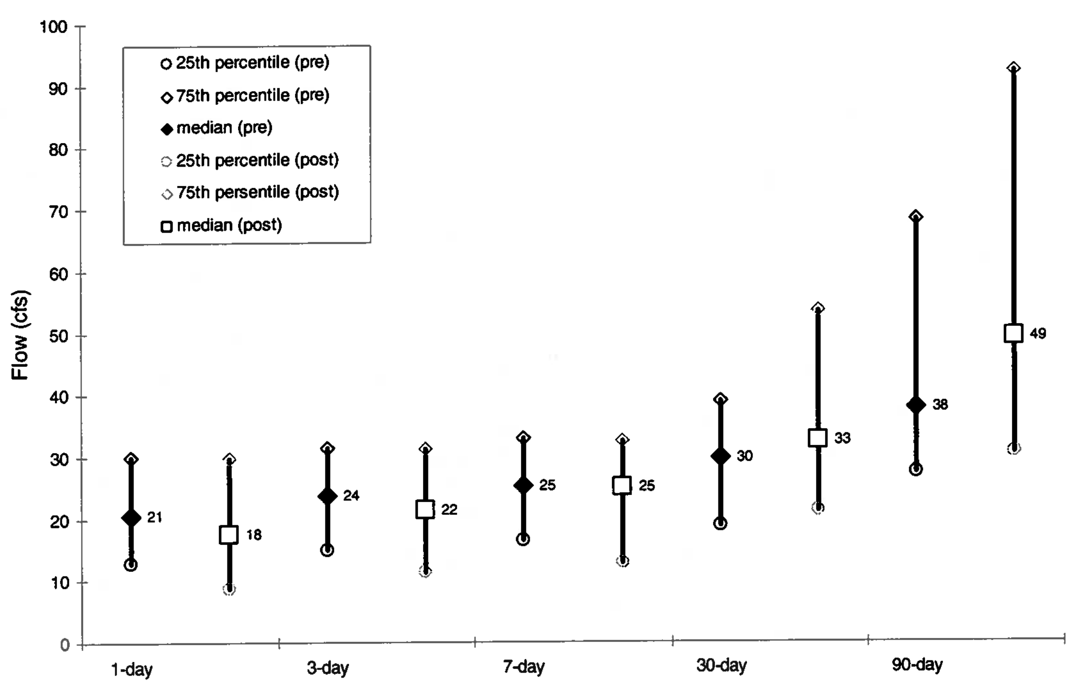


Figure 35. Median, 25th and 75th percentile values for annual occurrence frequency and duration of low- and high-flow pulses for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

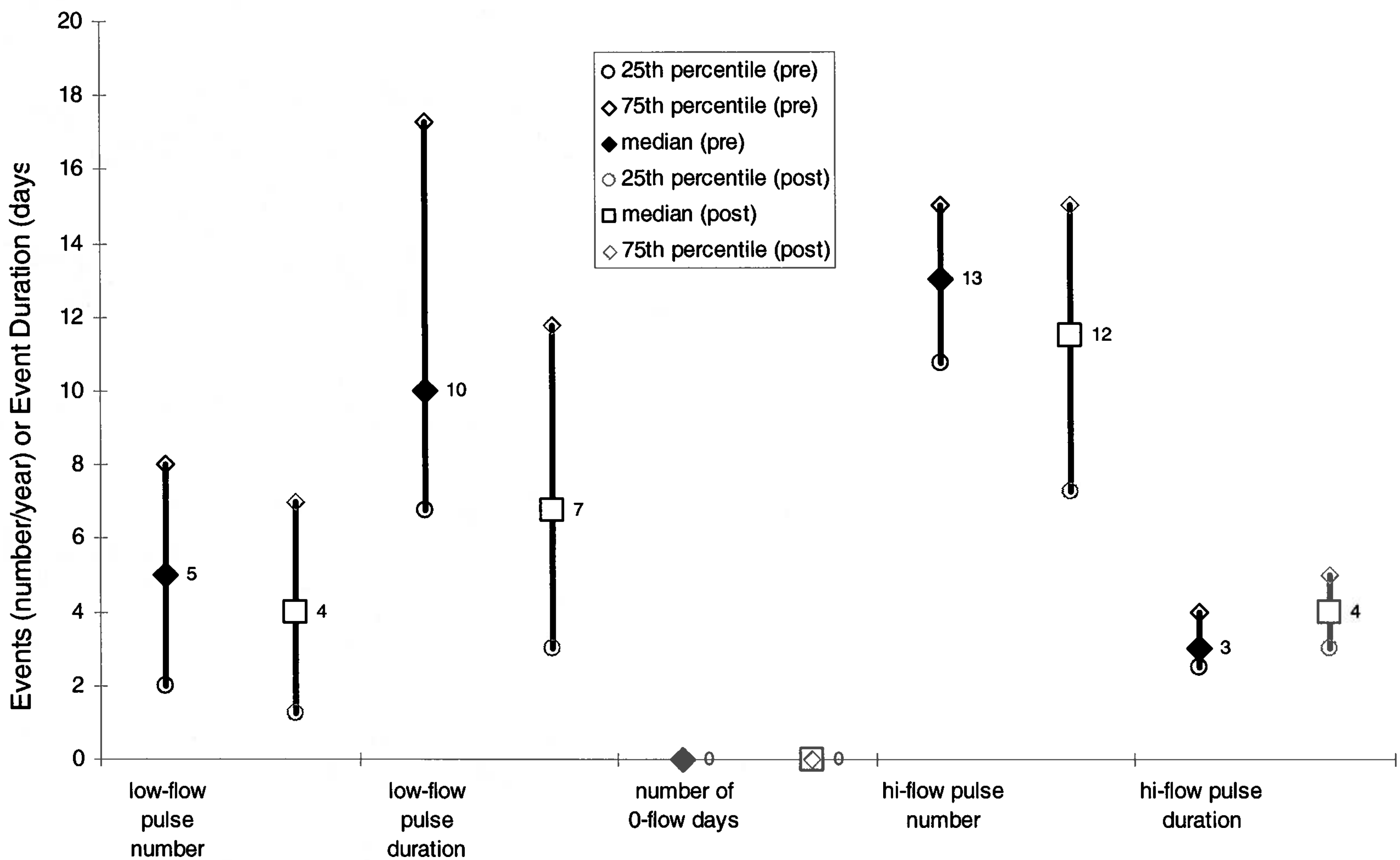


Figure 36. 7-day low flow recurrence interval for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

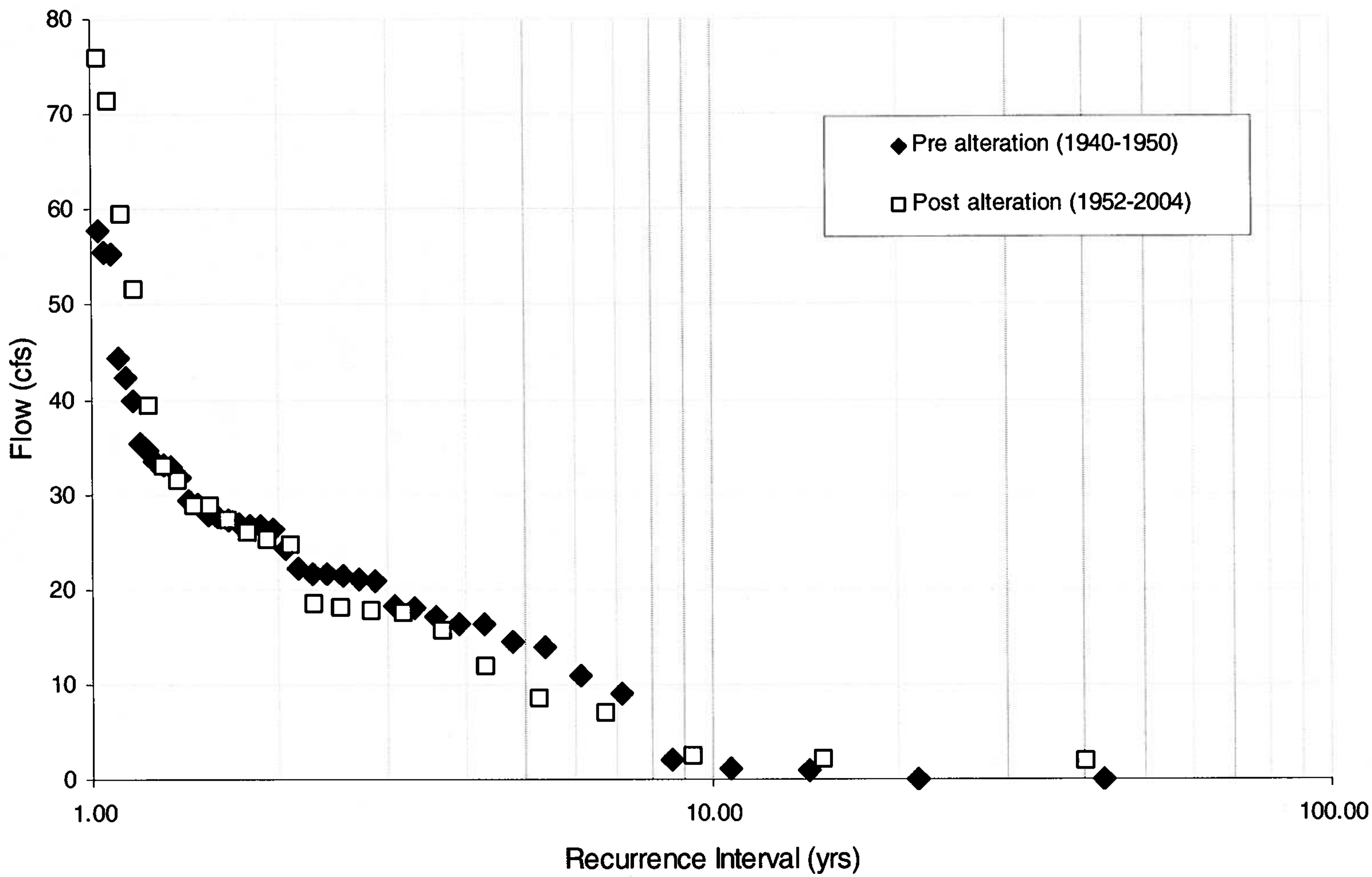


Figure 37. Annual instantaneous peak flow recurrence interval for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

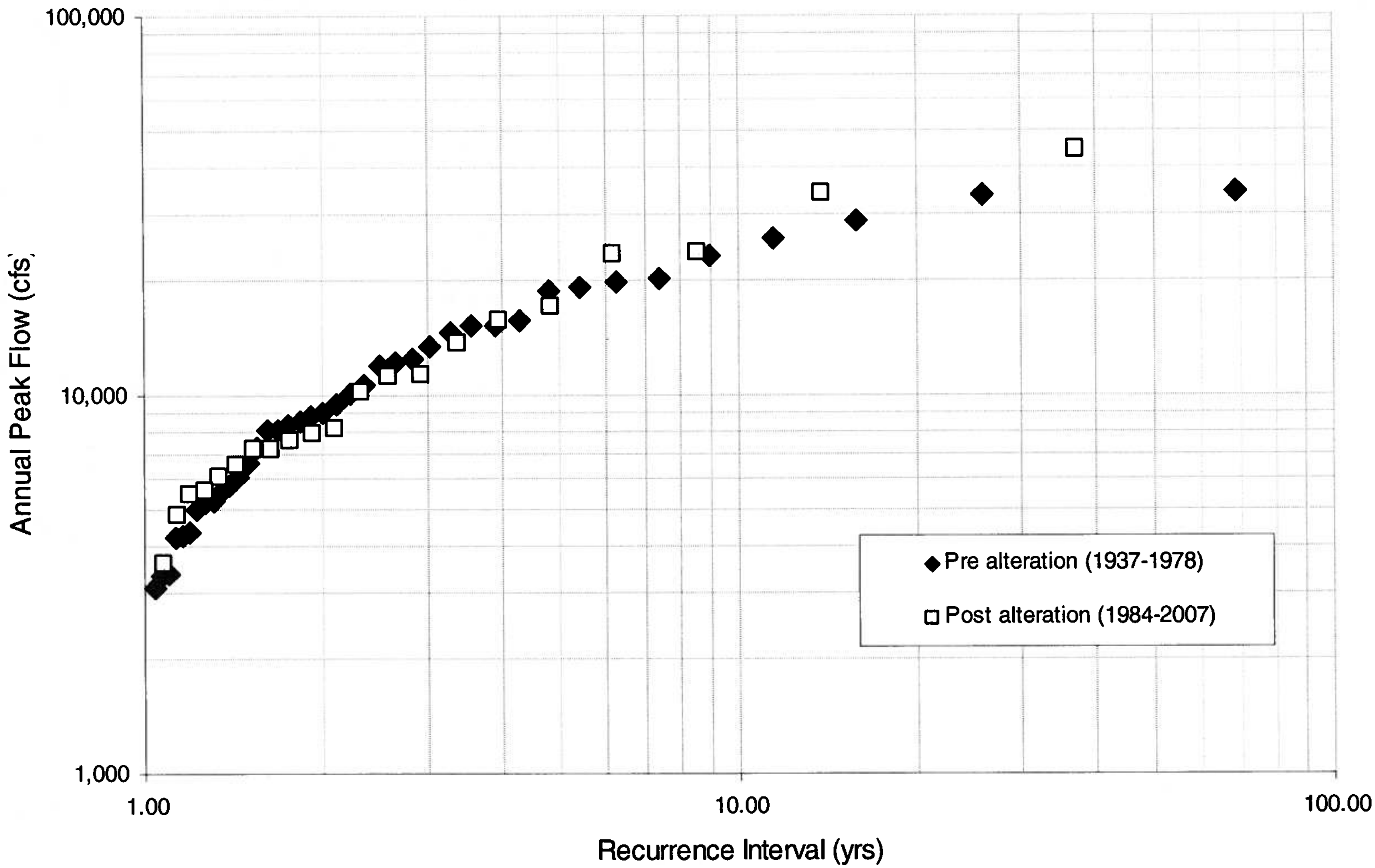


Figure 38. Percentage of annual instantaneous peak flow due to stormflow and ratio of annual instantaneous peak flow to mean daily flow recorded for that day on which peak flow was measured for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

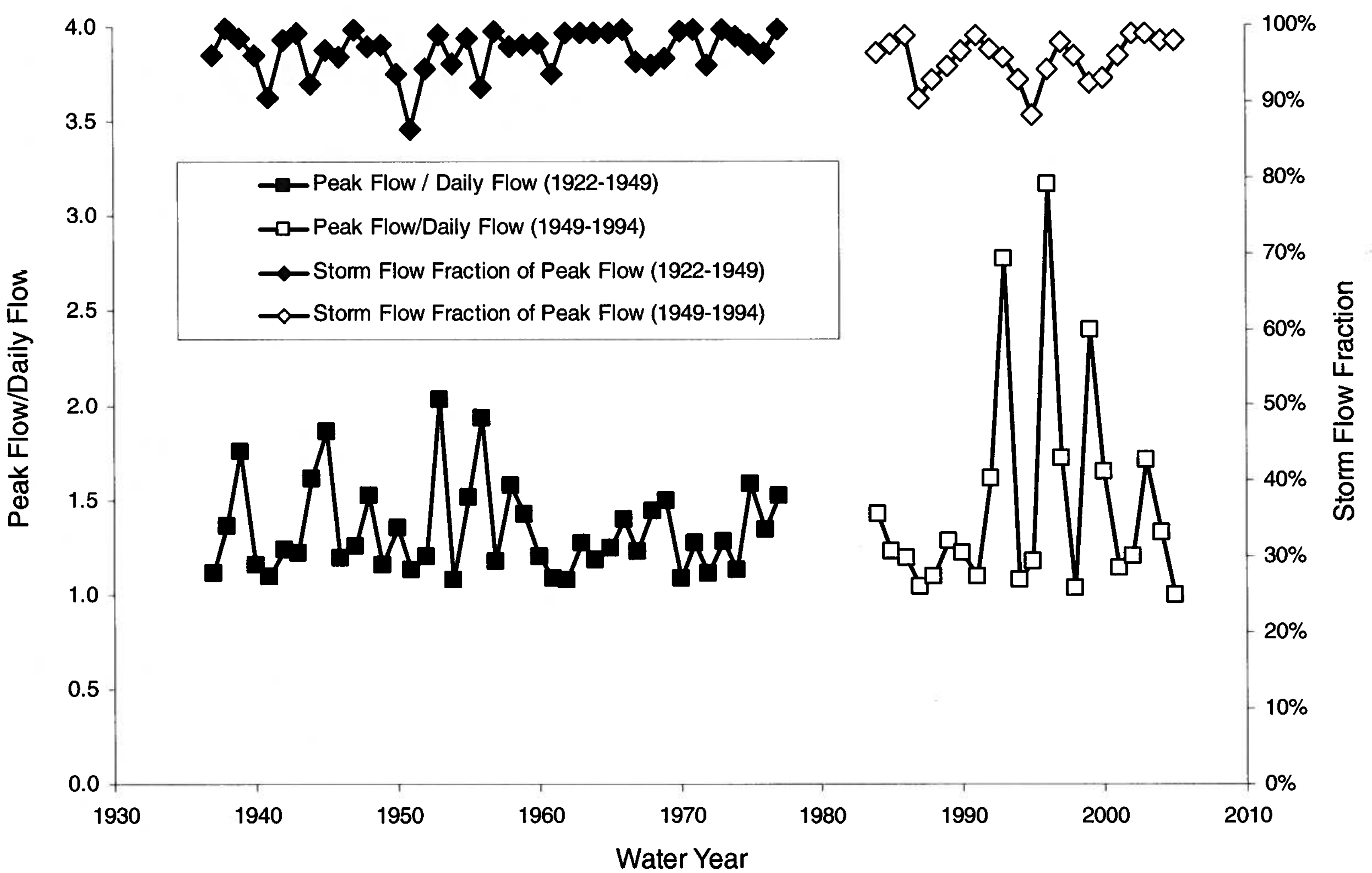


Figure 39. Total magnitude of hydrologic alteration for 33 core IHA parameters for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

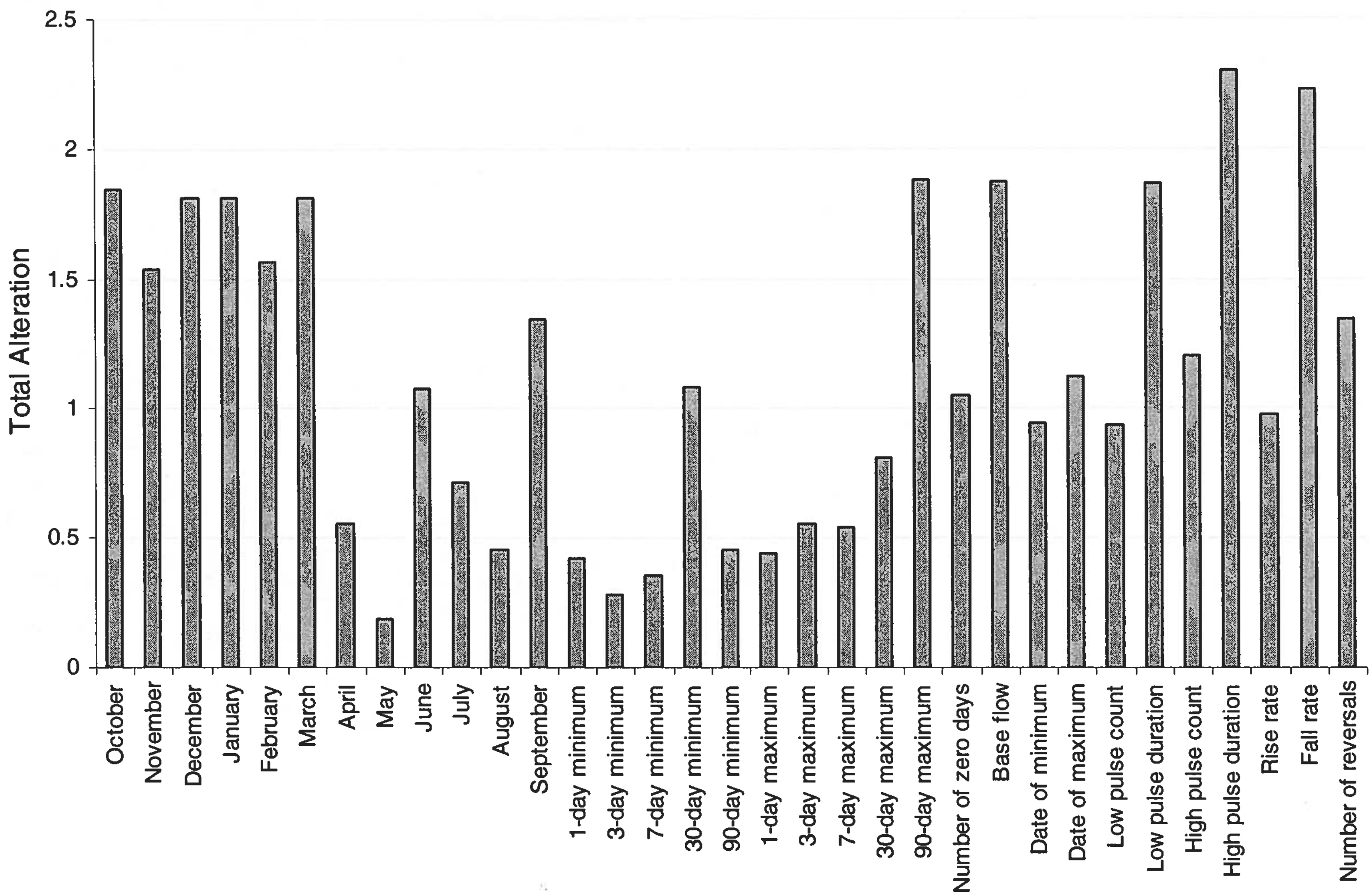


Figure 40. Ranked total magnitude of hydrologic alteration for 33 core IHA parameters for the Blue River gage at Blue, OK using measured data for water years 1937-2007. Data are stratified around water year 1981.

