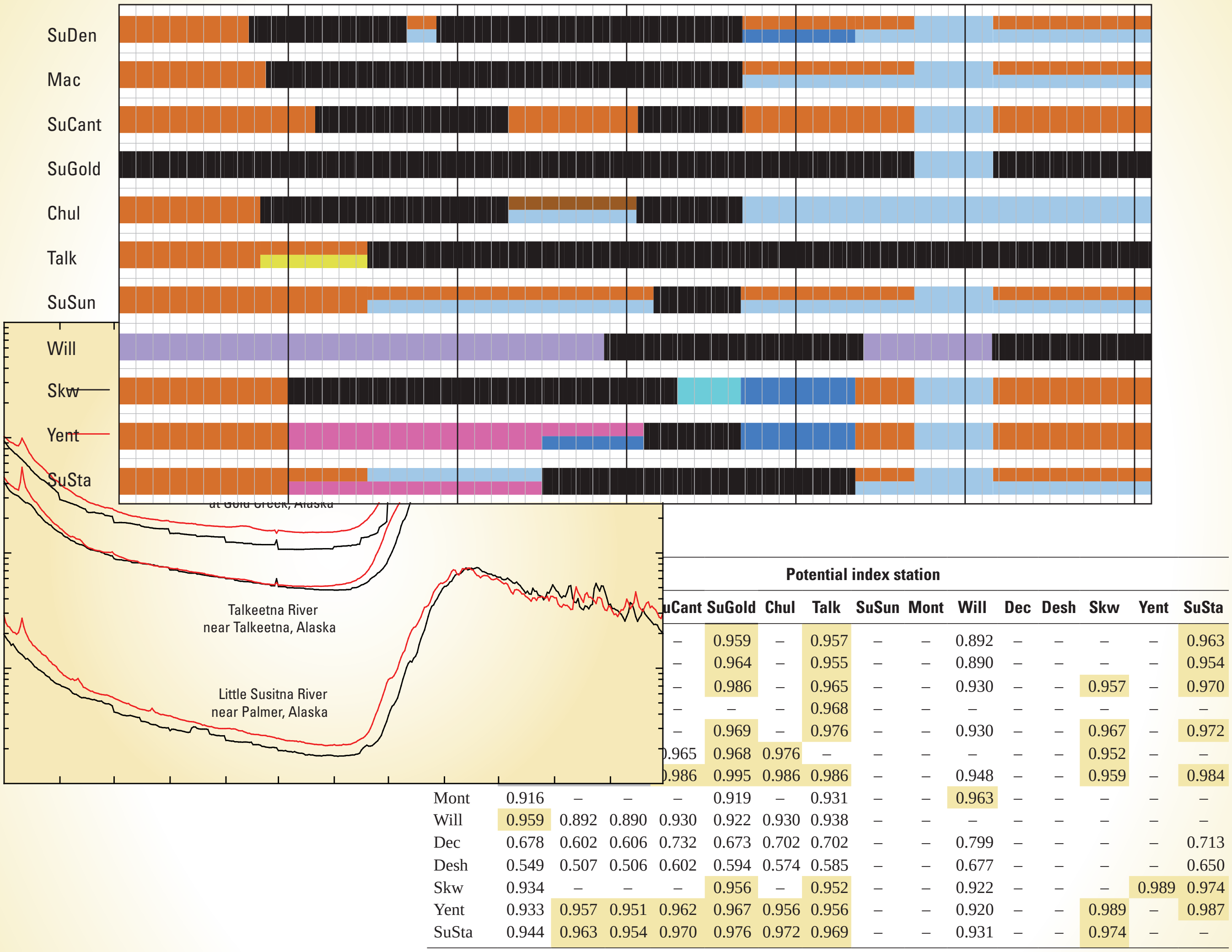
Prepared in cooperation with the Alaska Energy Authority

Streamflow Record Extension for Selected Streams in the Susitna River Basin, Alaska



							Potential index station								
				uCant	SuGold	Chul	Talk	SuSun	Mont	Will	Dec	Desh	Skw	Yent	SuSta
				–	0.959	–	0.957	–	–	0.892	–	–	–	–	0.963
				–	0.964	–	0.955	–	–	0.890	–	–	–	–	0.954
				–	0.986	–	0.965	–	–	0.930	–	–	0.957	–	0.970
				–	–	–	0.968	–	–	–	–	–	–	–	–
				–	0.969	–	0.976	–	–	0.930	–	–	0.967	–	0.972
				.965	0.968	0.976	–	–	–	–	–	–	0.952	–	–
				.986	0.995	0.986	0.986	–	–	0.948	–	–	0.959	–	0.984
Mont	0.916	–	–	–	0.919	–	0.931	–	–	0.963	–	–	–	–	–
Will	0.959	0.892	0.890	0.930	0.922	0.930	0.938	–	–	–	–	–	–	–	–
Dec	0.678	0.602	0.606	0.732	0.673	0.702	0.702	–	–	0.799	–	–	–	–	0.713
Desh	0.549	0.507	0.506	0.602	0.594	0.574	0.585	–	–	0.677	–	–	–	–	0.650
Skw	0.934	–	–	–	0.956	–	0.952	–	–	0.922	–	–	–	0.989	0.974
Yent	0.933	0.957	0.951	0.962	0.967	0.956	0.956	–	–	0.920	–	–	0.989	–	0.987
SuSta	0.944	0.963	0.954	0.970	0.976	0.972	0.969	–	–	0.931	–	–	0.974	–	–

Scientific Investigations Report 2012–5210

U.S. Department of the Interior
U.S. Geological Survey

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KEN SALAZAR, Secretary

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U.S. Geological Survey, Reston, Virginia: 2012

Suggested citation:
Curran, J.H., 2012, Streamflow record extension for selected streams in the Susitna River Basin, Alaska: U.S. Geological Survey Scientific Investigations Report 2012–5210, 36 p.

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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NAVD 29).

Horizontal coordinate information is referenced to the North American Vertical Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

Abbreviation or Acronym	Definition
AEA	Alaska Energy Authority
KTRL	Kendall-Theil Robust Line
LOWESS	locally-weighted scatterplot smoothing
MOVE	Maintenance of Variance-Extension
MSE	mean square error
NSE	Nash-Suttcliffe efficiency
NWIS	National Water Information System
PDO	Pacific Decadal Oscillation
RMSE	root mean square error
USGS	U.S. Geological Survey
WY	water year