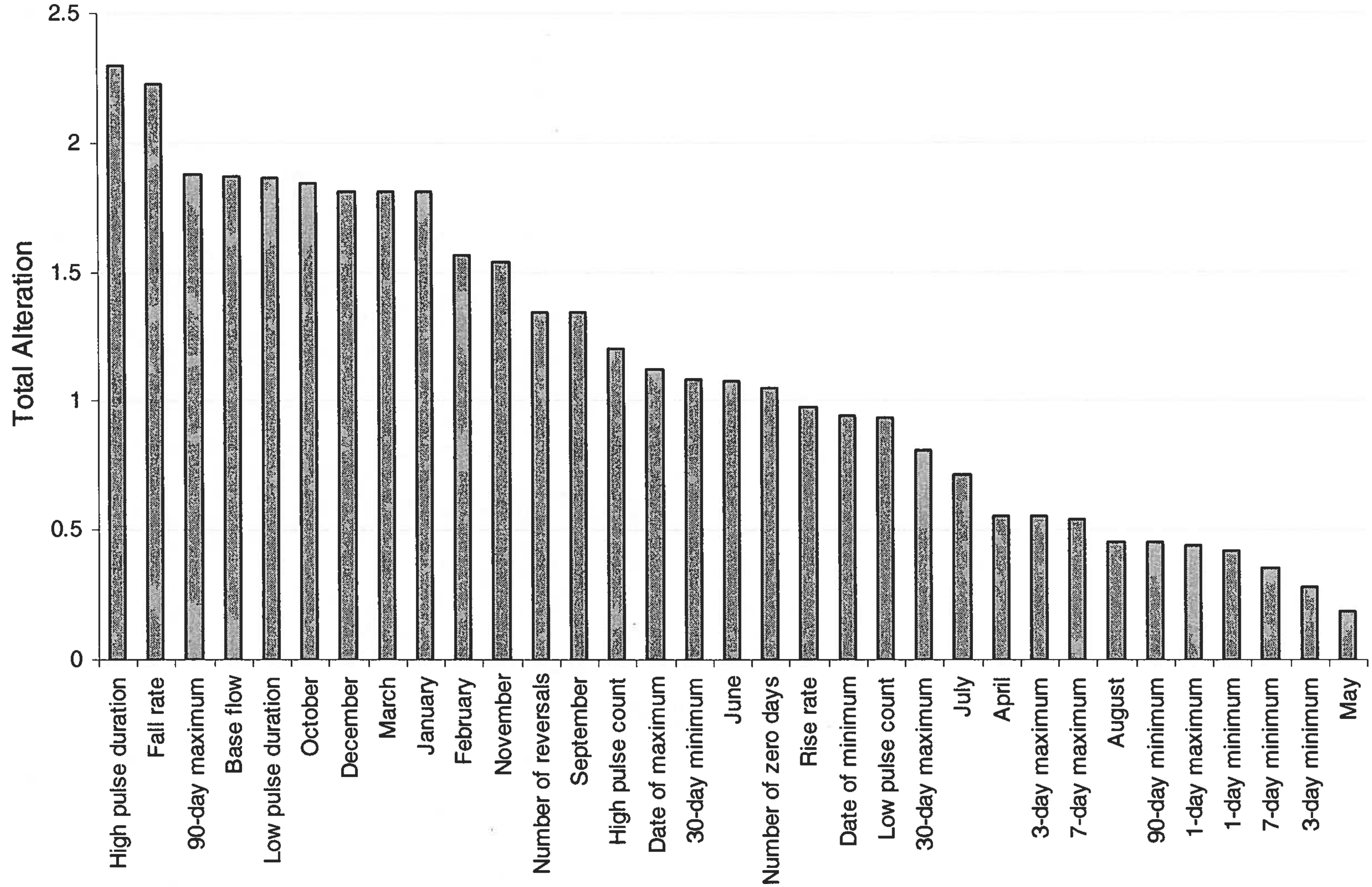


Figure 41. Flow duration curve for mean daily flows for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966- 2007.

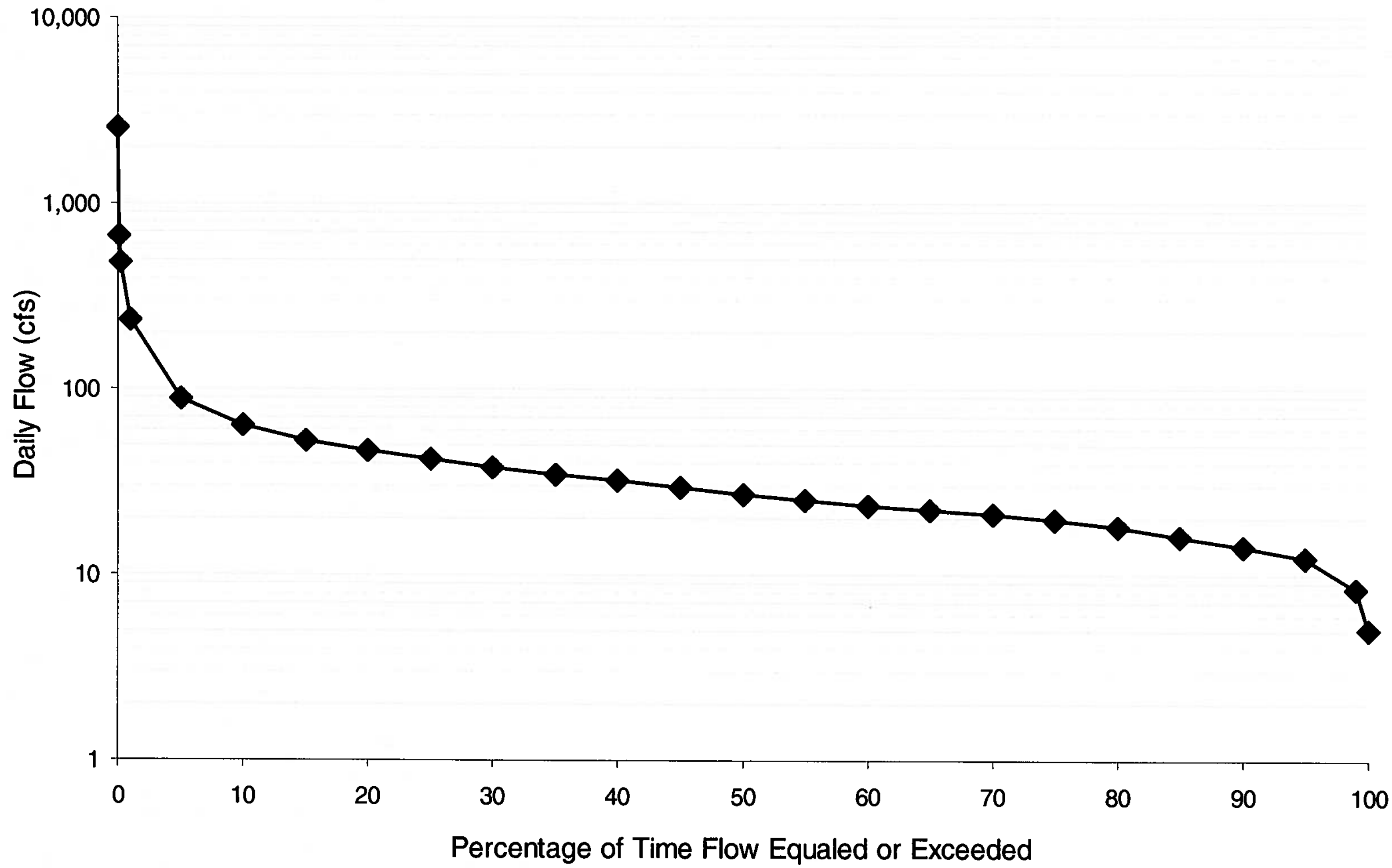


Figure 42. Median, 25th and 75th percentile values for monthly mean flows for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966- 2007.

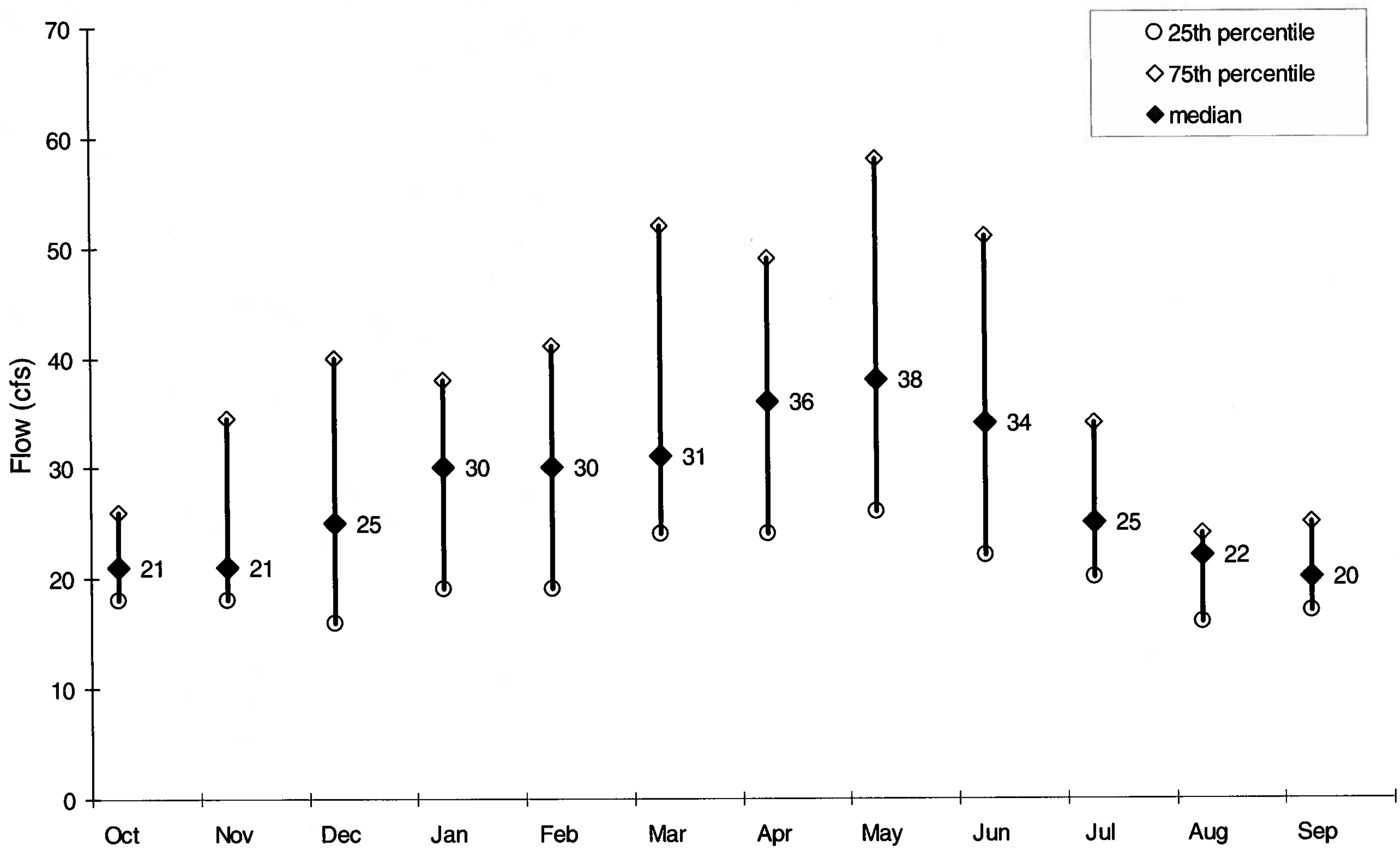
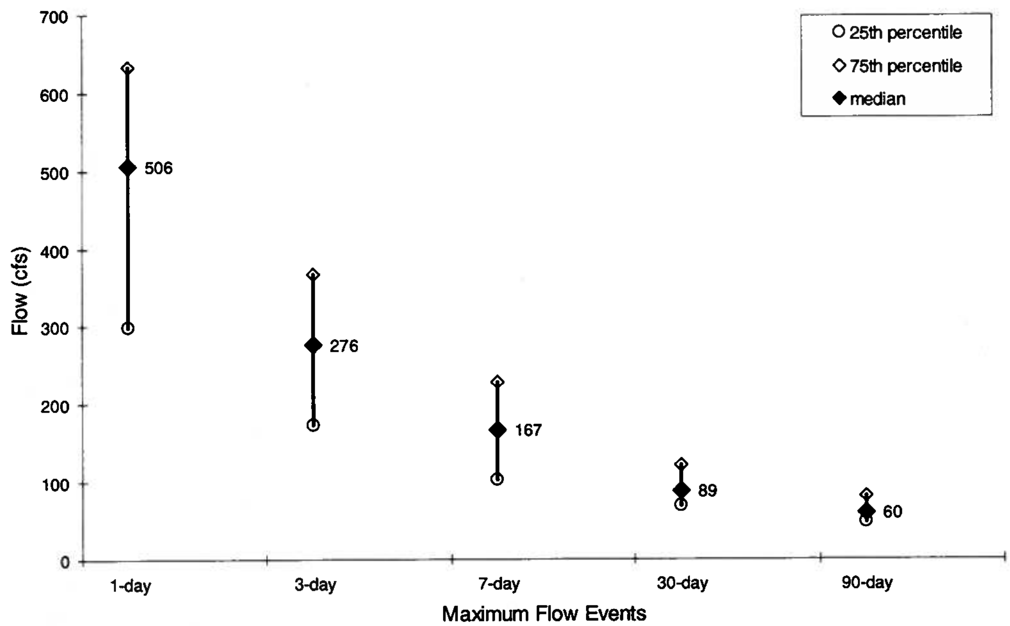


Figure 43. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-day a) maximum annual flows and b) minimum annual flows for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966- 2007.

a)



b)

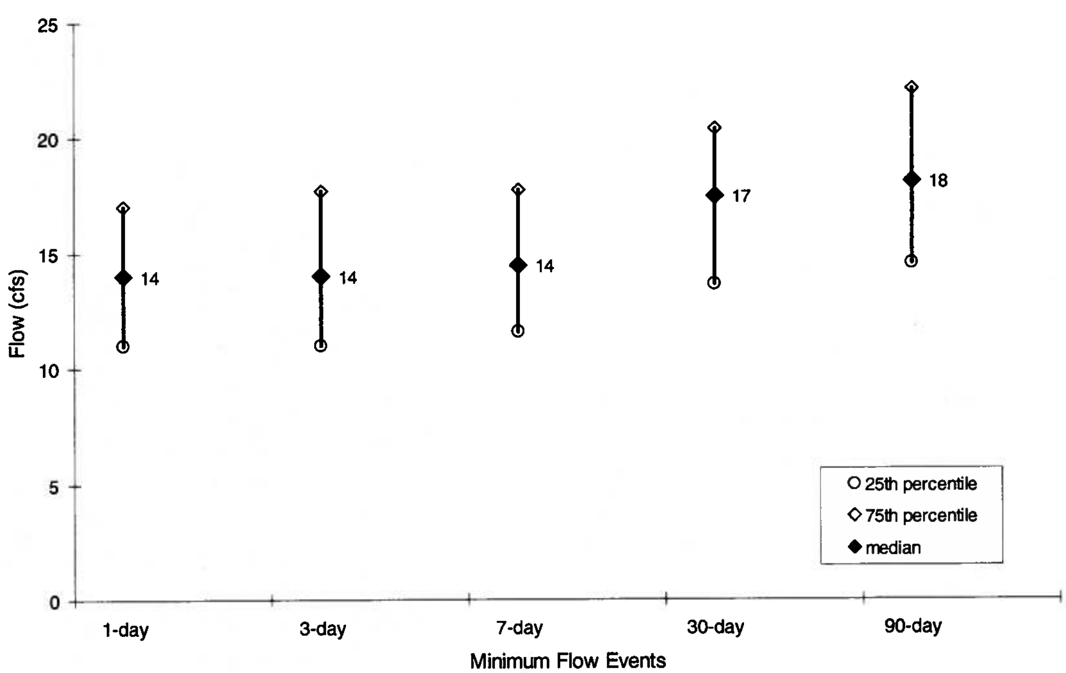


Figure 44. 7-day low flow recurrence interval for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966- 2007.

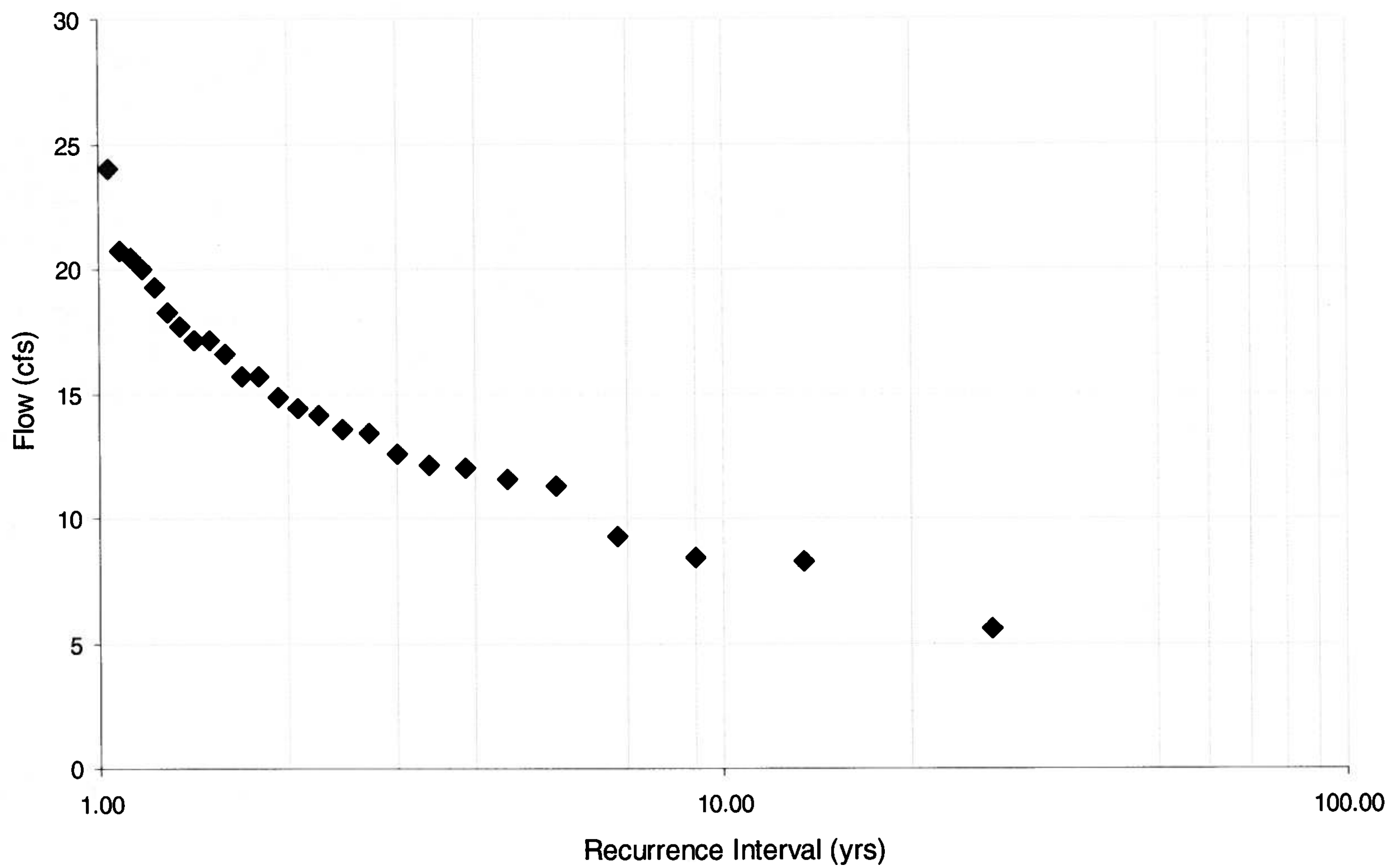


Figure 45. Median, 25th and 75th percentile values for annual occurrence frequency and duration of low- and high-flow pulses for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966-2007.

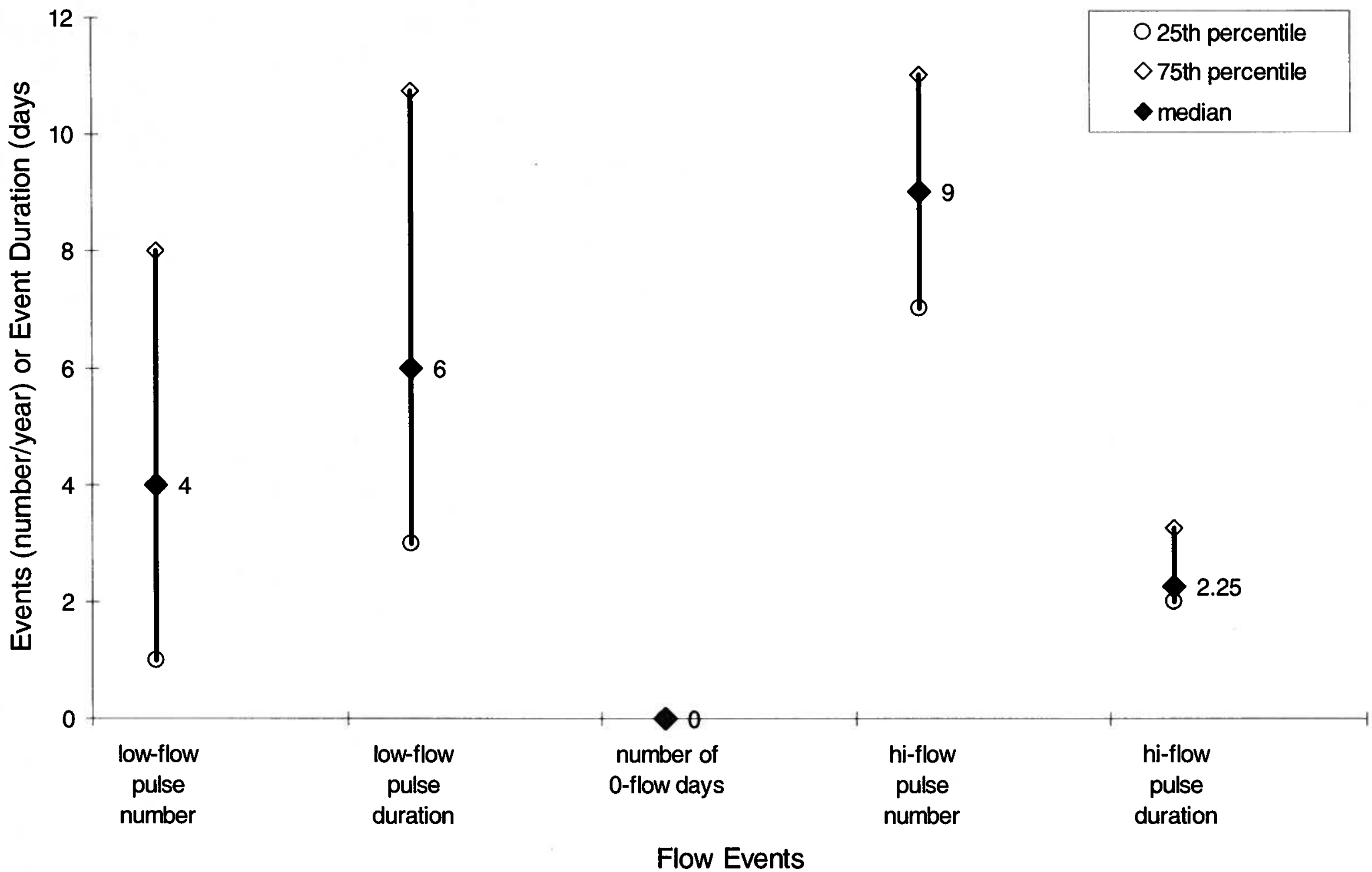


Figure 46. Median, 25th and 75th percentile monthly low flows for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966- 2007.

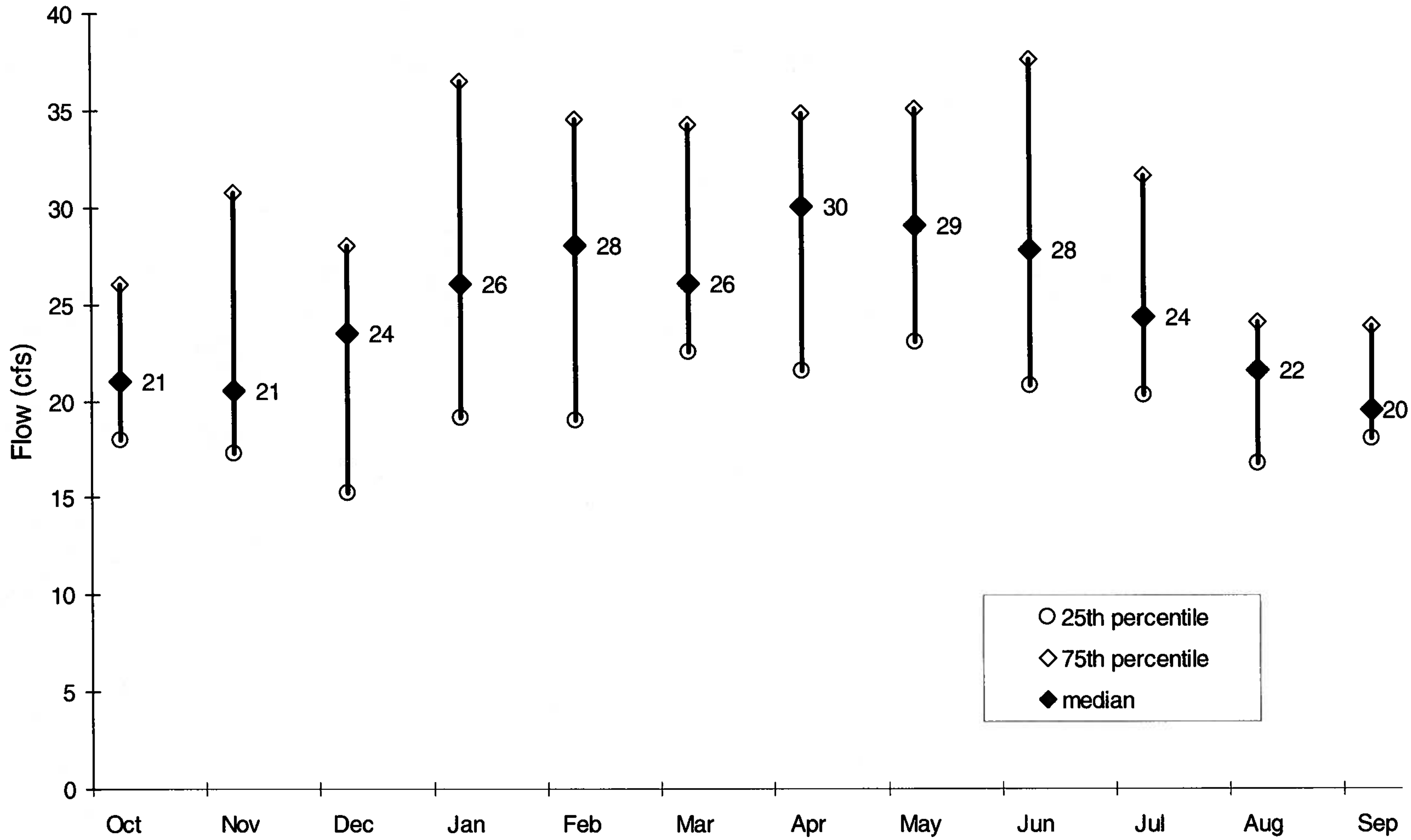
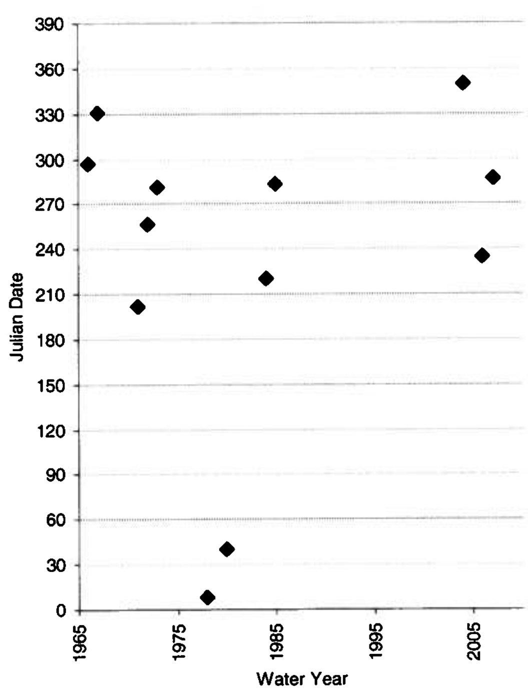
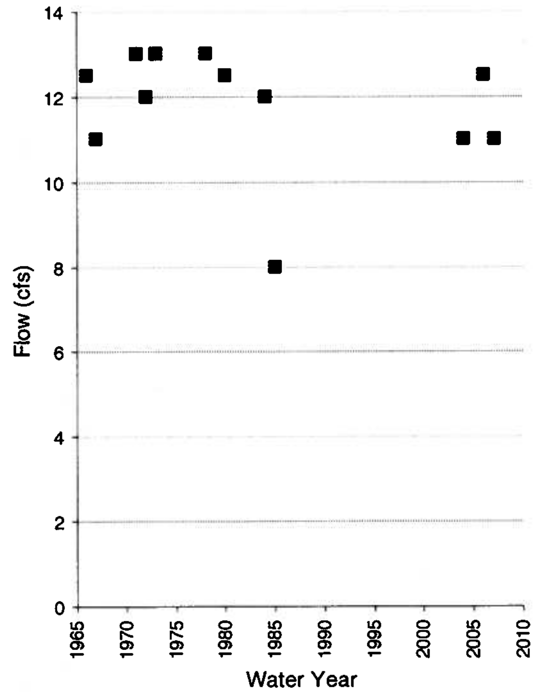


Figure 47. Extreme low flow event information for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966-2007. a) date of occurrence for the first event, b) annual mean magnitude c) annual mean duration and d) annual mean frequency.

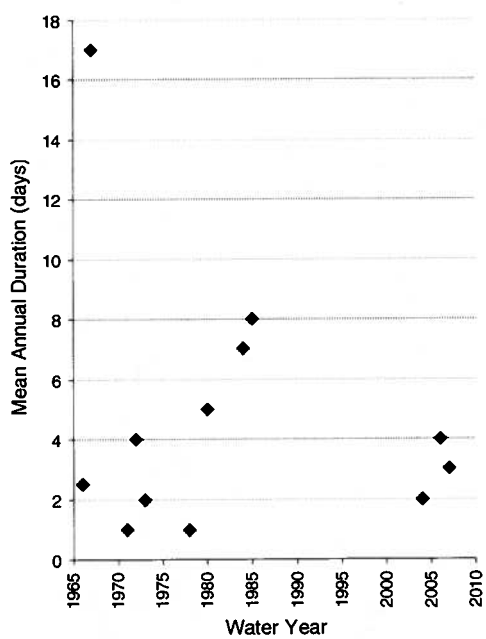
a)



b)



c)



d)

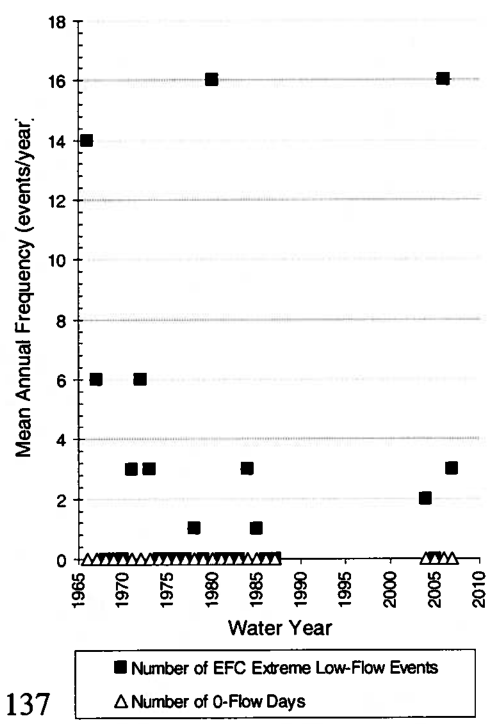


Figure 48. Annual mean base flow index for the Pennington Creek gage near Reagan, OK. The period of record included estimated and measured flow values for water years 1966-2007.

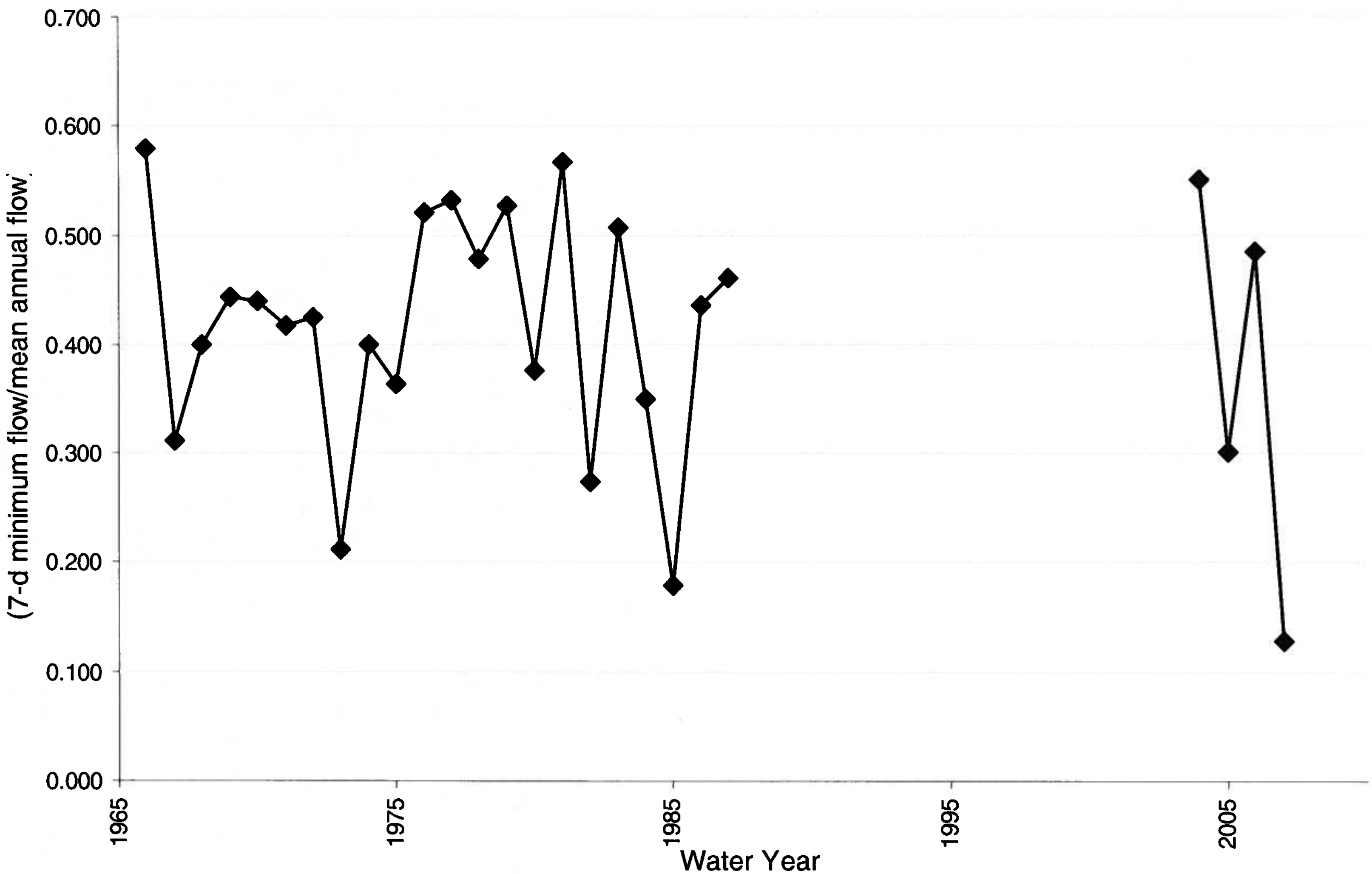


Figure 49. Flow duration curve for mean daily flows for the Honey Creek gage near Turner Falls, OK. The graph is based on measured data for water years 2004-2007.

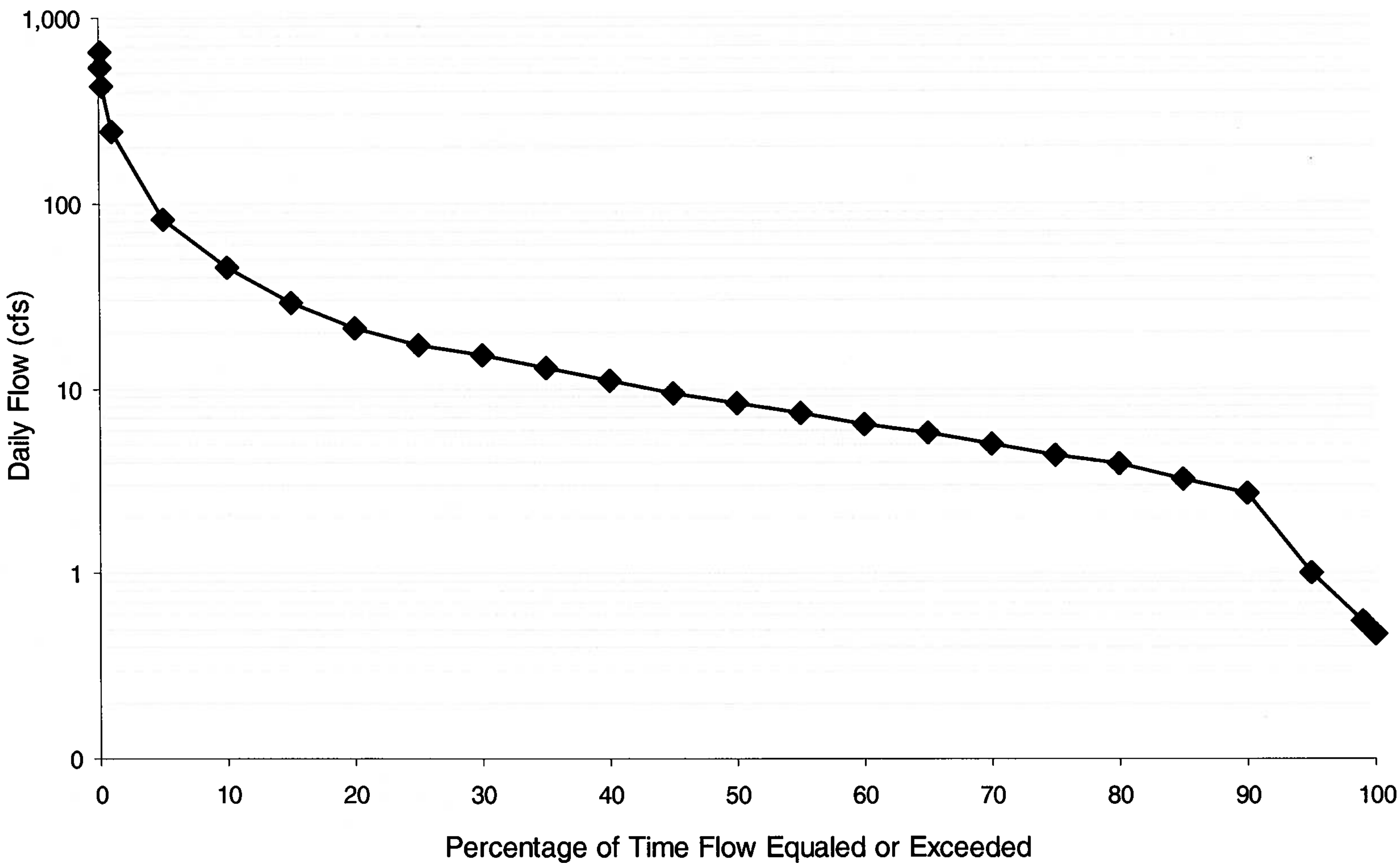


Figure 50. Median, 25th and 75th percentile monthly mean daily flows for the Honey Creek gage near Turner Falls, OK. The graph is based on measured data for water years 2004-2007.