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By Janet H. Curran

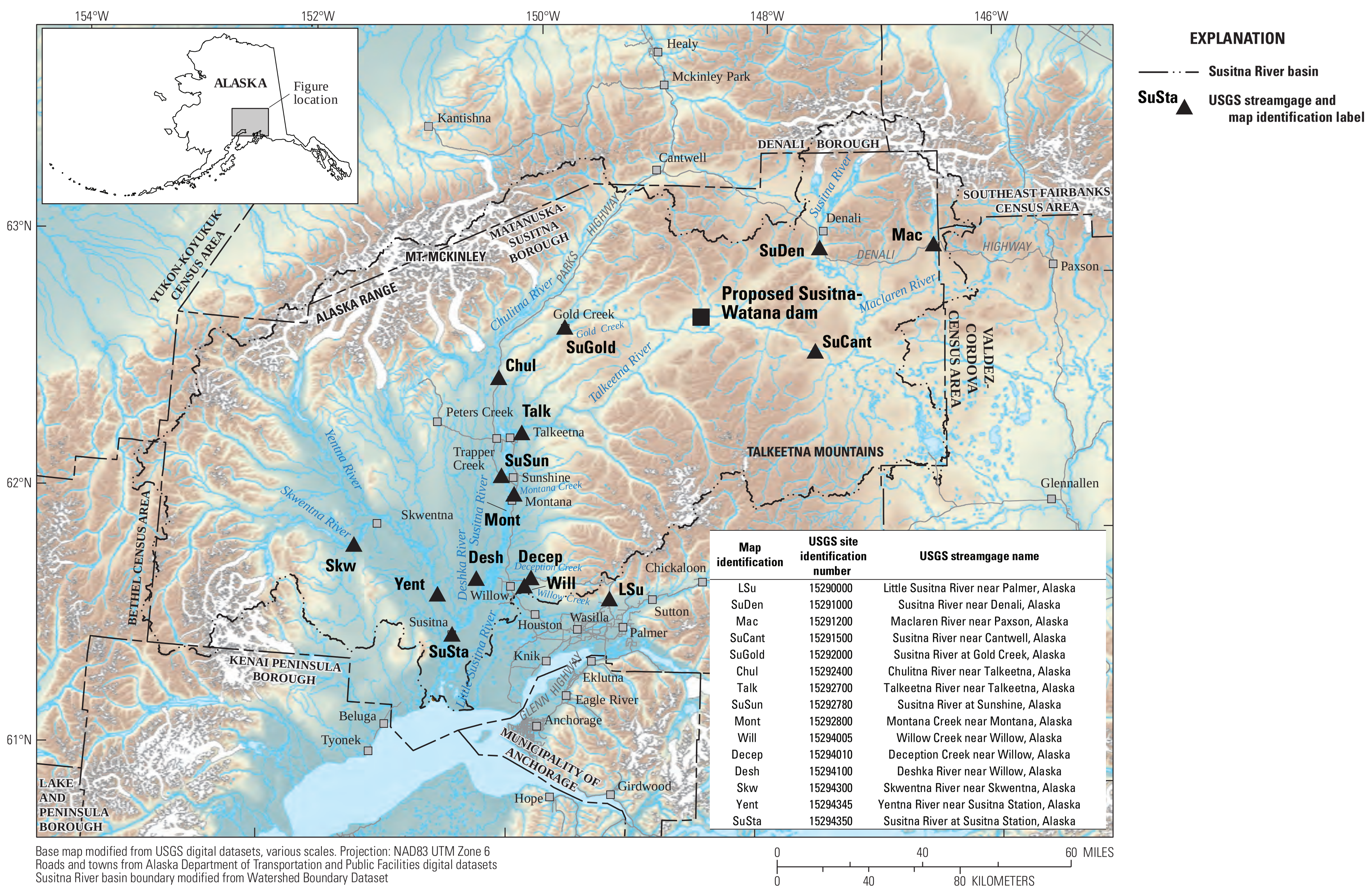
Abstract

Daily streamflow records for water years 1950–2010 in the Susitna River Basin range in length from 4 to 57 years, and many are distributed within that period in a way that might not adequately represent long-term streamflow conditions. Streamflow in the basin is affected by the Pacific Decadal Oscillation (PDO), a multi-decadal climate pattern that shifted from a cool phase to a warm phase in 1976. Records for many streamgages in the basin fell mostly within one phase of the PDO, such that monthly and annual statistics from observed records might not reflect streamflow conditions over a longer period. Correlations between daily discharge values sufficed for extending streamflow records at 11 of the 14 streamgages in the basin on the basis of relatively long-term records for one or more of the streamgages within the basin, or one outside the basin, that were defined as index stations. Streamflow at the index stations was hydrologically responsive to glacier melt and snowmelt, and correlated well with flow from similar high-elevation, glaciated basins, but flow in low-elevation basins without glaciers could not be correlated to flow at any of the index stations. Kendall-Theil Robust Line multi-segment regression equations developed for one or more index stations were used to extend daily discharge values to the full 61-year period for all 11 streamgages. Monthly and annual statistics prepared for the extended records show shifts in timing of breakup and freeze-up and magnitude of snowmelt peaks largely predicted by the PDO phase.

Introduction

In 2010, the Alaska Energy Authority (AEA) declared the intent to pursue development of a large hydroelectric project on the Susitna River, Alaska (fig. 1) to meet projected energy needs for southcentral and interior Alaska. The Susitna-Watana Project entered the federal licensing process in 2011. The AEA proposes construction of a single dam on the river near Watana Creek, about 90 river miles northeast of Talkeetna, at the same location as the upstream-most of two sites proposed for a hydroelectric project pursued from the early 1980s until 1986 (Alaska Energy Authority, 2011). The proposed Susitna-Watana dam would alter the natural flow of the Susitna River downstream of the dam site and replace it with a load-following operating regime that would increase winter flows to meet peak energy needs and decrease summer flows to refill the reservoir. This regulation would dampen the natural difference between low flows in the winter and high flows in the summer downstream of the dam site.

Designing and evaluating potential impacts of the proposed Susitna-Watana project required streamflow information beyond the observed streamflow values available for the U.S. Geological Survey (USGS) streamgages in the Susitna River Basin. An unbroken record of daily discharge values was needed for engineering purposes such as modeling the power generation capacity of the proposed dam and for environmental assessments such as the ecosystem response to changes in the timing and range of variability of altered flows. Natural variations in streamflow at an annual scale, coupled with known multi-decadal variations driven by the Pacific Decadal Oscillation (PDO) (Neal and others, 2002; Hodgkins, 2009), increase the need for the longest period of record possible to account for the inability of short records to represent long-term conditions. For the 61-year period from water year (WY) 1950 to WY 2010, the 14 USGS streamgages in the Susitna River Basin that capture daily discharge values have record lengths ranging from 4 to 57 years (fig. 2). Several of these records fall entirely within one phase of the PDO, resulting in a likely misrepresentation of long-term streamflow patterns.



Map identification	USGS site identification number	USGS streamgage name
LSu	15290000	Little Susitna River near Palmer, Alaska
SuDen	15291000	Susitna River near Denali, Alaska
Mac	15291200	Maclaren River near Paxson, Alaska
SuCant	15291500	Susitna River near Cantwell, Alaska
SuGold	15292000	Susitna River at Gold Creek, Alaska
Chul	15292400	Chulitna River near Talkeetna, Alaska
Talk	15292700	Talkeetna River near Talkeetna, Alaska
SuSun	15292780	Susitna River at Sunshine, Alaska
Mont	15292800	Montana Creek near Montana, Alaska
Will	15294005	Willow Creek near Willow, Alaska
Decep	15294010	Deception Creek near Willow, Alaska
Desh	15294100	Deshka River near Willow, Alaska
Skw	15294300	Skwentna River near Skwentna, Alaska
Yent	15294345	Yentna River near Susitna Station, Alaska
SuSta	15294350	Susitna River at Susitna Station, Alaska

Base map modified from USGS digital datasets, various scales. Projection: NAD83 UTM Zone 6
Roads and towns from Alaska Department of Transportation and Public Facilities digital datasets
Susitna River basin boundary modified from Watershed Boundary Dataset

Figure 1. Location and streamgages used in the study of Susitna River Basin, Alaska.

Streamflow analysis methods have been developed to enable record extension, or estimation of values for a short-record station on the basis of a longer record at an index station, when daily discharge values are closely correlated. Record extension creates a continuous string of daily values at the short-record streamgage for the period of record of the longer-record streamgage. Opportunities for extending streamflow records in Alaska are typically limited by the lack of closely-spaced streamgages with concurrent record, but the relatively large population and road density in the Susitna River Basin, coupled with the early recognition of the potential for hydropower generation, resulted in the collection of more streamflow data in the basin than is typical for the state. Streamgages have been operated simultaneously for certain periods at multiple locations on the Susitna River, and all major tributaries to the river have been gaged at some time. The Susitna River at Gold Creek streamgage has a nearly-unbroken, long-term record that overlaps records from all other streamgages. An additional streamgage, Little Susitna River near Palmer, neighbors the Susitna River Basin and has an unbroken record for the study period. The large size of many of the gaged streams and the common presence of glaciers in their basins increases the chance of streamflow correlation. The combination of data availability and similarity of basin characteristics make record extension feasible for much of the Susitna River Basin streamgaging network.

Purpose and Scope

This report presents the results of a USGS study conducted in cooperation with the AEA to enhance streamflow records in the Susitna River Basin. The study explored the suitability of record extension for the 14 USGS streamgages in the basin that had records within the period WY 1950–2010, extended discharge records for suitable streamgages, and estimated long-term monthly and annual streamflow statistics for the extended record period of WY 1950–2010.

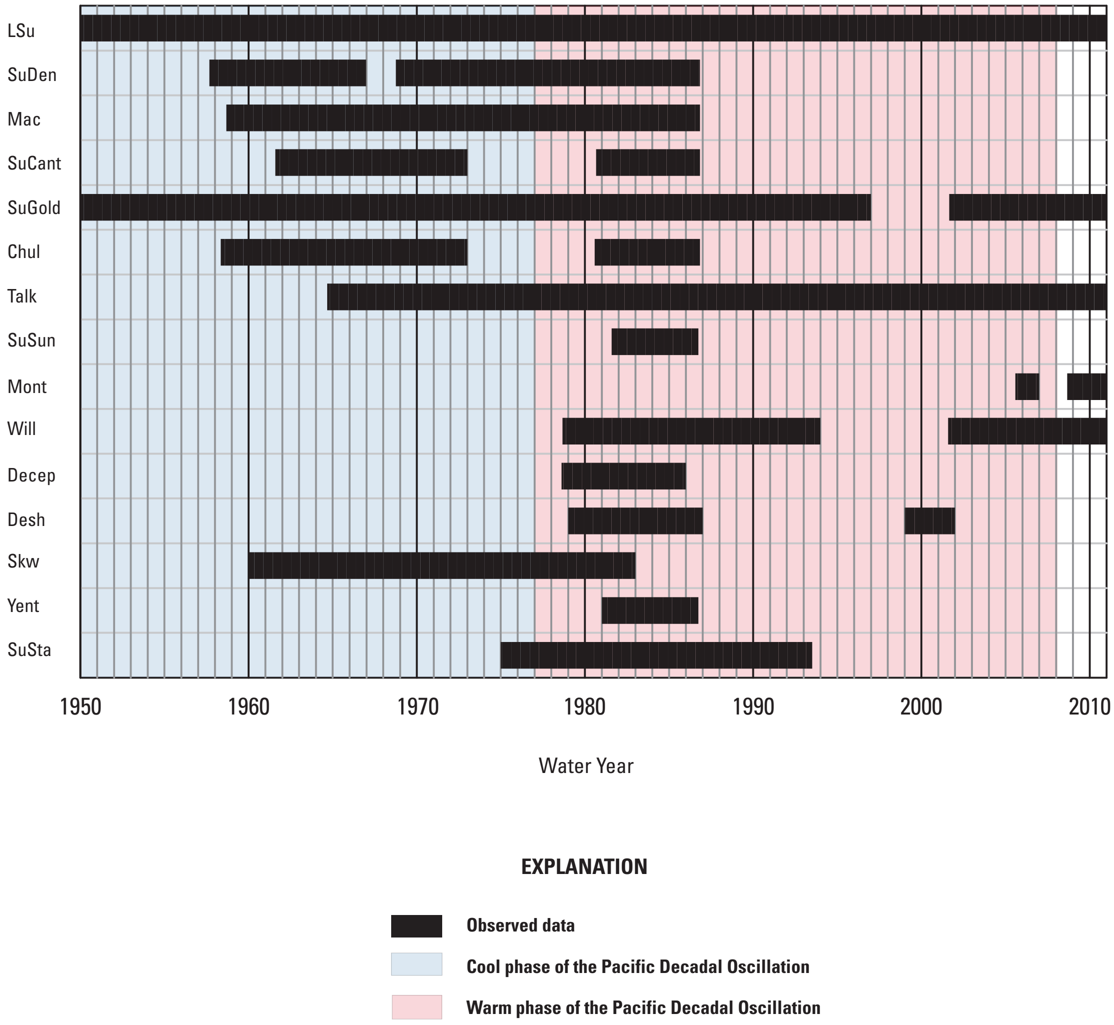


Figure 2. Periods of observed record for selected streamgages in and near the Susitna River Basin, Alaska, and phase of the Pacific Decadal Oscillation (PDO) for water years 1950–2010. Locations, full station names, numbers, and map identifiers are shown in figure 1.

Description of the Susitna River Basin

General

The Susitna River drains a 20,010 mi^2 basin containing parts of the Alaska Range and the Talkeetna Mountains, a high plateau including the 23 mi^2 Lake Louise, and an extensive lowland in the Matanuska-Susitna Borough of southcentral Alaska. Elevations in the basin range from 20,320 ft at the summit of Mt. McKinley to sea level at the river mouth (fig. 1). Glaciers, which are common on higher summits in the Alaska Range and Talkeetna Mountains (see white areas on fig. 1), collectively occupy 11 percent of the Susitna River Basin. The Susitna River Basin has an average annual precipitation of 35 in., with local values exceeding 100 in. at higher elevations (Gibson, 2009a). Basin air temperatures average 29 °F annually (Gibson, 2009b) and generally remain below freezing for the winter season of October–April.

Developed areas in the basin include the small towns of Willow and Talkeetna, together supporting a population of several thousand, and numerous small settlements mostly dispersed along the Parks Highway, the only major paved road through the area. The unpaved Denali Highway traverses a highland between the Alaska Range and the Talkeetna Mountains and supports small settlements. Land ownership in the Susitna River Basin is primarily state and federal, including parts of Denali National Park and Preserve and Denali State Park, but includes corridors of Alaska Native lands along the Susitna River near the proposed dam site and private lands along the highway corridor and Susitna lowland. The Susitna River Basin supports five species of Pacific salmon that drive commercial, sport, personal use, and subsistence fisheries.

Basin Characteristics

The Susitna River ranks 15th in the nation by discharge, although not by drainage area or length (Kammerer, 1990). The largest tributaries to the Susitna River—the Yentna, Chulitna, and Talkeetna Rivers—as well as the Skwentna River, a tributary to the Yentna River, are large streams that drain basins of at least 2,000 mi^2 (table 1). The drainage areas of other gaged streams in the basin, the Maclaren and Deshka Rivers, and Montana, Willow, and Deception Creeks, range from about 50 to 600 mi^2. Glaciers are abundant (10–27 percent of basin area) in seven of the study basins, present in smaller amounts (5–7 percent of basin area) in four of the basins, and absent in four of the basins.

Table 1. Basin characteristics for selected streams in and near the Susitna River Basin, Alaska.

[Streamgage locations are shown in figure 1. **Abbreviations:** ft, foot; in., inch; mi^2, square mile]

Streamgage name	Map identifier	USGS station identification No.	Drainage area (mi^2)	Mean basin elevation (ft)	Lakes and ponds (percent)	Glaciers (percent)	Mean annual precipitation (in.)
Little Susitna River near Palmer, Alaska	LSu	15290000	61.9	3,700	0	5	50
Susitna River near Denali, Alaska	SuDen	15291000	950	4,510	1	25	50
Maclaren River near Paxson, Alaska	Mac	15291200	280	4,520	1	19	50
Susitna River near Cantwell, Alaska	SuCant	15291500	4,140	3,560	2	7	30
Susitna River at Gold Creek, Alaska	SuGold	15292000	6,160	3,420	1	5	30
Chulitna River near Talkeetna, Alaska	Chul	15292400	2,570	3,760	1	27	55
Talkeetna River near Talkeetna, Alaska	Talk	15292700	2,000	3,630	0	7	35
Susitna River at Sunshine, Alaska	SuSun	15292780	11,100	3,480	2	10	35
Montana Creek near Montana, Alaska	Mont	15292800	164	1,930	3	0	30
Willow Creek near Willow, Alaska	Will	15294005	166	2,890	1	0	30
Deception Creek near Willow, Alaska	Decep	15294010	48	1,310	2	0	30
Deshka River near Willow, Alaska	Desh	15294100	591	492	5	0	25
Skwentna River near Skwentna, Alaska	Skw	15294300	2,250	2,810	5	16	45
Yentna River near Susitna Station, Alaska	Yent	15294345	6,180	2,730	1	15	50
Susitna River at Susitna Station, Alaska	SuSta	15294350	19,400	3,200	2	11	35

Streamflow in the Susitna River Basin

Streamflow Data

As of 2010, the network of USGS streamgages with daily streamflow records contained 14 stations in the Susitna River Basin and 1 streamgage adjacent to the basin, the Little Susitna River near Palmer, whose record showed streamflow characteristics similar to some streams in the basin. (fig. 1). The present dam licensing process prompted resumption of gaging at several previously discontinued stations and the installation of two additional streamgages in the basin in 2011 but these additional records are not included in this study.

The Susitna River Basin streamgaging network began with the installation of a streamgage on the Susitna River at Gold Creek in August 1949, and consisted of seven streamgages by 1964. An extensive study of the hydropower potential of the Susitna River brought the total number of concurrently active streamgages in the basin to a maximum of 13 in 1982. When the study ended in 1986, streamgaging ceased at two-thirds of the streamgages in operation in the basin at the time, but records of at least 5 years had been obtained at all streamgages. A 14th streamgage was installed in 2005.