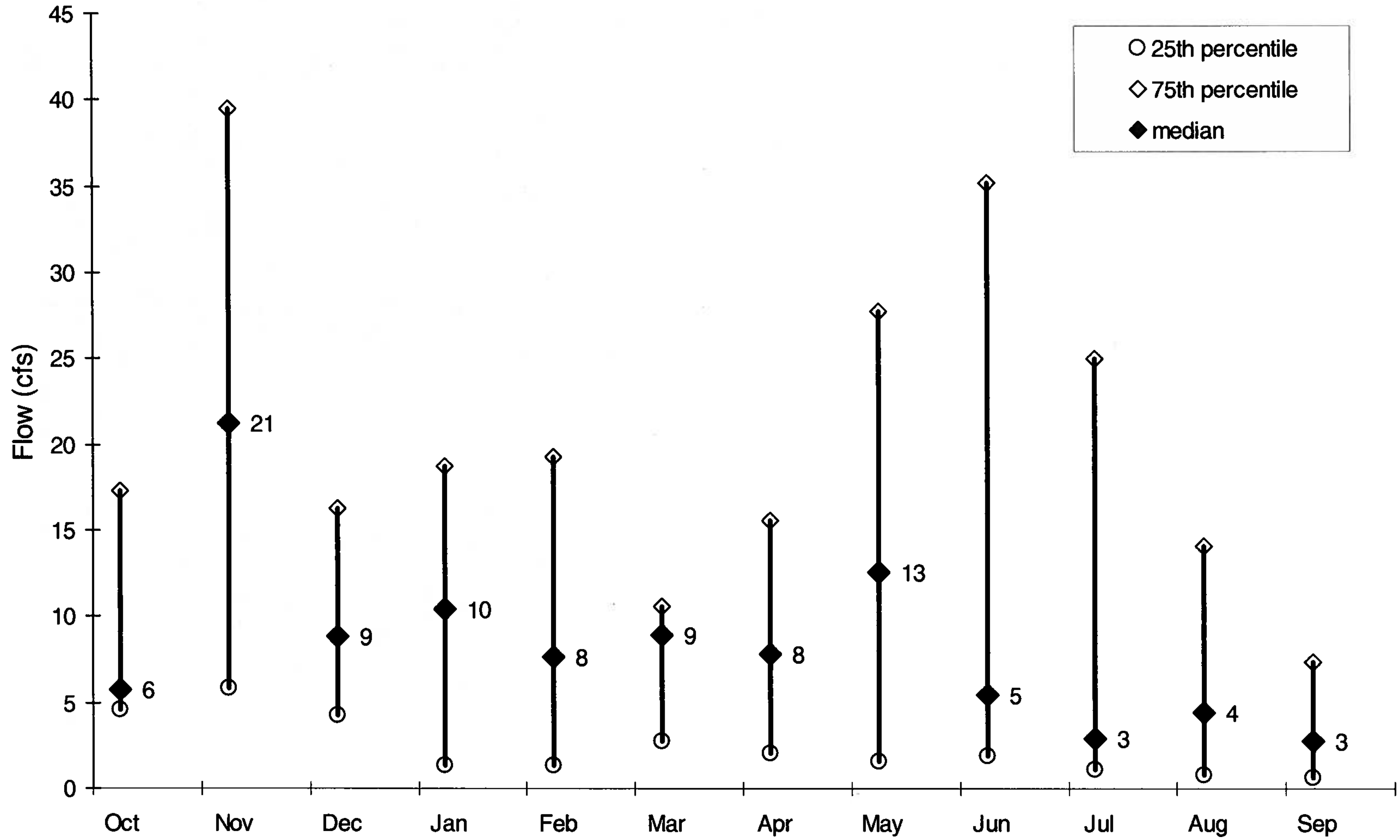


Figure 51. Flow duration curve for mean daily flows for the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and pipe data for water years 1991-2001.

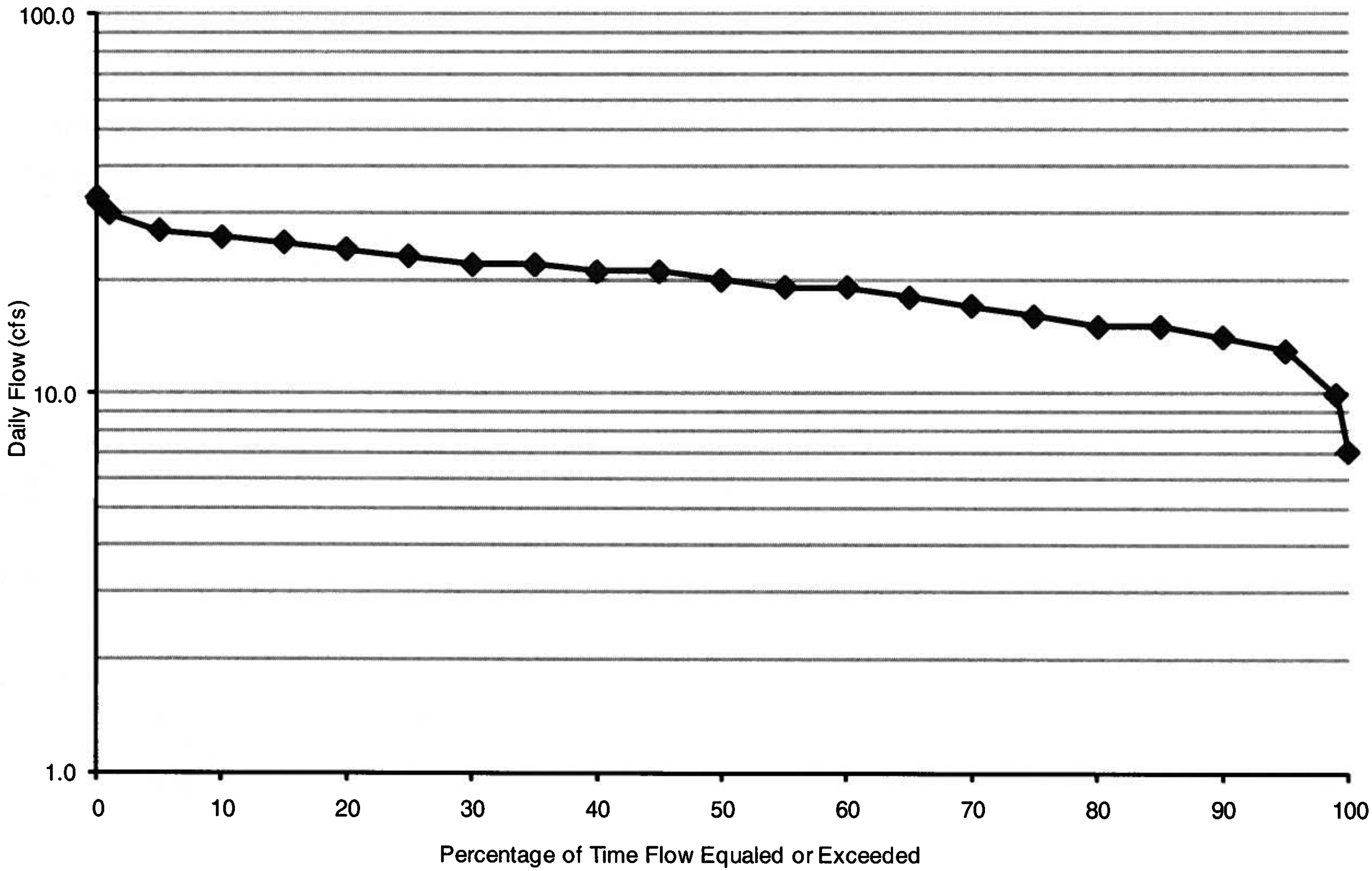


Figure 52. Median, 25th and 75th percentile median monthly mean flows for the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and pipe data for water years 1991-2001.

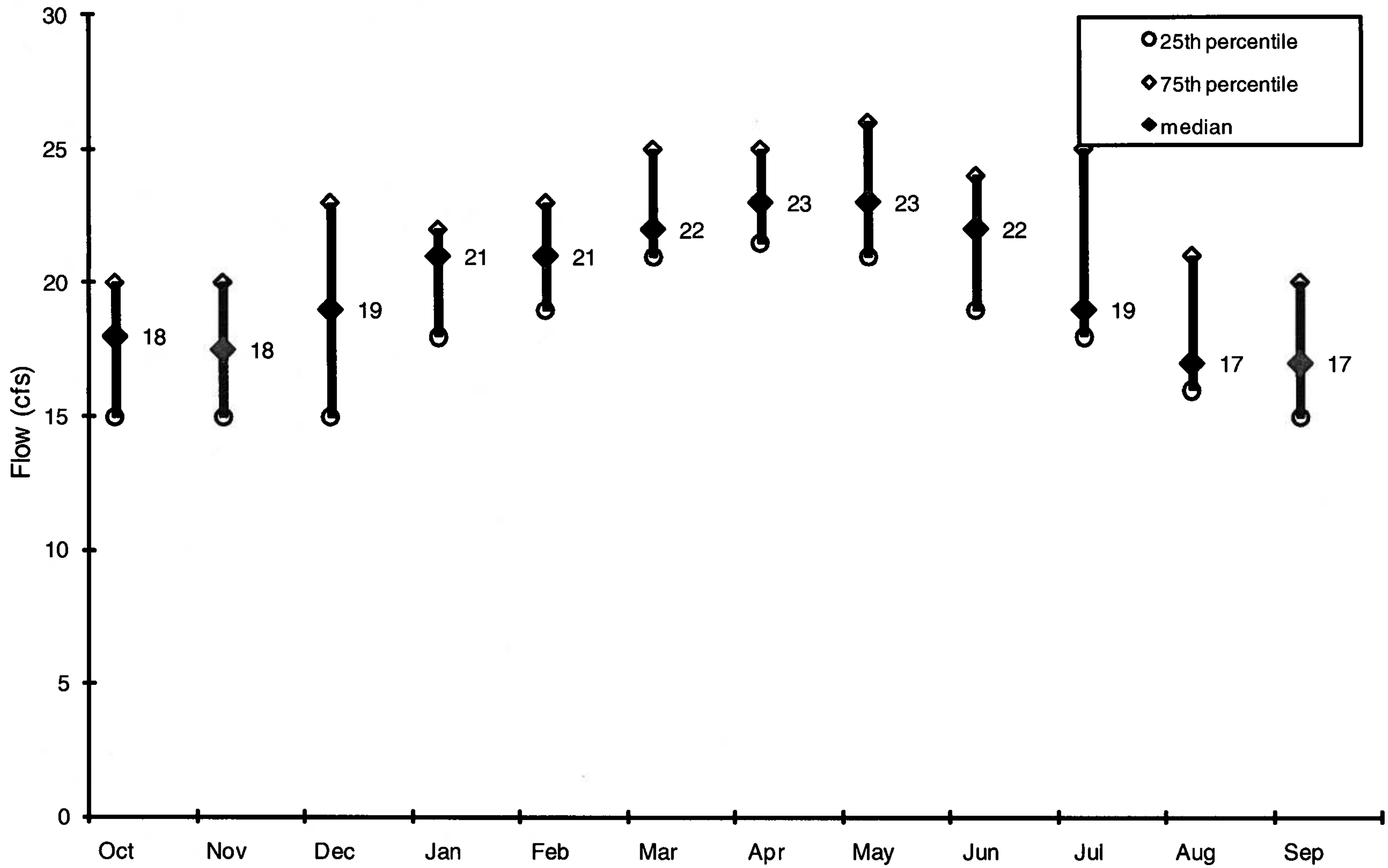
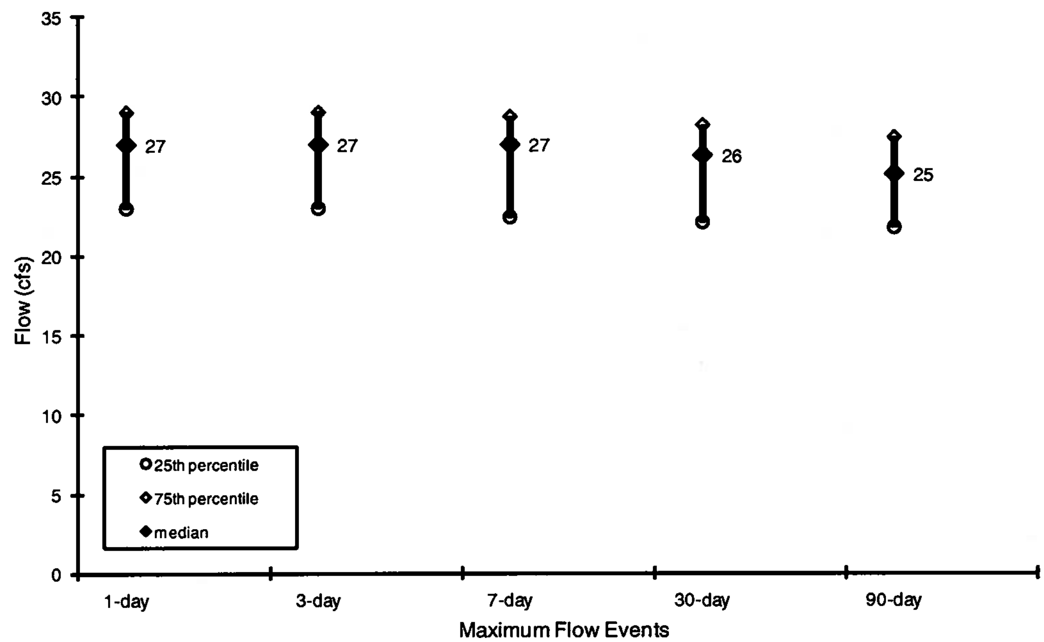


Figure 53. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-d a)maximum annual flows and b) minimum annual flows the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and pipe data for water years 1991-2001.

a)



b)

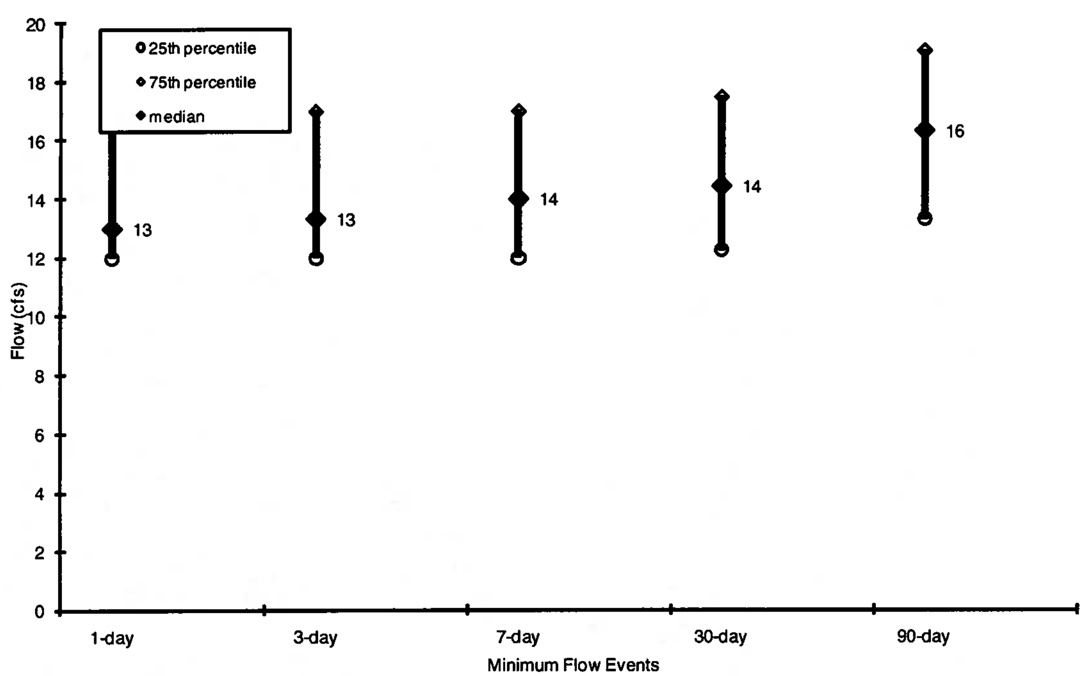


Figure 54. 7-day low flow recurrence interval for the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and pipe data for water years 1991-2001.

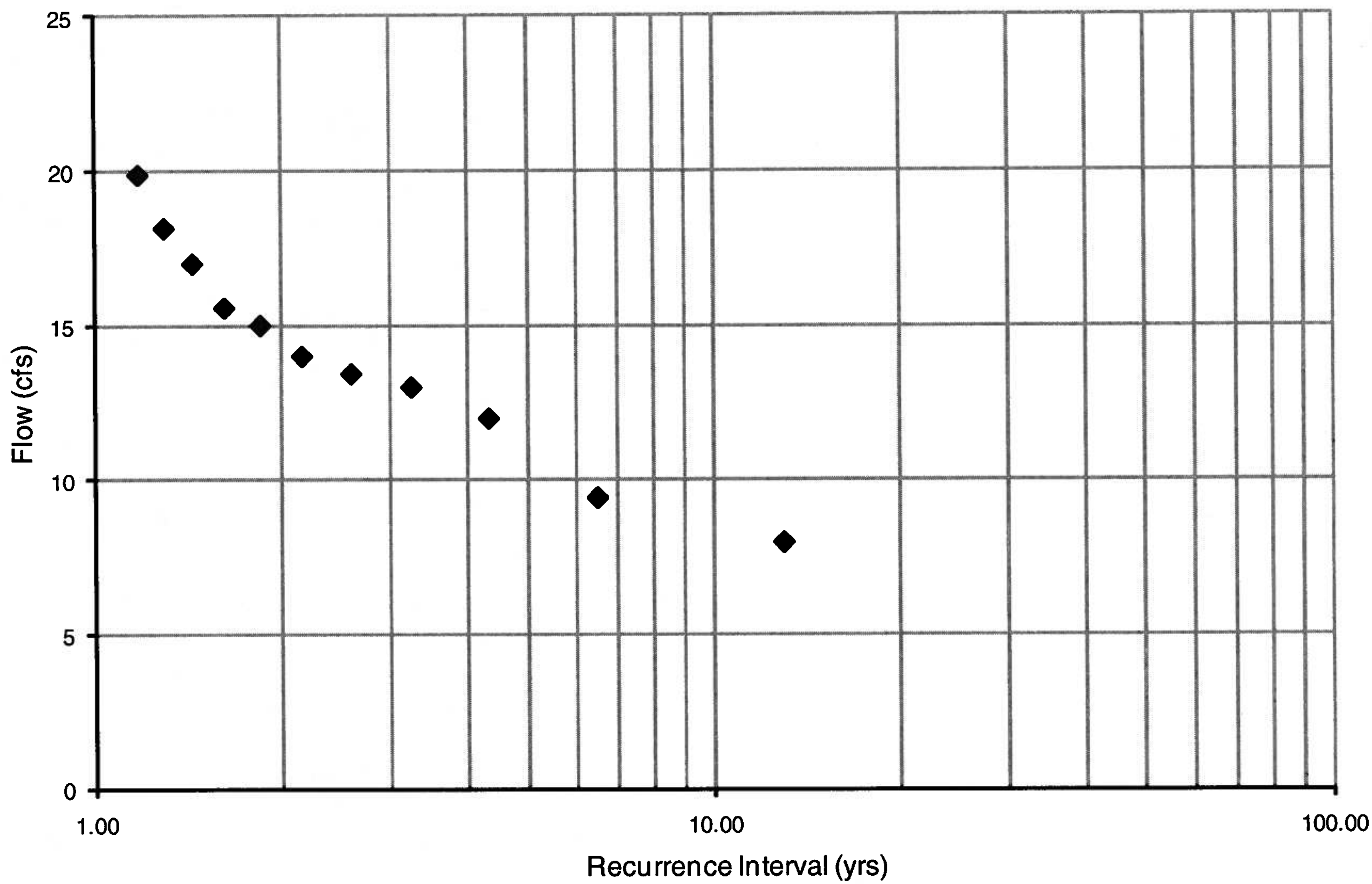


Figure 55. Median, 25th and 75th percentile monthly low flow values for the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and pipe data for water years 1991-2001.

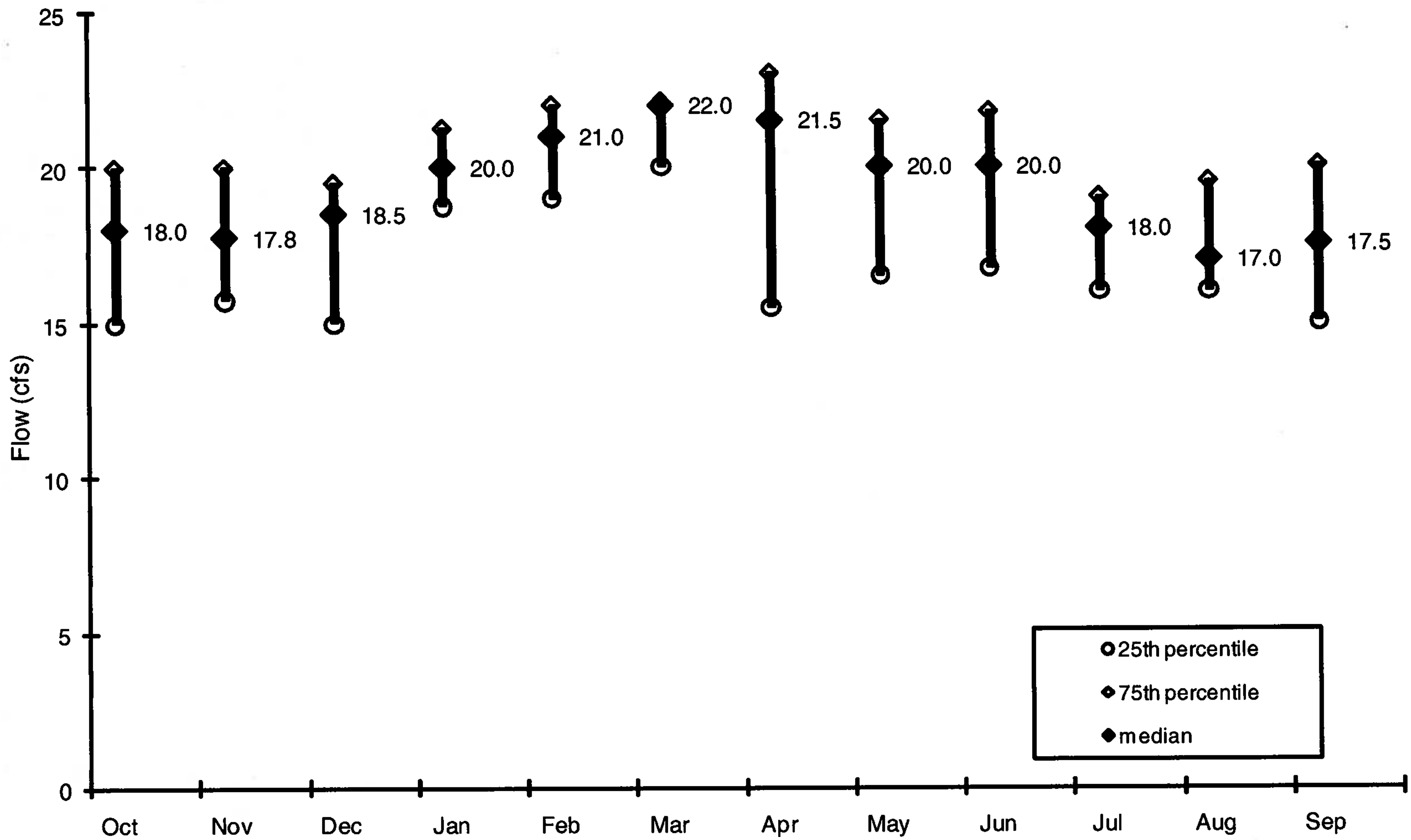


Figure 56. Extreme low flow event information for the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and pipe data for water years 1991-2001. a) date of occurrence for the first event, b) annual mean magnitude c) annual mean duration and d) annual mean frequency.

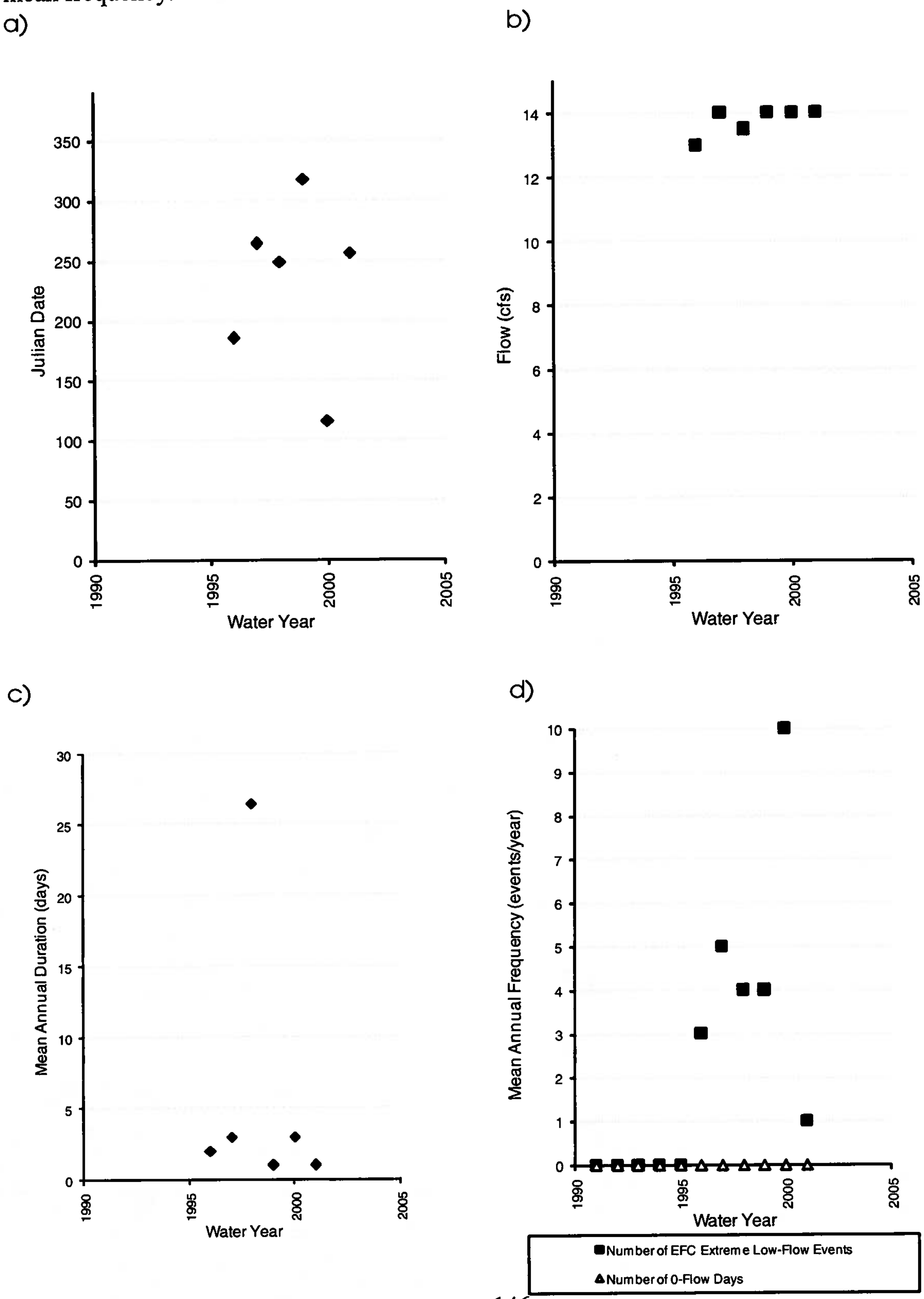


Figure 57. Annual base flow index for the Byrds Mill Spring gage near Fittstown, OK. The graph is based on combined stream and springflow data for water years 1991-2001.

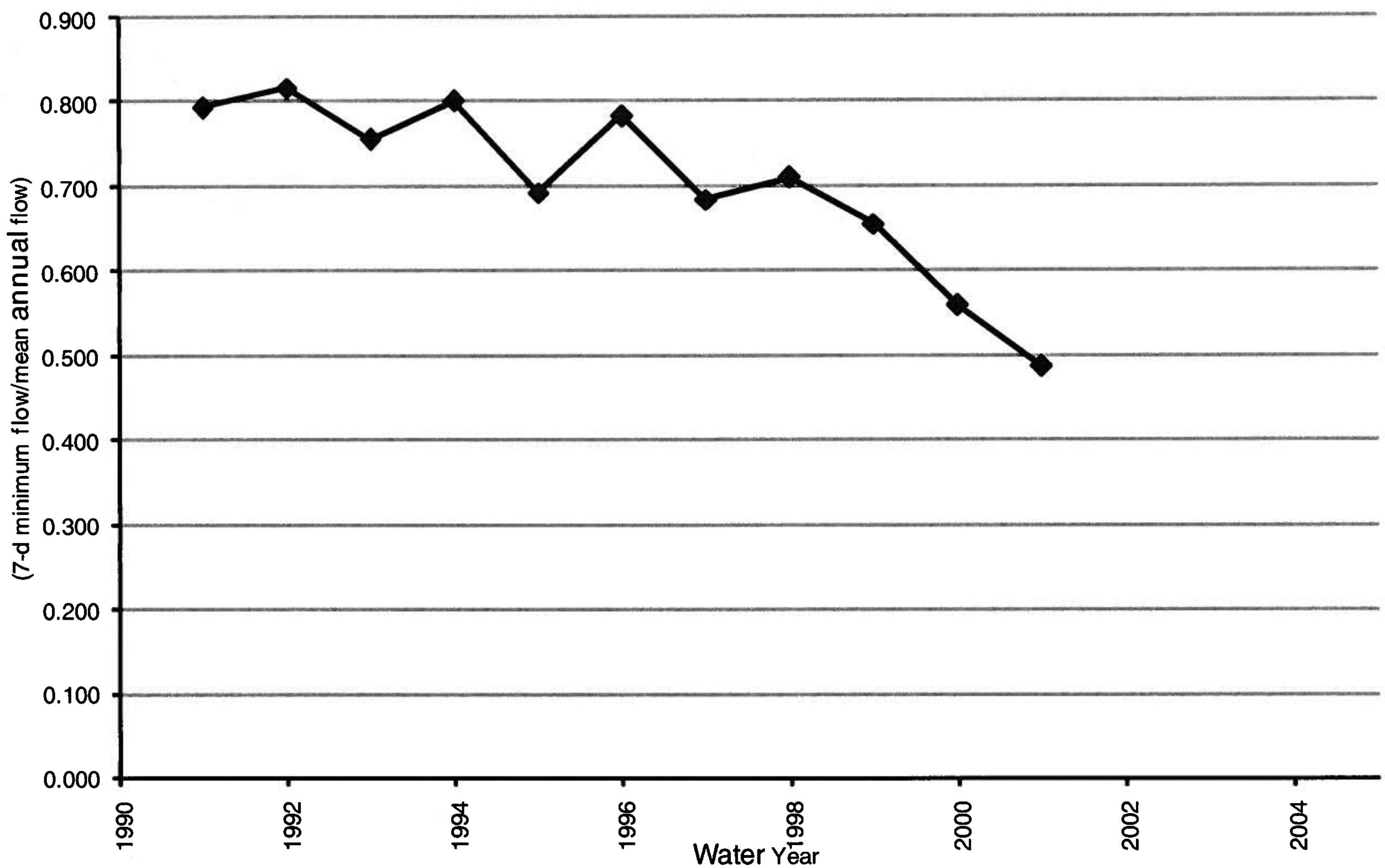
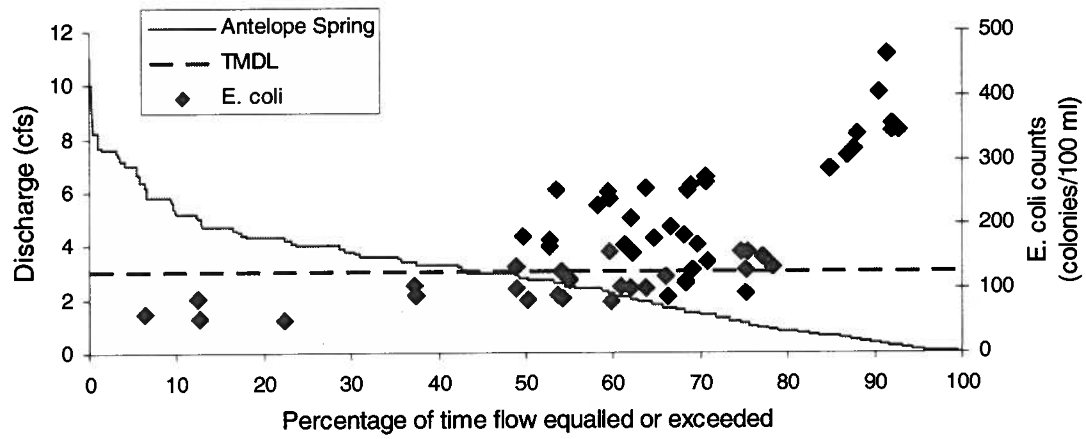
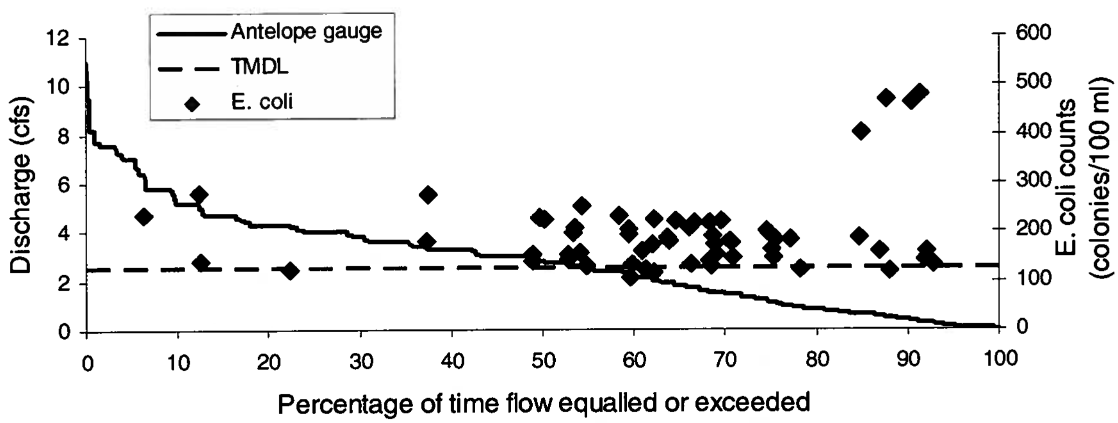


Figure 58. Flow duration at Antelope Spring gage near Sulphur, OK and *E. coli* TMDL exceedence using geometric means at a) Little Niagara, b) Bear Falls and c) Panther Falls.

a)



b)



c)

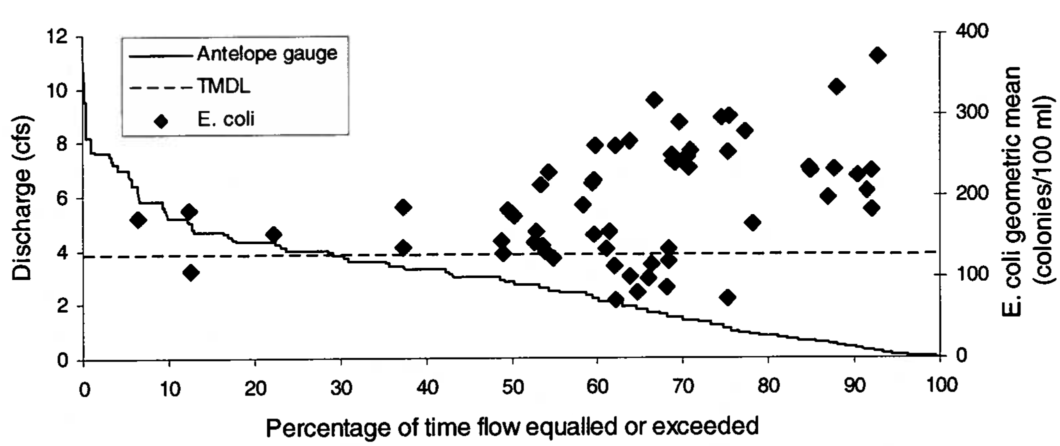


Figure 59. Flow duration at Rock Creek gage near Sulphur, OK and *E. coli* TMDL exceedence at Black Sulphur Springs using geometric means.

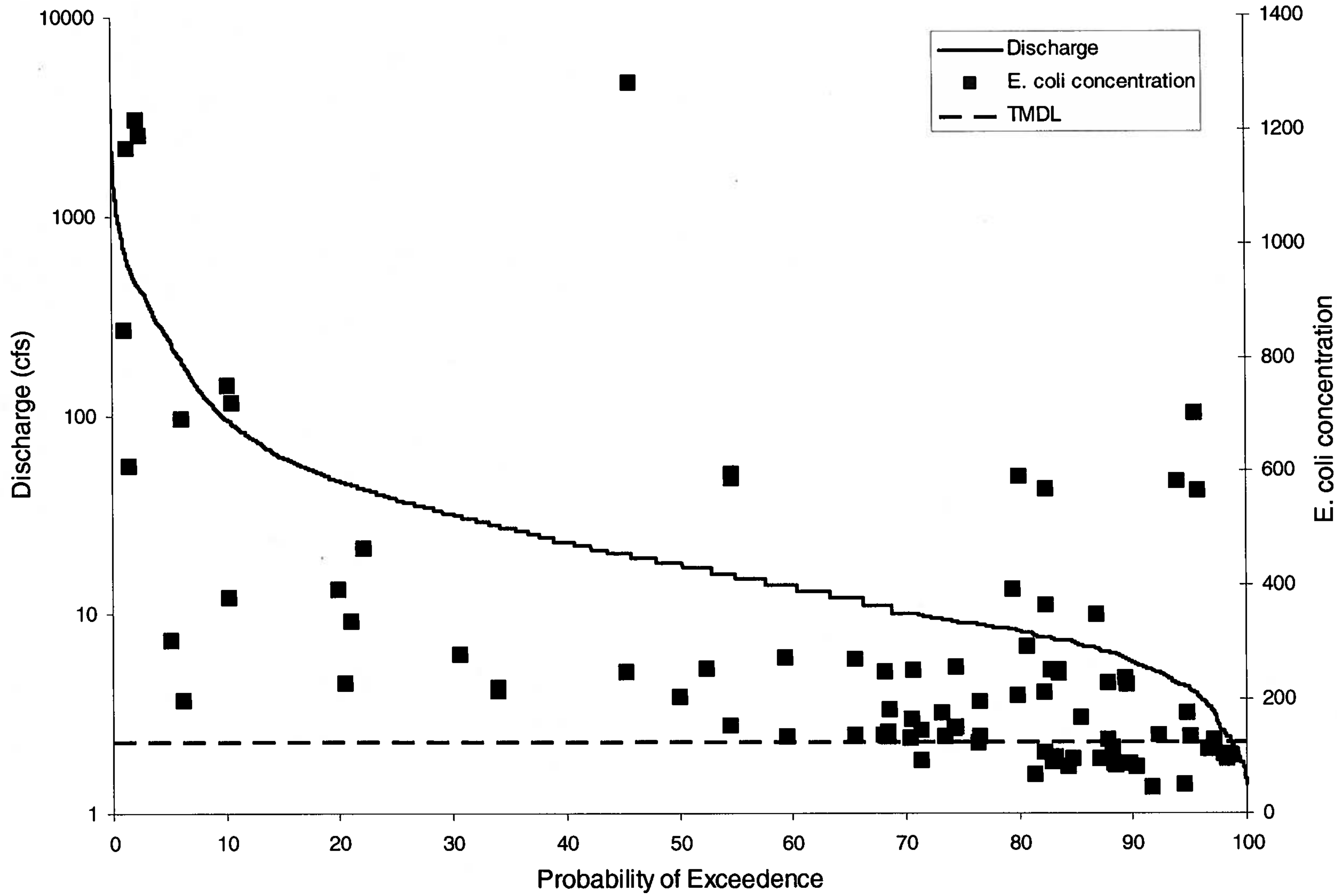


Figure 60. Flow duration curve for mean daily flows for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