The streamflow data collected in the Susitna River Basin enabled designation of two streamgages as primary potential index stations: Susitna River at Gold Creek, operated since August 1949 but discontinued between 1997 and 2001, and Talkeetna River near Talkeetna, which was installed in June 1964 and has since been operated continuously. The other stations on the Susitna River and its tributaries constitute potential secondary index stations for shorter periods. Although the Little Susitna River near Palmer streamgage is outside the Susitna River Basin (fig. 1), it records streamflow from a similar setting in the Talkeetna Mountains and has an unbroken record since water year 1949, making it an additional potential index station. None of the 14 gaged Susitna River Basin streams have been regulated or subjected to broad-scale land-use change, ensuring that streamflow reflects natural conditions at all sites.

Streamflow Patterns

Daily discharge in many large nested or neighboring Susitna River Basin streams corresponded closely, and any lags in flow between nested sites along the Susitna River did not appear to affect correlation of daily discharge. Large streams generally owe their flow patterns to basin-wide conditions, such that daily flow at neighboring or nested streamgages is likely driven by the same regional climatic conditions and precipitation events.

Annual streamflow patterns in the Susitna River Basin are driven by the relative timing and magnitude of glacier melt, snowmelt, and rainfall. Plots of mean daily discharge for the observed period of record helped place Susitna River Basin streamgages into four groups along a continuum of these streamflow drivers (fig. 3). Mean daily discharge was computed as the mean of all daily mean values occurring on that calendar day for the chosen period. February 29 commonly shows an anomalous spike because that date occurs less often in the record. For the purposes of comparison, figure 3 shows the mean daily discharge for a 4-year period, WY 1982–1985, which was common to all study streams except Montana Creek and Skwentna River, for which an alternative period was used.

All study streams have a winter period of declining flows (November or December through March or April). Breakup occurs in the spring, when stream ice cover melts and discharge begins to increase abruptly with the contribution of snowmelt. In the Susitna River Basin, breakup occurs in April or early May. Streams with a defined snowmelt peak attain that peak in the period May to mid-June. Glacier melt reaches a maximum rate later in the summer than snowmelt, such that Susitna River Basin streams whose flow is dominated by glacier melt have higher mean flows in July than in June (fig. 3*A*). No decrease following snowmelt is discernible for these streams.

Instead, mean daily discharge continues to increase until a glacier-melt peak is reached. The flow of several Susitna River Basin streams shows traits from both glacier and snowmelt contributions (fig. 3*B*). The percentage of basin glacier cover alone could not explain the shift toward higher snowmelt-driven streamflows than glacier-melt-driven streamflows. Streams with higher glacier-melt-driven flows (fig. 3*A*) had a basin glacier cover of at least 10 percent, but two streams whose basins have more than 15 percent glacier cover had higher snowmelt-driven flows (fig. 3*B*). Flow in the lowest elevation streams (fig. 3*D*) reaches a snowmelt peak, decreases farther than for snowmelt-driven streams (fig. 3*C*), then may remain steady or increase during the summer and autumn in response to rainfall runoff.

The most well documented influence on longer-term patterns in streamflow in the Susitna River Basin is the PDO, a multi-decadal pattern in North Pacific sea surface temperature variability that has been shown to have an effect on precipitation and air temperature in Alaska (Hartmann and Wendler, 2005). During the warm phase of the PDO, sea surface temperatures in the Gulf of Alaska are warmer (Mantua and others, 1997) and air temperatures and precipitation tend to be higher across most of Alaska (Hartmann and Wendler, 2005) than in the cool phase. Monthly PDO index values, defined as the leading principal component of North Pacific monthly sea surface temperature variability, were obtained from the University of Washington

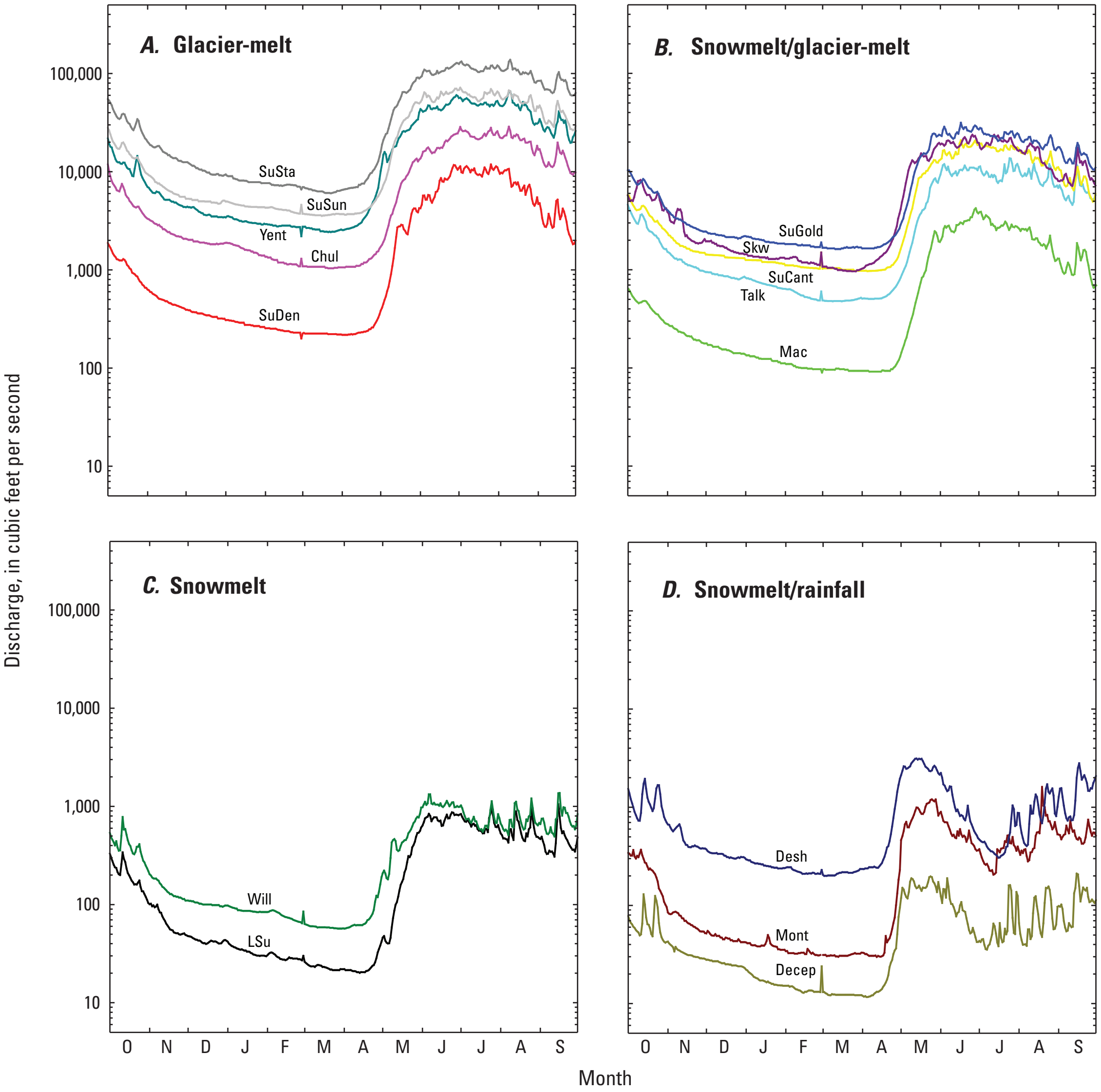


Figure 3. Mean daily discharge for selected streamgages in and near the Susitna River Basin, Alaska, categorized by relative contribution of glacier melt, snowmelt, and rainfall. Values are the mean of all daily discharge values for each calendar day of a 4-year period (water years 1982–1985) for all streamgages except those on Montana Creek (water years 2005–2010, including partial years), and Skwentna River (water years 1979–1982). Locations, full station names, numbers, and map identifiers are shown in figure 1.