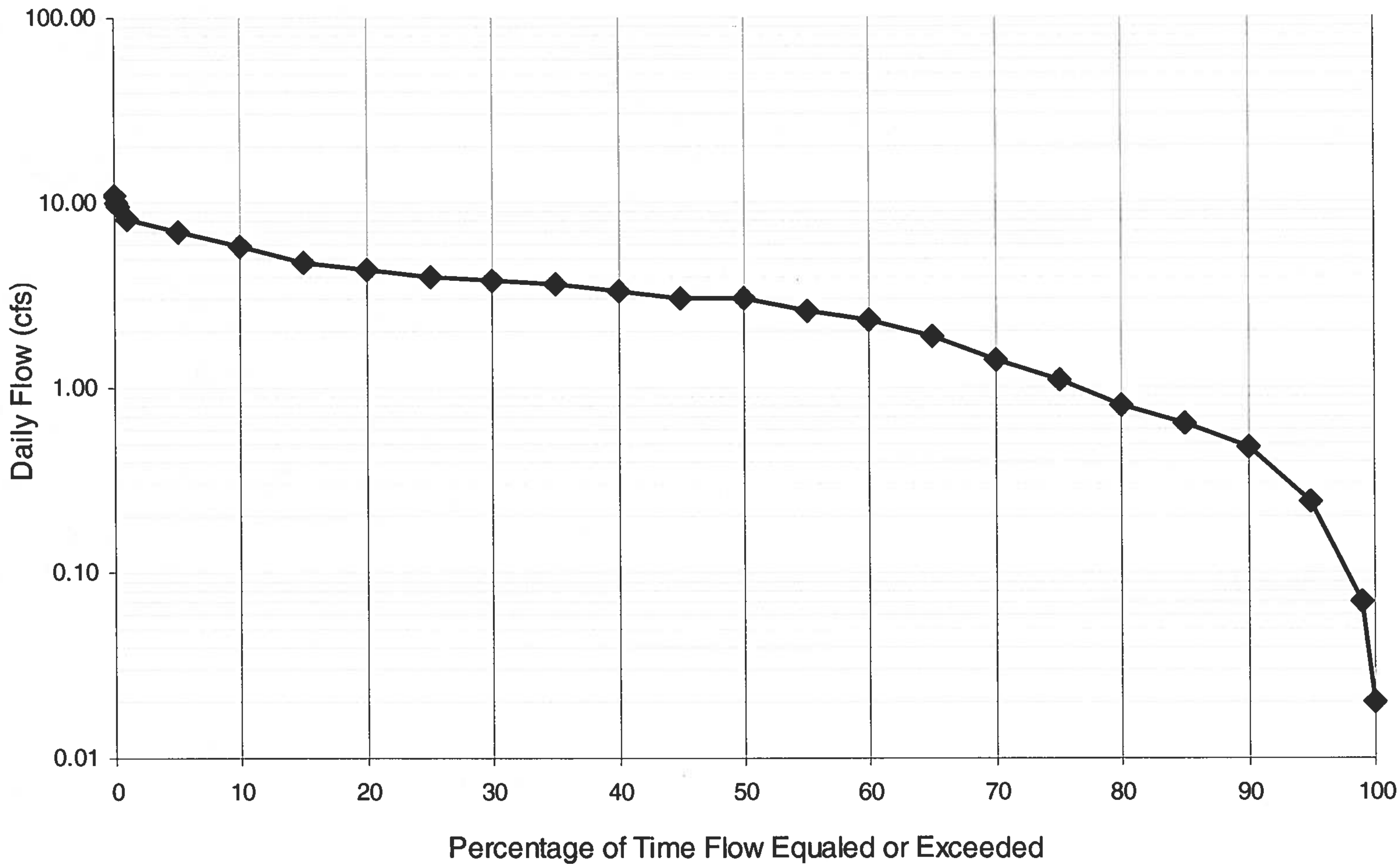


Figure 61. Median, 25th and 75th percentile values for mean monthly flows for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

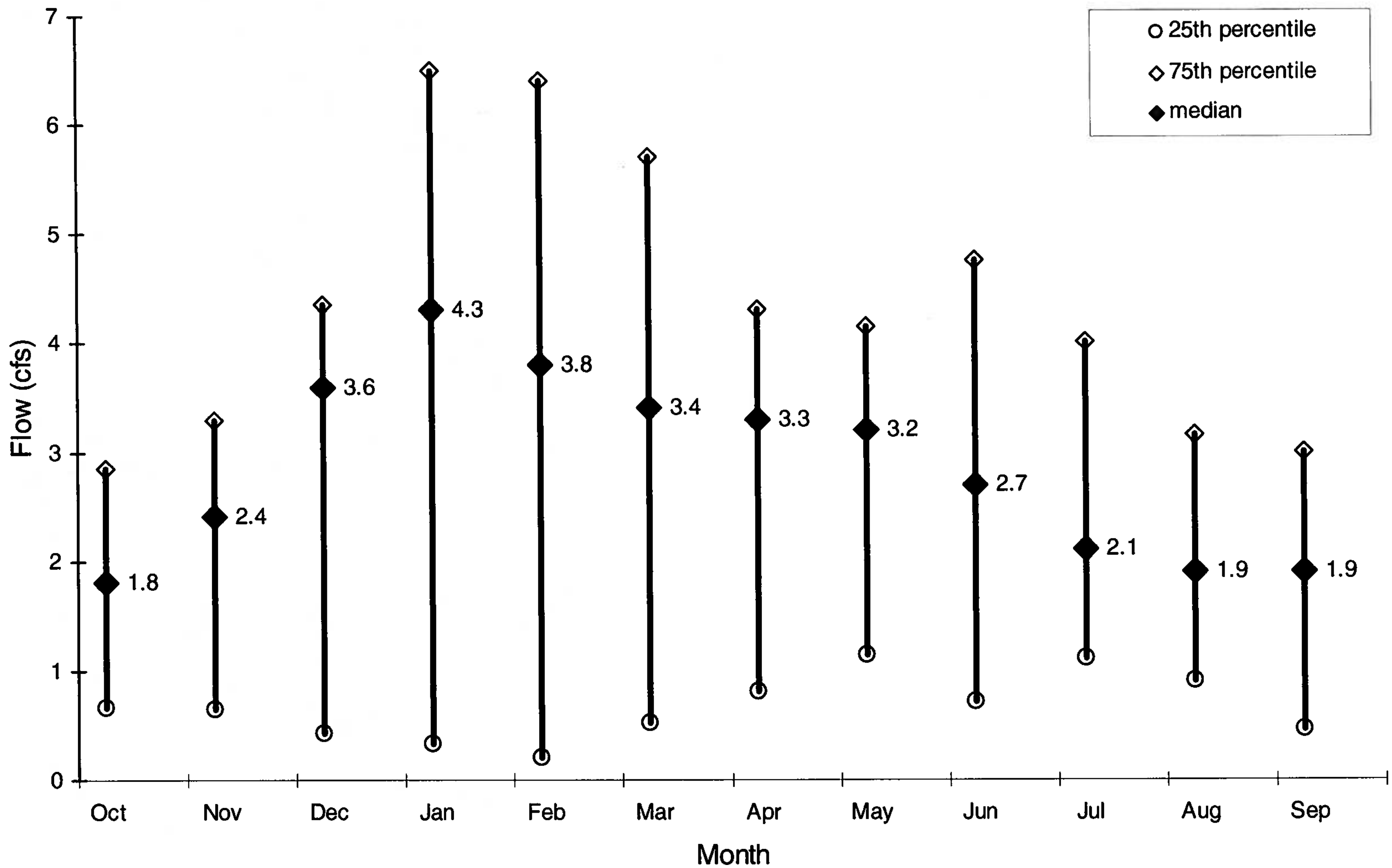
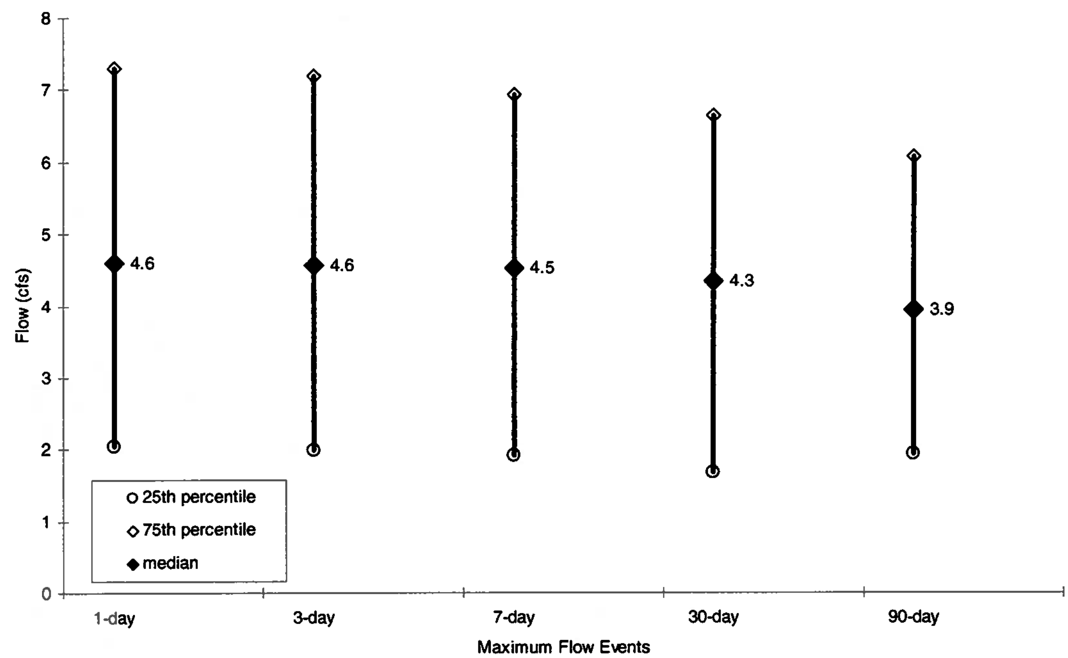


Figure 62. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-d maximum annual flows (a) and minimum flows (b) for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

a)



b)

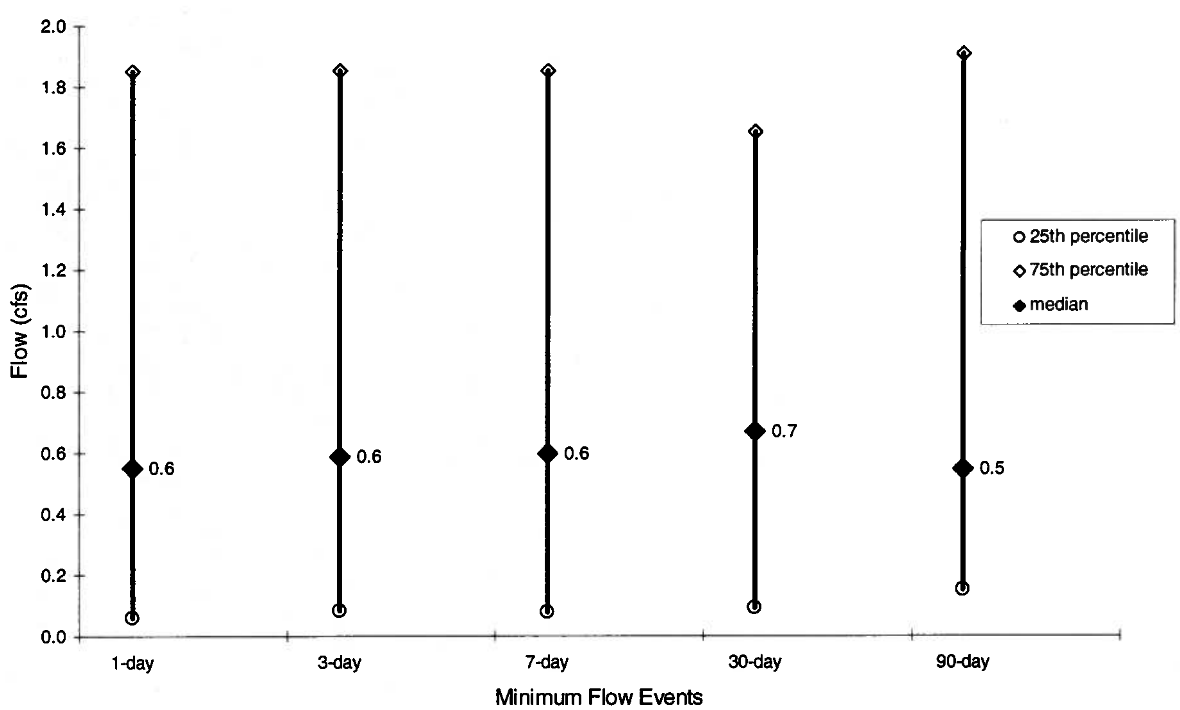


Figure 63. 7-day low flow recurrence interval for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

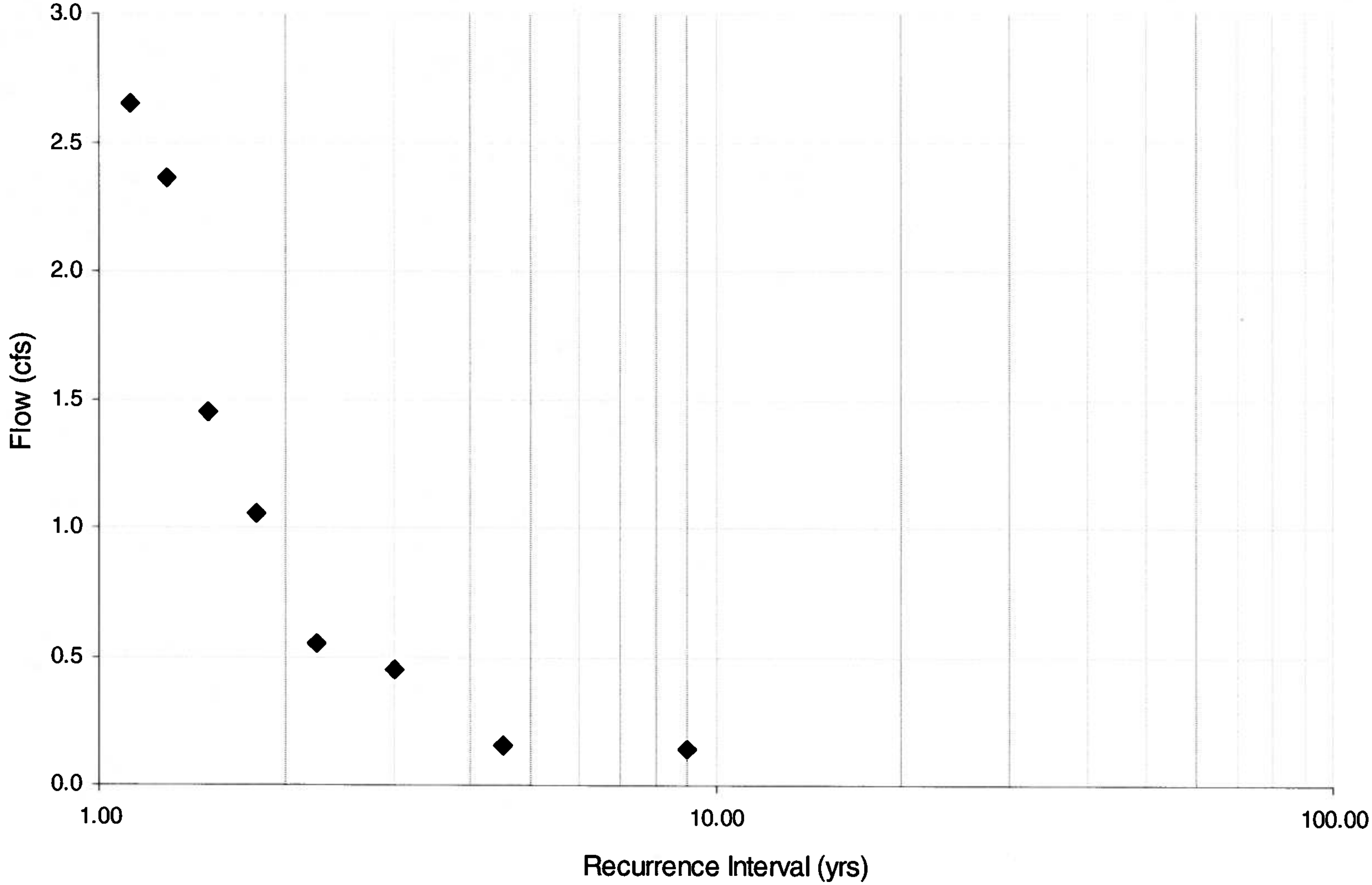


Figure 64. Median, 25th and 75th percentile values of annual occurrence frequency and duration of low- and high-flow pulses for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

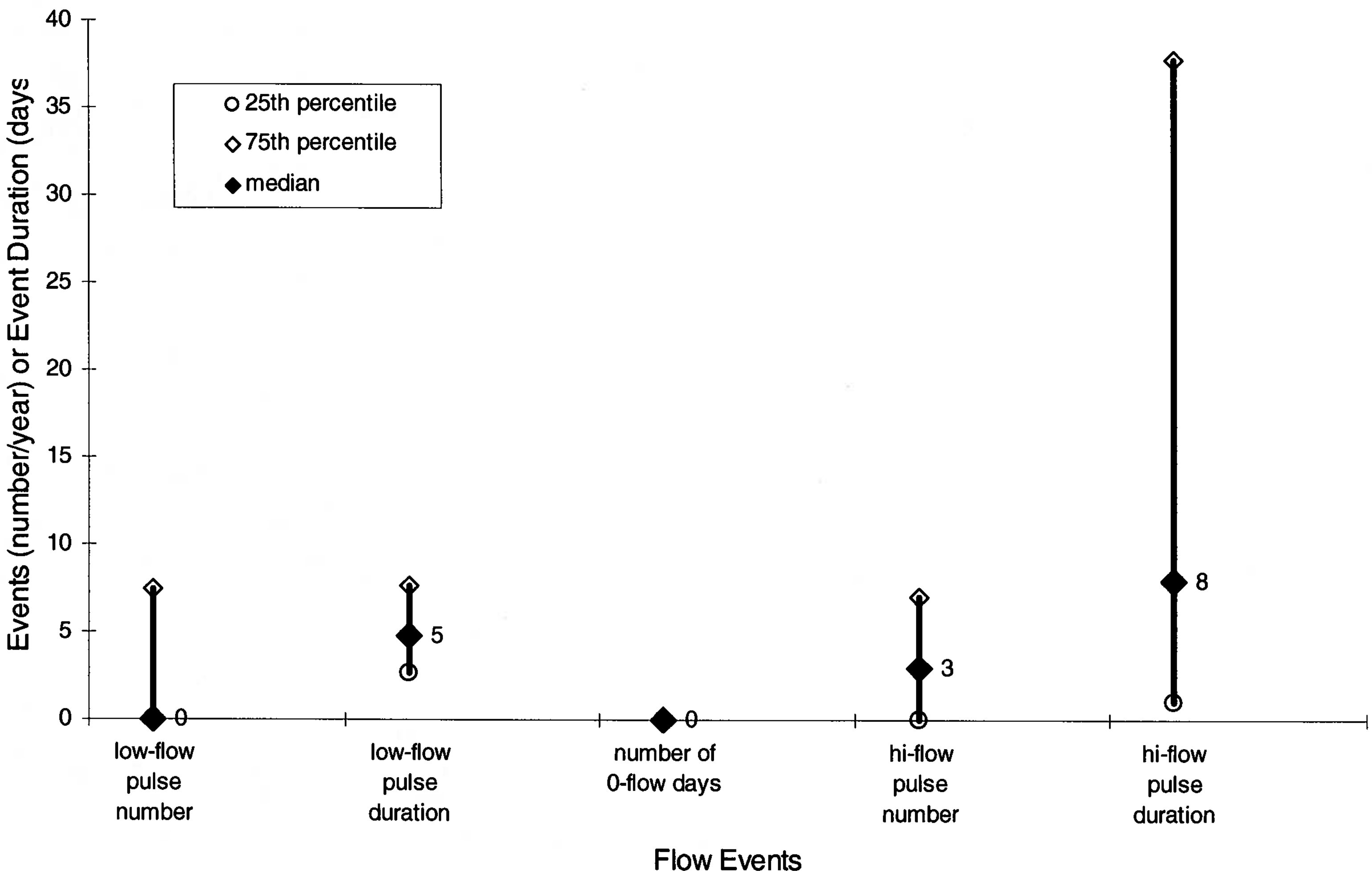


Figure 65.Median, 25th and 75th percentile monthly low flows for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