Joint Institute of the Atmosphere and Ocean (2012) for 1920–2011 and plotted (fig. 4) to help define warm and cool periods when the index was predominantly positive and negative, respectively. Researchers have delineated alternating warm and cool PDO phases, each persisting for two to three decades but including short periods of the opposite-signed index. The year-to-year fluctuations in the index make defining boundaries difficult, especially for a recent phase shift. Although many researchers recognize a phase shift in the PDO in 1976, the ending date for the recent warm phase varies. For computations in this study, the most recent cool phase was defined as 1947–1976 and the most recent warm phase was defined as 1977–2007.

Studies linking Alaska streamflow to the PDO determined that, compared to flows during the most recent cool phase of the PDO, flows during the most recent warm phase were higher in winter, particularly for glaciated basins (Neal and others, 2002; Hodgkins, 2009). In summer, streamflows during the most recent warm phase were higher for glaciated basins and lower for nonglaciated basins. On average, mean annual discharge was not significantly different between PDO phases in Southeast Alaska (Neal and others, 2002). However, Hodgkins (2009) determined a slight increase in mean annual discharge statewide during the warm phase (Hodgkins, 2009). For the Susitna River at Gold Creek, Hodgkins (2009) reported minimal changes in mean annual discharge (1 percent greater during warm phase), appreciable increases in winter (October–April) mean monthly discharge (19–50 percent higher during warm phase), and a slight decrease in summer (June–August) discharge (1 percent higher to 8 percent lower during warm phase).

A plot of mean daily discharge in the warm phase (1977–2007) relative to flows in the cool phase (truncated to 1950–1976 to match the study period) of the PDO for the primary index stations in and near the Susitna River Basin shows an increase in flows during winter and an earlier and slightly smaller snowmelt peak (fig. 5) during the warm phase. The variability in flows during the rest of the summer season is smaller and less well defined. Freeze-up, although not as dramatic as breakup, occurs during the autumn decrease in streamflow and shifts to later in autumn during the warm phase.

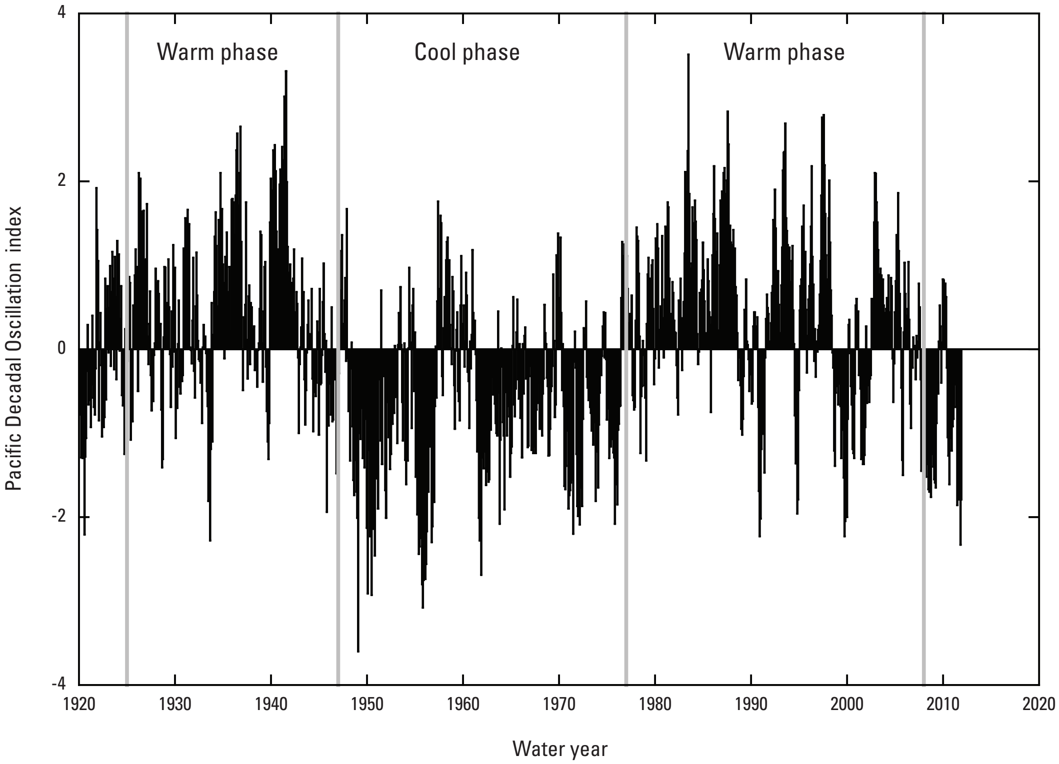


Figure 4. Index values and phase shifts in the Pacific Decadal Oscillation, 1920–2011. Index values were obtained June 5, 2012 (University of Washington Joint Institute for the Study of the Atmosphere and Ocean, 2012).

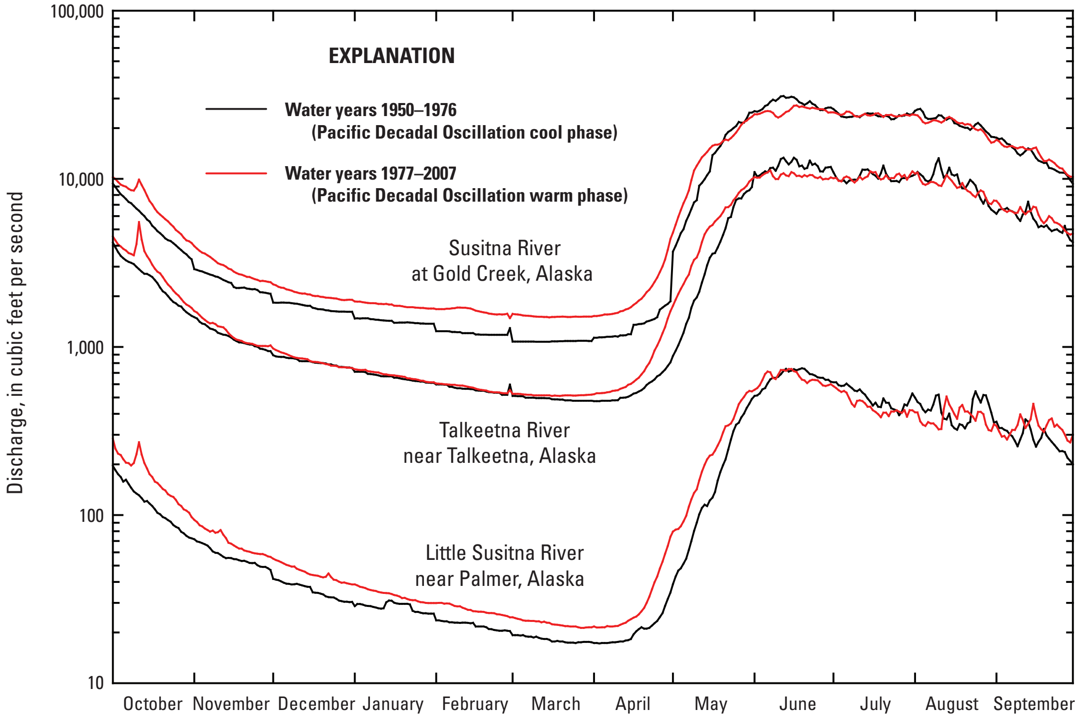


Figure 5. Variability in mean daily discharge during the most recent cool phase and warm phase of the Pacific Decadal Oscillation for primary index stations in and near the Susitna River Basin, Alaska. The cool phase began in 1947, but the study period began in water year 1950. The period of record shown is water years 1950–96, 2001–10, (Susitna River at Gold Creek), water years 1964–2010 (Talkeetna River near Talkeetna), and water years 1950–2010 (Little Susitna River near Palmer). Locations, full station names, numbers, and map identifiers are shown in figure 1.

Methods of Analysis

Selection of Period of Analysis

The period selected for analysis extended from WY 1950, the first full water year of data collection for the primary index station Susitna River at Gold Creek, to the end of WY 2010. A few months of data prior to October 1, 1949, are available for the Susitna River at Gold Creek, and flow data for the Little Susitna River near Palmer begins on July 1, 1948, but the study period was set to coincide with the start of WY 1950 for convenience of computing monthly statistics and consistency between extended records.

Data Review

Observed discharge data for USGS streamgages are available online through the National Water Information System (NWIS; U.S. Geological Survey, 2012). Although all data used in this study are published final values, annual hydrographs were inspected for potential anomalies that might limit streamgage suitability as an index station. Hydrographs for the Susitna River at Gold Creek for 1954, 1956, 1958, and 1961 through 1963 display a stepped pattern consisting of values that remain constant for a period of weeks, but then jump to a new, constant value. Although Alaska USGS streamflow records prior to the 1980s do not contain a code to indicate data quality, this pattern is typical of periods when discharge must be estimated because of equipment failure, the presence of ice, or other reasons. The Susitna River at Gold Creek was the primary index station for this study and was the only index station available prior to 1958 with the exception of the Little Susitna River near Palmer, which was suitable as an index station for only one stream. No alternatives to the Susitna River at Gold Creek were available for the estimated periods in 1954 and 1956, but other Susitna River streamgages near Denali and near Cantwell were considered as index stations for the 1958 and 1961–63 estimated periods. The values estimated for Susitna River at Gold Creek followed the general trends in flow at the possible alternative index stations as well as the general trends in other years of Susitna River at Gold Creek record, so no substitutions were made.

The inspection of the hydrographs suggested that although daily variations in discharge were not captured during these estimated periods, mean monthly values are likely to be of good quality.

Winter streamflow conditions for all sites in this study include periods of ice cover. Ice-affected discharge must be estimated and is indicated as such in the gaging record. Although USGS streamgaging practices aim to constrain these values as closely as possible, estimated winter values could not be used as confidently as open-water season values for comparing the performance of the various equations used in the extension of streamflow records.

In 1964, the Susitna River at the three streamgages then operating (Susitna River near Denali, near Cantwell, and at Gold Creek) displayed an unusual pattern consisting of a high snowmelt peak in early June, followed by a steady decrease. Although the Talkeetna River streamgage did not begin operating until June 1, 1964, the partial record available for summer 1964 displays a similar pattern. The similarity in patterns across all available streamgages suggests this unusual pattern was related to basin-wide conditions, making it suitable for use in estimating flows at other stations.

Selection of Index Stations

For each site of interest, one or more potential index stations were selected on the basis of strength of correlation of daily values, hydrologic similarity, length of concurrent record, and length of extension possible. Log-scale scatterplots of concurrent daily records (appendix A) were visually examined for tightness of fit and extent of outliers, and log-scale plots of mean daily discharge for the period of record (similar to figure 3) were examined for similarities in seasonality and streamflow drivers. Pearson's correlation coefficients (*r*) were computed for the logarithms of daily discharge at all combinations of potential index stations and sites of interest (table 2). Inspection of the various plots and statistical metrics showed that a minimum *r* of 0.95 produced the best matches. Spearman's correlation coefficients, a nonparametric statistic that can measure dependence even when the fit is not linear (when very low flows or very high flows have a different fit than mid-range flows, for example), was computed but did not vary enough from *r* to alter the selection of index stations.

The length of concurrent record for adequately correlated sites was at least 5 years for all sites except for Skwentna River near Skwentna and Yentna River near Susitna Station, which overlapped for only 2 years, but are nested sites with many similar basin characteristics. Sites were considered as index stations only if they provided at least 3 years of record extension for the site of interest. Extending a record for shorter lengths of time was technically feasible, but the increased number of computations needed to compute and review estimates from an additional index station outweighed the benefit of improving 1–2 years of a record.

In addition to the primary index stations (Susitna River at Gold Creek and Talkeetna River near Talkeetna), as many as three additional potential index stations that met the minimum requirements were considered for each site of interest by ranking correlation coefficients. Typically, one or two correlation coefficients were notably larger than the others so that selection of an index station was straightforward. When several correlation coefficients were similar, priority was given to the closest sites and to sites on the same stream. The sites meeting these screening requirements formed the initial suite of index stations for computation of predicted values and evaluation of fit of predicted to observed values.

Table 2. Correlation coefficients (Pearson's *r*) between logarithms of daily discharge values at sites of interest and potential index stations for streams in the Susitna River Basin, Alaska.

[Shading indicates values equal to or greater than 0.950. LSu, Little Susitna River near Palmer, Alaska. –, index station not suitable because length of potential extension or overlap is inadequate]

Streamgage name	Map identifier	Potential index station														
		LSu	SuDen	Mac	SuCant	SuGold	Chul	Talk	SuSun	Mont	Will	Dec	Desh	Skw	Yent	SuSta
Susitna River near Denali, Alaska	SuDen	0.928	–	–	–	0.959	–	0.957	–	–	0.892	–	–	–	–	0.963
Maclaren River near Paxson, Alaska	Mac	0.935	–	–	–	0.964	–	0.955	–	–	0.890	–	–	–	–	0.954
Susitna River near Cantwell, Alaska	SuCant	0.941	0.971	0.970	–	0.986	–	0.965	–	–	0.930	–	–	0.957	–	0.970
Susitna River at Gold Creek, Alaska	SuGold	0.946	–	–	–	–	–	0.968	–	–	–	–	–	–	–	–
Chulitna River near Talkeetna, Alaska	Chul	0.954	0.970	0.964	–	0.969	–	0.976	–	–	0.930	–	–	0.967	–	0.972
Talkeetna River near Talkeetna, Alaska	Talk	0.963	0.957	0.955	0.965	0.968	0.976	–	–	–	–	–	–	0.952	–	–
Susitna River at Sunshine, Alaska	SuSun	0.960	0.975	0.966	0.986	0.995	0.986	0.986	–	–	0.948	–	–	0.959	–	0.984
Montana Creek near Montana, Alaska	Mont	0.916	–	–	–	0.919	–	0.931	–	–	0.963	–	–	–	–	–
Willow Creek near Willow, Alaska	Will	0.959	0.892	0.890	0.930	0.922	0.930	0.938	–	–	–	–	–	–	–	–
Deception Creek near Willow, Alaska	Dec	0.678	0.602	0.606	0.732	0.673	0.702	0.702	–	–	0.799	–	–	–	–	0.713
Deshka River near Willow, Alaska	Desh	0.549	0.507	0.506	0.602	0.594	0.574	0.585	–	–	0.677	–	–	–	–	0.650
Skwentna River near Skwentna, Alaska	Skw	0.934	–	–	–	0.956	–	0.952	–	–	0.922	–	–	–	0.989	0.974
Yentna River near Susitna Station, Alaska	Yent	0.933	0.957	0.951	0.962	0.967	0.956	0.956	–	–	0.920	–	–	0.989	–	0.987
Susitna River at Susitna Station, Alaska	SuSta	0.944	0.963	0.954	0.970	0.976	0.972	0.969	–	–	0.931	–	–	0.974	–	–

Record Extension Techniques

Quantitative methods for estimating daily discharge values at a site of interest on the basis of daily discharge values at an index station generally employ some form of linear regression, but each approach has slight variations that provide an advantage for a particular application. The line of organic correlation provides a more suitable method for streamflow record extension than ordinary least squares or least normal squares (Helsel and Hirsch, 2002). Also known as Maintenance of Variance-Extension (MOVE), the technique provides a means to retain the long-term variance of the index station data. The Kendall-Theil Robust Line (KTRL) method is a nonparametric technique, providing an advantage where outliers are present (Helsel and Hirsch, 2002). Two MOVE methods, MOVE.1 (Hirsch, 1982) and MOVE.3 (Vogel and Stedinger, 1985), and the nonparametric KTRL method were selected as suitable for use with the Susitna River Basin data. Criteria for selection of a particular method for this study included the theoretical applicability of the method, suitability of the data given the requirements of the method, and ease of computation.

Streamflow record extension computations are performed on the logarithms of daily discharge values; results are then retransformed to obtain estimated daily discharge. The general form for a daily discharge regression equation is based on the equation for a straight line using the logarithms of discharge,

$$Y_i = mX_i + b + e_i \tag{1}$$

where

Y_i is the logarithm of the discharge value for the ith day at the site of interest,
m is the slope of the regression line,
X_i is the logarithm of the discharge value for the ith day at the index station,
b is the intercept of the regression line, and
e_i is the residual error (the difference between Y_i and the regression-line estimate for the ith day.

The estimated discharge values are then obtained as 10^{Y_i}.

MOVE.1 is a parametric method that calculates the slope (m) as the product of the sign of the correlation coefficient (r) and the ratio of the standard deviations of the Y values and concurrent X values. The intercept (b) is calculated so that the line passes through the mean of the X and Y populations.