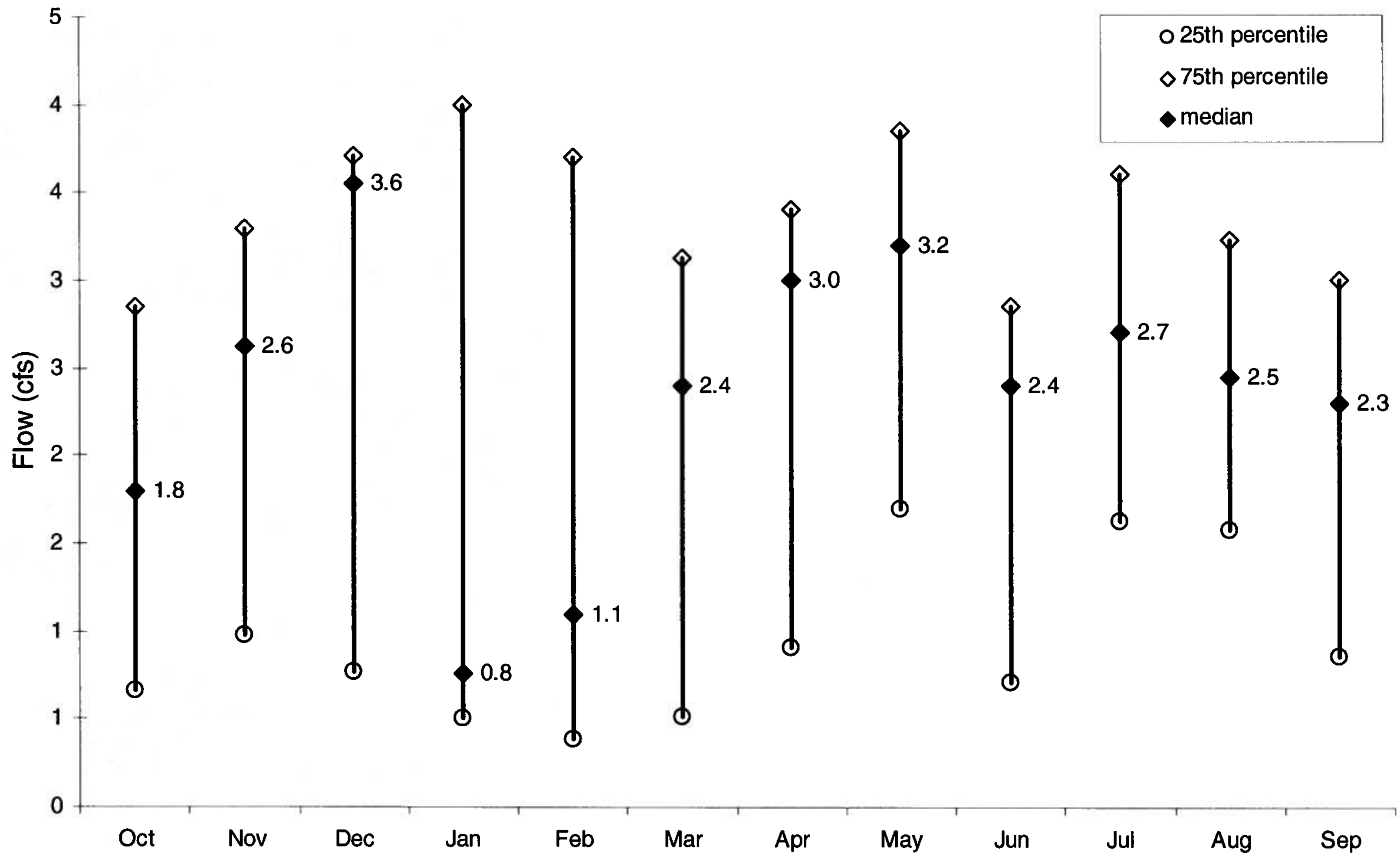


Figure 66. Extreme low flow event information for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007. a) date of occurrence for the first event, b) annual mean magnitude c) annual mean duration and d) annual mean frequency.

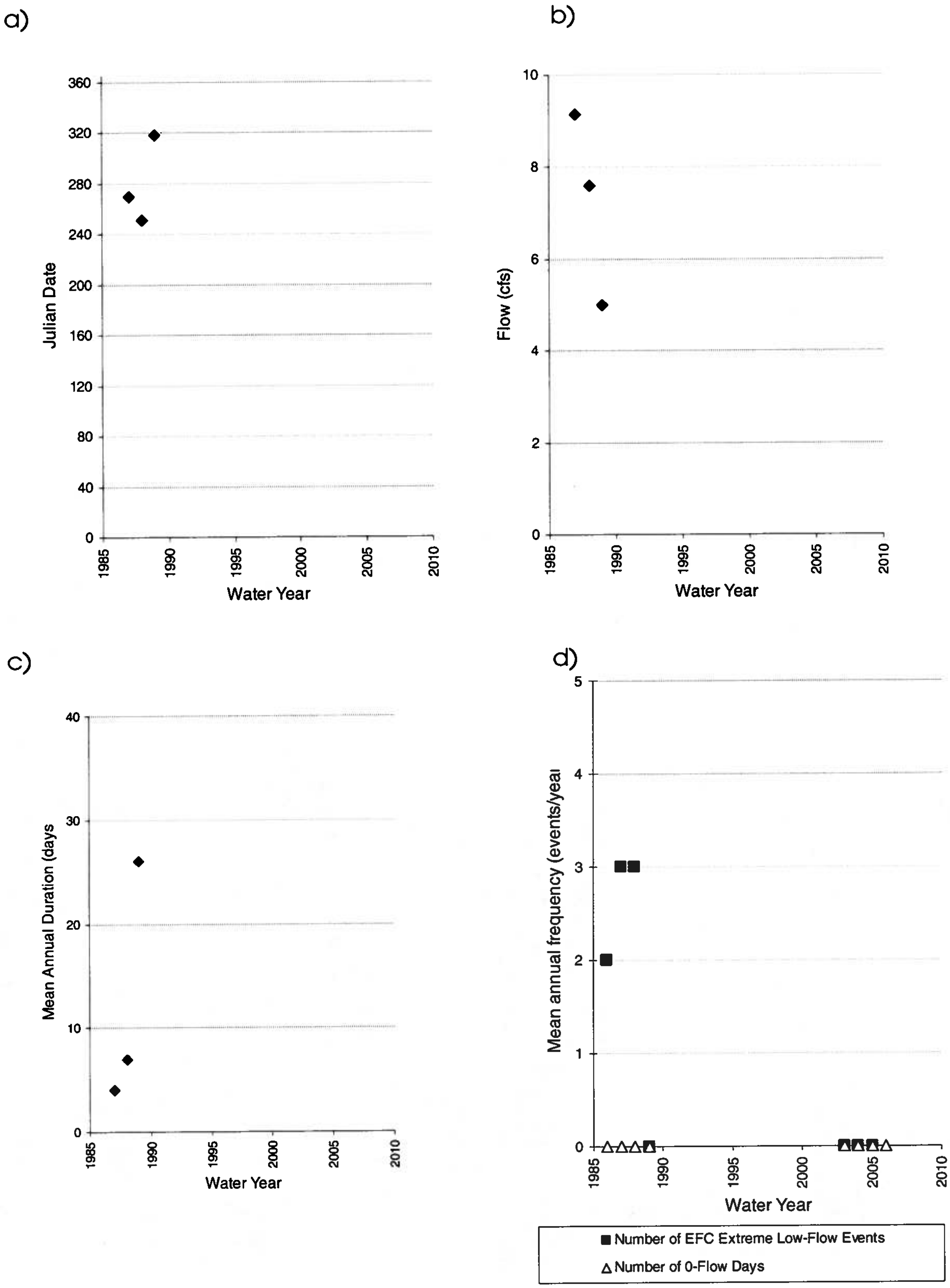


Figure 67. Median annual base flow index for the Antelope Spring gage at Sulphur, OK. The period of record includes measured flow values from water years 1986 through 1989 and 2002 through 2007.

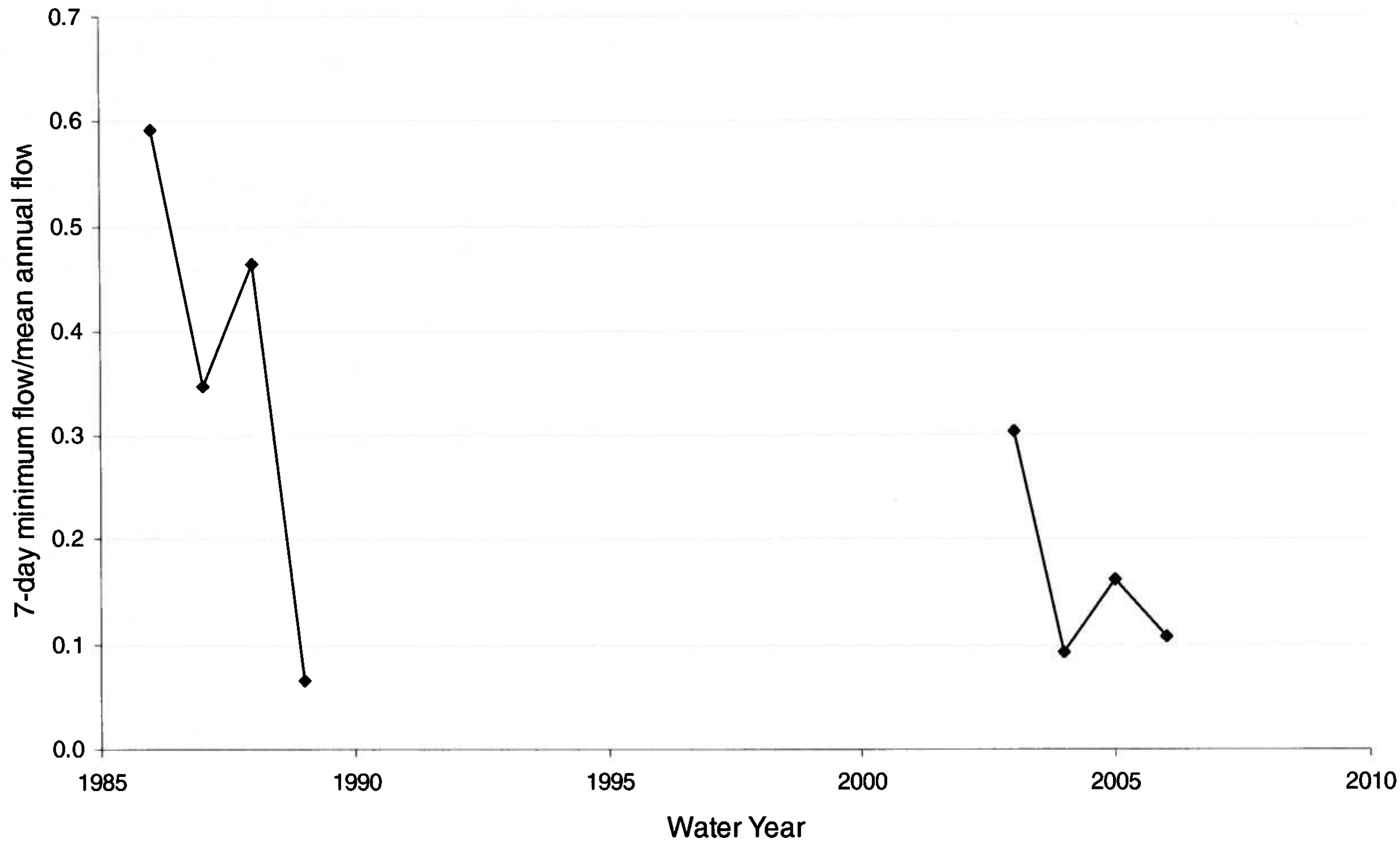


Figure 68. Flow duration curve for mean daily flows for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.

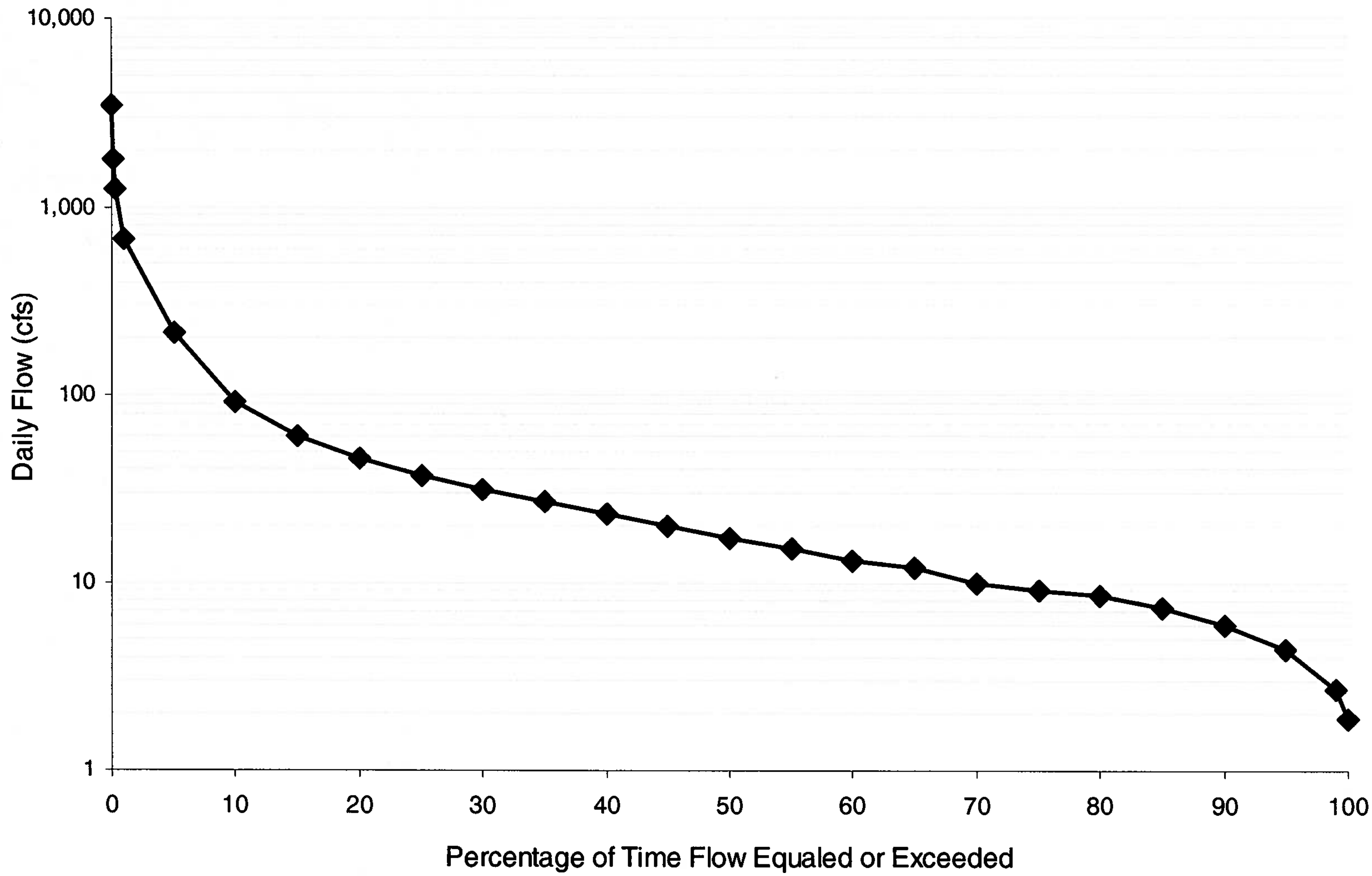


Figure 69. Median, 25th and 75th percentile values for mean monthly flows for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.

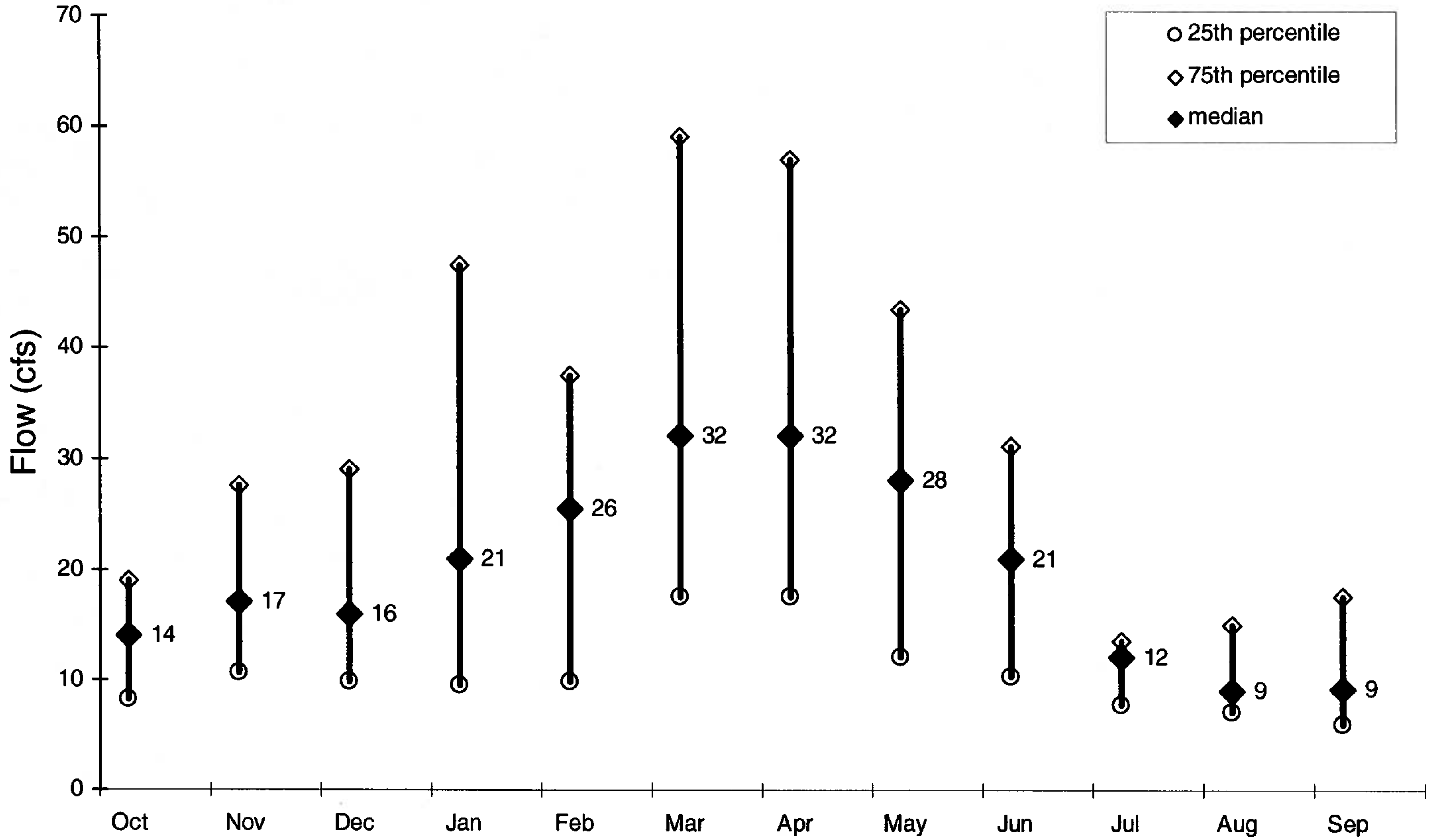
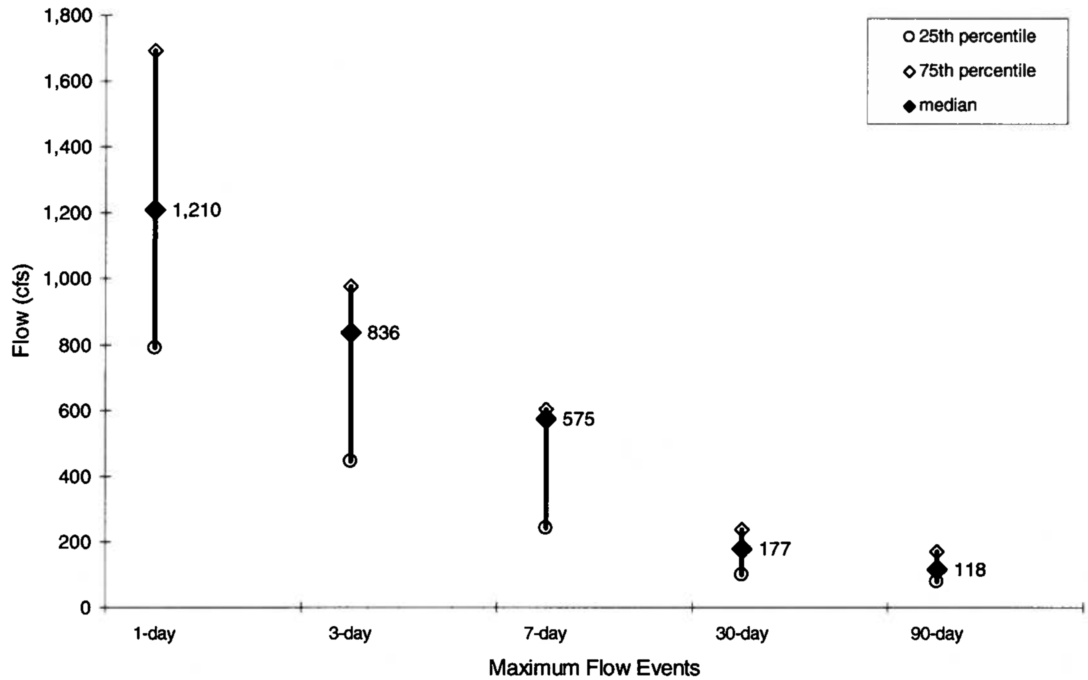