MOVE.3 is a variation of the MOVE method that captures statistics from the full length of available record. MOVE.3 uses estimates of the mean and standard deviation for the concurrent period from both stations but also incorporates the mean and standard deviation for the nonconcurrent period from the index station.

The KTRL method, as a nonparametric technique, avoids use of the mean and instead estimates the slope (m) as the median of all pairwise slopes between each pair of points in the data set (Theil, 1950; Sen, 1968). The intercept (b) is calculated so that the line passes through the median of the X and Y populations (Conover, 1980).

Regardless of the method used, a multi-segment line can improve fit when particularly high or low flows have a different correlation to index station values than do mid-range flows. A model is constructed from two or more straight-line segments, each applicable to a range of flow magnitudes. Additionally, independent estimates from multiple index stations can be combined to improve the overall estimate.

The USGS has developed a suite of software to facilitate the use of MOVE and KTRL equations. The Streamflow Record Extension Facilitator (SREF) program (Granato, 2009) fits MOVE.1 and MOVE.3 equations to data for one or more index stations, computes estimated values for the site of interest using each index station individually, and then provides a method for weighting values for multiple index stations. This program does not automate the computation of multiple line segments for a single index station. The KTRLine program (Granato, 2006) provides a graphical interface that assists the user in selection of breakpoints for multiple line segments for a single index station. The KTRL equations computed for each line in the multi-segment model are then entered in the SREF program for computation of the estimated values. Weighting values from multiple stations must be done manually.

For the Susitna River Basin data, log-scale scatterplots of daily values for each site of interest against each prospective index station (appendix A) were inspected for patterns that would require a particular method of analysis. A first-degree-polynomial locally-weighted scatterplot smoothing (LOWESS) curve fitted to the scatterplot revealed a generally good fit of a straight line to the bulk of the data. The largest and most frequent outliers, or points falling far from the densest concentration of points, occurred in the mid-range values. Inspection of dates of occurrence suggested these outliers occurred during the spring snowmelt period when one river began breakup before the other. Outliers at very high flows also were common, typically as sparse, scattered groups of values rather than outstanding single values. For most site pairs, a slight to moderately pronounced bending of the curve at very high flows, very low flows, or both suggested that a better fit could be obtained from multiple straight-line segments.

Application of all three methods to a few sites of interest helped narrow the choice of methods. Results of the solution of MOVE.1 and MOVE.3 equations varied extremely little relative to the difference between MOVE.1 and KTRL, and relative to the difference between the observed and predicted values. MOVE.3 offered no considerable advantage and is a more theoretically complicated method than MOVE.1, so it was omitted from further consideration. The fit of MOVE.1 relative to KTRL was tested for one site where no multiple-line segment was required, Willow Creek near Willow, and for a site where a multi-segment model was required by manually segregating the input data to SREF. For extending the record of Willow Creek near Willow with the data from Little Susitna River near Palmer, both equations produced acceptable results. The MOVE.1 and KTRL lines passed through high-flow data at similar locations but diverged slightly at lower flows, with the result that MOVE.1 produced the more expected result of higher winter flows with additional years of record from the PDO warm phase. However, producing a multi-segment MOVE.1 model in SREF required too much iteration involving extensive manual input data manipulation to converge on a solution with confidence. Multi-segment models with MOVE.1 were impractical for the tens of station pairs required for this study.

A seasonal approach to developing equations was considered because daily discharge values clustered into generally expected seasonal groups on the scatterplots. However, the overall fit was comparable to that obtained by a multiple-line segment in KTRL and the amount of manual manipulation of input data was prohibitive for the seasonal analysis.

Computing Record Extension Equations

Record Extension Equations for Individual Index Stations

The multi-segment capacity of the KTRLine program provided a convenient method for computing regression equations for all station pairs in this study. A log transform, commonly applied to streamflow data, created a more linear fit to the data for all station pairs. When a multi-segment line appeared appropriate, breakpoints visually determined from the LOWESS-smoothed line on the log-scale scatter plot of daily discharge were entered into the KTRLine program and adjusted until improvements diminished. Iterations included the default 1-segment line, then several attempts at multi-segment lines, increasing the model one segment at a time until the best fit was obtained with the fewest possible segments. Resulting equations (table 3) contained a maximum of four segments. An overlay of each equation on the scatterplot of concurrent daily discharge (appendix A) shows the fit of the equation to the source data. Values from table 3 for each equation were entered into SREF, which computed the extended discharge values and retransformed them from logarithmic values to produce a suite of predicted (estimated values for the period concurrent with the index station) and extended (estimated values for the nonconcurrent period) daily discharge values for the site of interest.

Weighting Multiple Index Stations

If more than one index station was available for a particular subperiod, the fit of predicted values from the various stations singly and in combination compared to the observed values guided compilation of a final date-specific set of index stations. Index station selection also relied on a measure of fit termed the modified Nash-Sutcliffe efficiency (NSE). Alternative measures of model fit in hydrologic applications avoid the influence of extreme values and other issues with the more familiar correlation-based measures such as the coefficient of determination, r^2. The NSE suggested by Legates and McCabe (1999) ranges from 1, indicating that the model perfectly predicts the observed data, to minus infinity, indicating the model has no predictive ability. An NSE of 0 indicates that the model is no better a predictor than the average of the observed data. The modified efficiency is computed as

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left| Y_i - Y_p \right|}{\sum_{i=1}^{n} \left| Y_i - \overline{Y} \right|} \qquad (2)$$

where

n is the number of measurements,
Y_i is the ith observed daily discharge value,
Y_p is the predicted daily discharge value, and
$\overline{Y}$ is the average of the observed daily discharge values.

A second index station was added to the model when the addition improved NSE by at least 1 percentage point. The addition of a third index station was considered, but never improved NSE by enough over the improvement gained with two stations to warrant the added model complexity, such that no model used more than two index stations for any given time period.

Selection of index stations was always coupled with visual comparison of the hydrographs of observed and predicted data from each index station for WY 1980–86 (fig. 6), which was selected as a common period for which data were available at most sites. The fit of summer peak flows, including the general trend but more specifically focusing on fluctuations on a daily to weekly basis, provided a more attainable measure than the winter low flows.

The final extended streamflow record from the selected multiple stations was produced by weighting the extended discharge values from each index station by the respective mean square error (MSE). MSE was computed from the predicted compared to observed values by the KTRLine program.

Table 3. Values for variables, discharge input ranges, and measures of error for equations for estimating daily discharge from index station data at selected streamgages, Susitna River Basin, Alaska.

[Streamgage locations and map identifiers are shown in figure 1. **Slope, Intercept,** and **Range of daily discharge input values**: Values are logarithms of discharge in cubic feet per second. RMSE, root mean square error]