Figure 70. Median, 25th and 75th percentile 1-, 3-, 7-, 30-, and 90-d maximum annual flows (a) and minimum flows (b) for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.

a)



b)

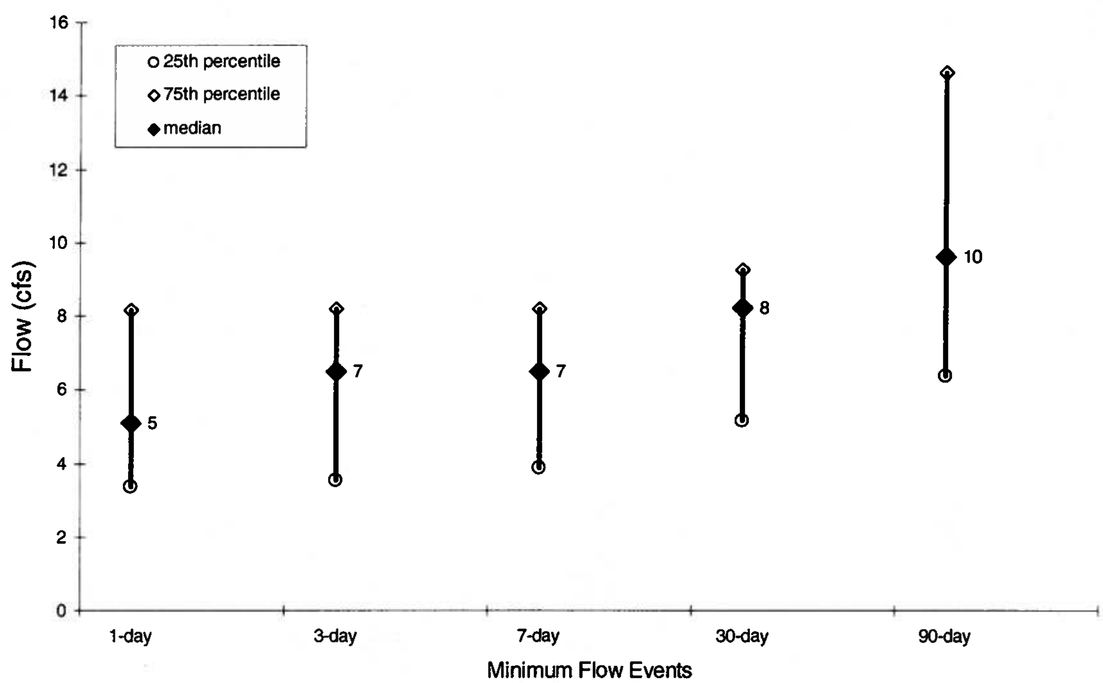


Figure 72. 7-day low flow recurrence interval for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.

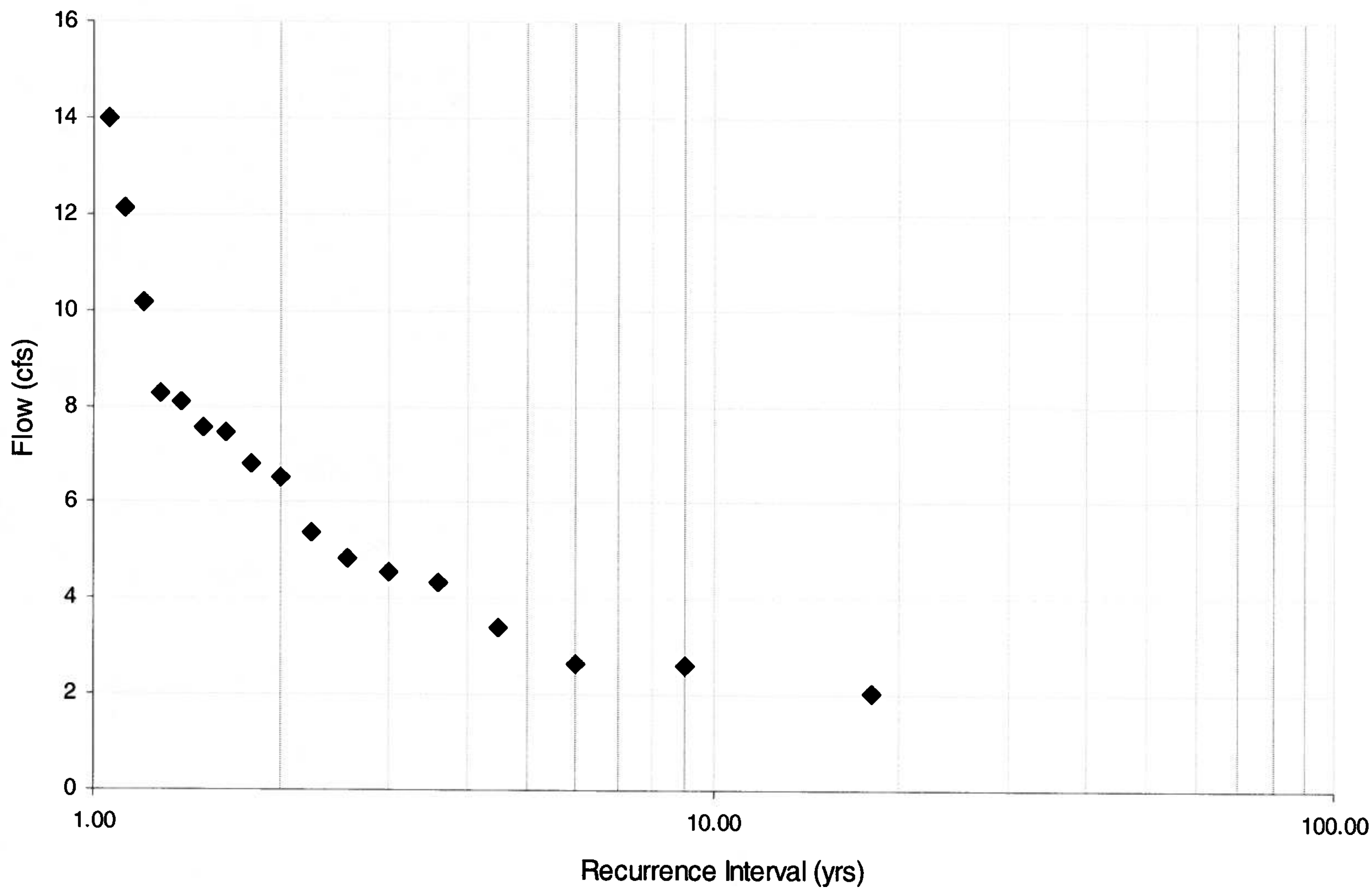


Figure 72. Median, 25th and 75th percentile values of annual occurrence frequency and duration of low- and high-flow pulses for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.

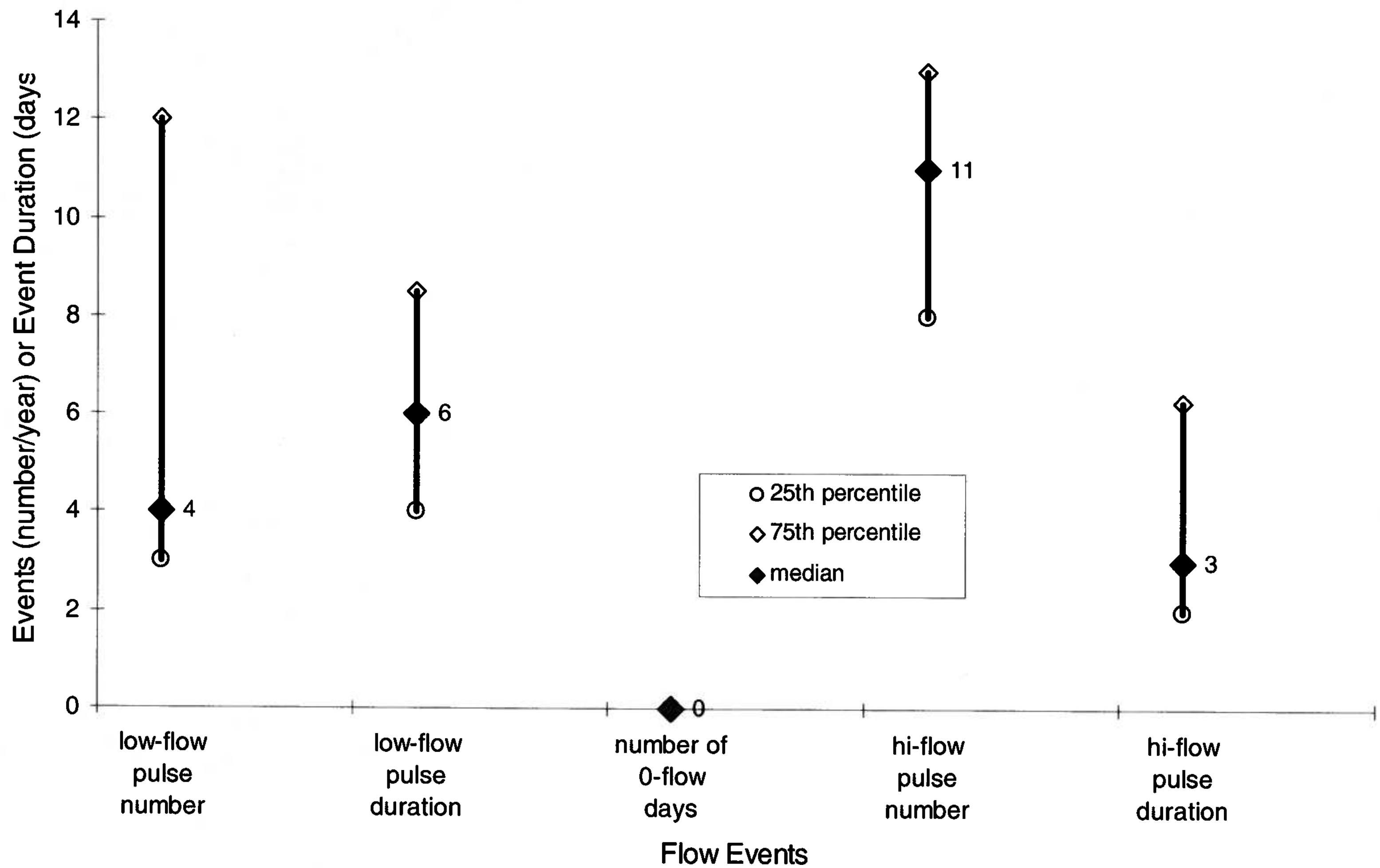


Figure 73. Median, 25th and 75th percentile monthly low flows for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.

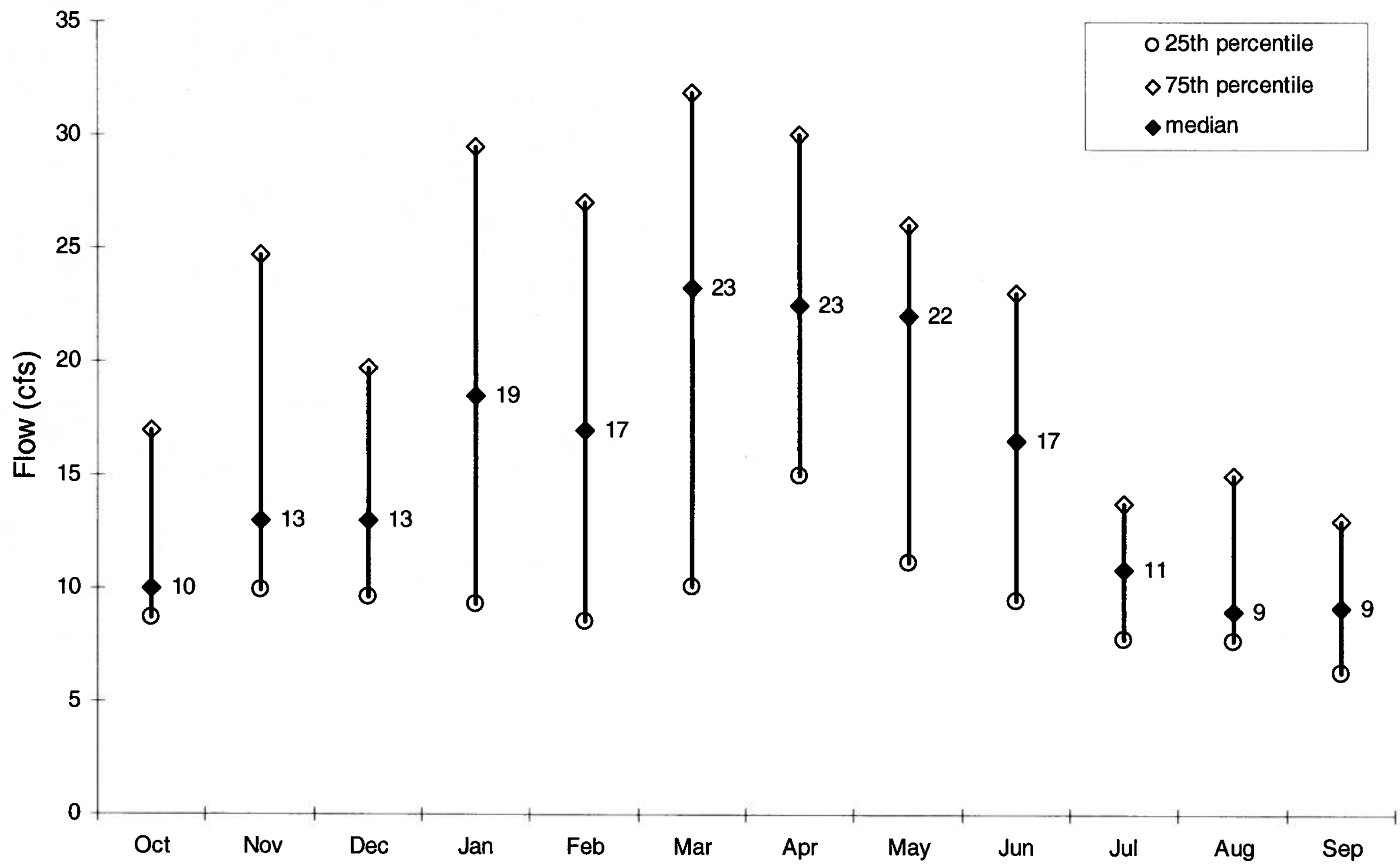


Figure 74. Extreme low flow event information for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006. a) date of occurrence for the first event, b) annual mean magnitude c) annual mean duration and d) annual mean frequency.

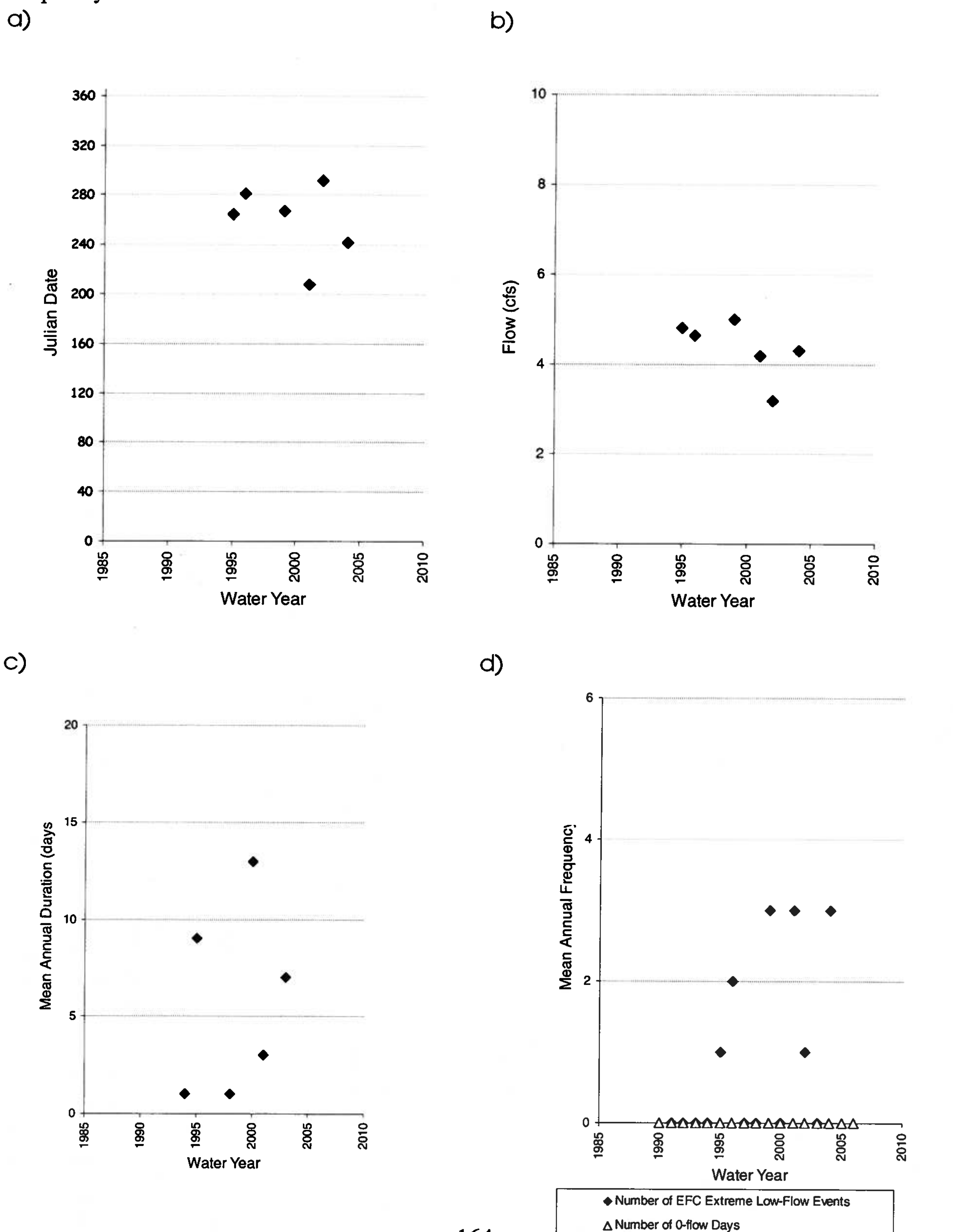


Figure 75. Median annual base flow index for Rock Creek at Sulphur, OK. The period of record includes measured flow values from water years 1990 through 2006.