Index station	Model RMSE	Segment No.	Slope	Intercept	Range of daily discharge input values		Bias correction factor
					Minimum	Maximum	
Susitna River near Denali, Alaska (SuDen)							
SuGold	0.182	1	0.338	1.286	2.820	3.165	0.964
		2	1.124	-1.201	3.165	4.010	1.089
		3	1.644	-3.287	4.010	4.381	1.200
		4	0.358	2.348	4.381	4.934	1.000
Talk	0.183	1	1.058	-0.533	2.415	3.422	1.041
		2	1.469	-1.939	3.422	3.960	1.171
		3	0.407	2.266	3.960	4.799	1.031
SuSta	0.162	1	2.364	-6.688	3.699	3.839	1.046
		2	1.009	-1.486	3.839	4.781	1.022
		3	2.066	-6.540	4.781	5.074	1.072
		4	0.665	0.573	5.074	5.358	1.005
Maclaren River near Paxson, Alaska (Mac)							
SuGold	0.165	1	0.984	-1.147	2.820	3.921	1.099
		2	1.756	-4.173	3.921	4.331	1.081
		3	0.627	0.716	4.331	4.934	0.973
Talk	0.183	1	0.844	-0.358	2.415	3.219	1.024
		2	1.369	-2.046	3.219	4.015	1.158
		3	0.504	1.426	4.015	4.799	0.986
Susitna River near Cantwell, Alaska (SuCant)							
SuGold	0.093	1	1.034	-0.339	2.820	4.553	1.029
		2	0.864	0.432	4.553	4.934	0.958
Talk	0.146	1	0.854	0.575	2.415	2.940	1.042
		2	1.077	-0.080	2.940	3.924	1.050
		3	0.598	1.800	3.924	4.799	1.028
Susitna River at Gold Creek, Alaska (SuGold)							
Talk	0.128	1	0.571	1.618	2.415	2.882	1.002
		2	1.034	0.282	2.882	3.914	1.010
		3	0.623	1.892	3.914	4.801	0.978
Chulitna River near Talkeetna, Alaska (Chul)							
SuGold	0.123	1	0.337	1.993	2.820	3.257	1.066
		2	1.145	-0.640	3.257	4.358	1.052
		3	0.455	2.367	4.358	4.934	0.992
Talk	0.111	1	0.597	1.431	2.415	2.855	1.035
		2	1.065	0.095	2.855	3.992	1.056
Talkeetna River near Talkeetna, Alaska (Talk)							
SuGold	0.129	1	0.348	1.657	2.820	3.173	1.051
		2	1.032	-0.514	3.173	4.890	1.031
Susitna River at Sunshine, Alaska (SuSun)							
SuGold	0.049	1	1.050	0.182	3.114	4.406	1.002
		2	0.797	1.295	4.406	4.784	0.996
Talk	0.079	1	0.795	1.396	2.415	2.826	1.054
		2	1.020	0.761	2.826	3.921	0.985
		3	0.546	2.618	3.921	4.607	0.976
Willow Creek near Willow, Alaska (Will)							
LSu	0.137	1	0.825	0.711	1.146	3.619	0.970
Skwentna River near Skwentna, Alaska (Skw)							
SuGold	0.156	1	0.947	0.059	2.820	4.432	1.037
		2	0.594	1.620	4.432	4.934	0.977
Talk	0.163	1	1.000	0.260	2.415	3.909	1.026
		2	0.502	2.206	3.909	4.799	0.999
Yent	0.078	1	0.989	-0.408	3.301	5.053	0.989
SuSta	0.117	1	1.069	-1.088	3.699	4.253	1.055
		2	0.846	-0.140	4.253	4.957	1.065
		3	1.321	-2.490	4.957	5.358	1.043
Yentna River near Susitna Station, Alaska (Yent)							
SuGold	0.131	1	1.068	0.032	3.114	4.346	1.040
		2	0.596	2.084	4.346	4.784	0.984
Talk	0.146	1	0.629	1.722	2.415	2.774	1.169
		2	1.070	0.501	2.774	3.863	1.100
		3	0.485	2.761	3.863	4.607	0.982
Skw	0.078	1	0.992	0.480	2.833	4.611	1.048
SuSta	0.082	1	0.909	-0.028	3.699	4.441	0.979
		2	1.109	-0.915	4.441	5.358	1.007
Susitna River at Susitna Station, Alaska (SuSta)							
SuGold	0.107	1	0.544	2.131	2.954	3.263	1.080
		2	1.364	-0.543	3.263	3.619	1.068
		3	0.921	1.059	3.619	4.357	1.028
		4	0.610	2.414	4.357	4.784	0.984
Talk	0.121	1	0.993	1.146	2.415	3.954	1.070
		2	0.405	3.472	3.954	4.801	0.995
Skw	0.102	1	0.471	2.433	2.833	3.256	1.050
		2	1.231	-0.042	3.256	4.129	1.069
		3	0.453	3.170	4.129	4.707	0.996

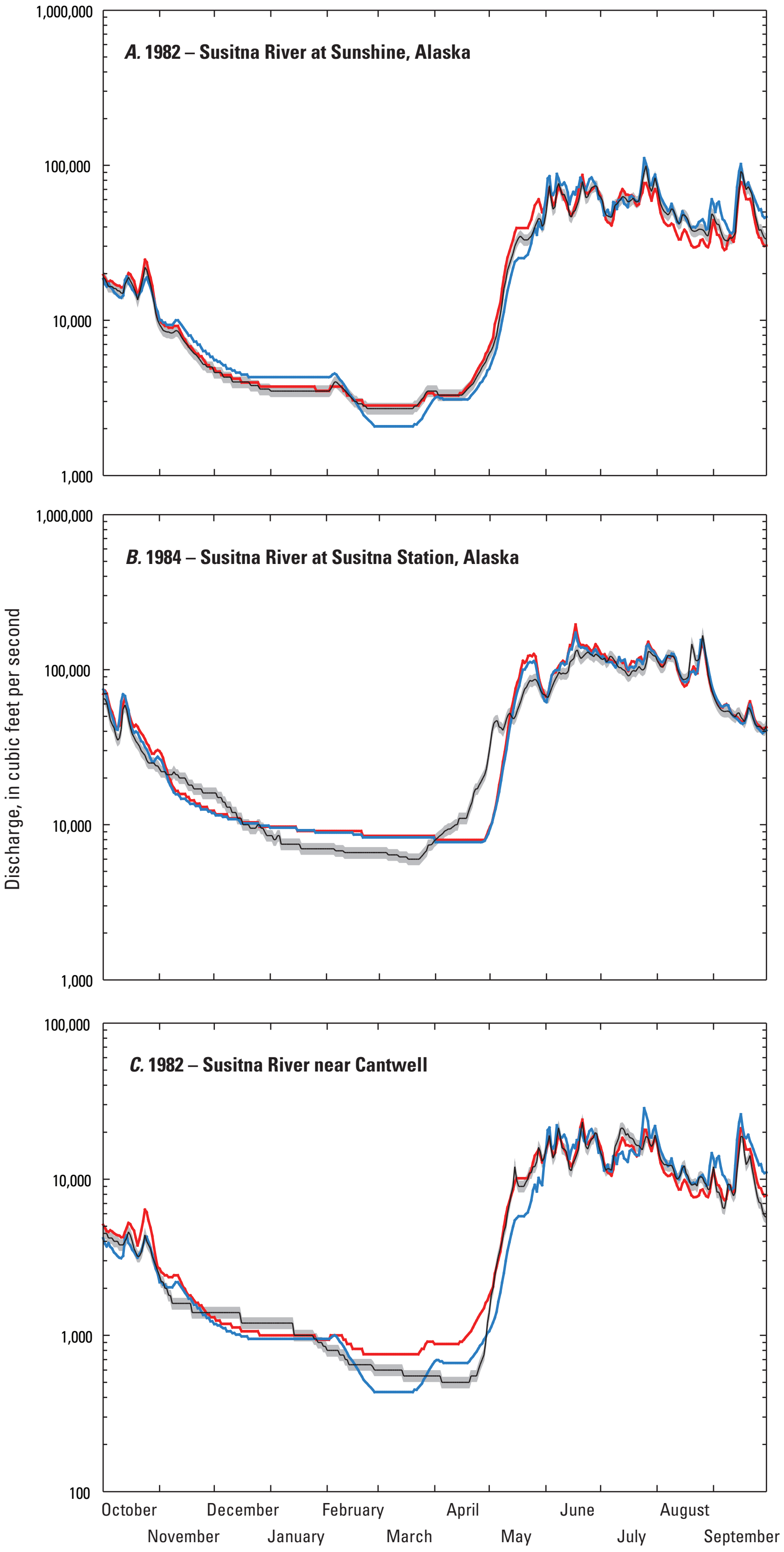


Figure 6. Examples of predicted and observed discharge values for selected streamgages in the Susitna River Basin, Alaska. Predicted values are independent estimates of discharge at the site of interest based on records for index stations Susitna River at Gold Creek, Alaska (SuGold) and Talkeetna River near Talkeetna, Alaska (Talk), respectively. (*A*) Example of a good fit for two index stations. Final values were computed as a weighted estimate of values from both index stations. (*B*) Example of poor fit during winter, breakup, and snowmelt periods. In this particular year, streams at the index stations were ice-covered longer than the site of interest. (*C*) Example of a better fit for one index station. The fit is reflected in the respective correlation coefficients (table 2, 0.986 for Susitna River at Gold Creek, Alaska and 0.965 for Talkeetna River near Talkeetna, Alaska). Locations, full station names, numbers, and map identifiers are shown in figure 1.

Extended Streamflow Records

Index Stations Used to Extend Streamflow

Index stations were available to enable computation of extended streamflow records for WY 1950–2010 for 11 of the 14 streamgages in the Susitna River Basin. The streamgages on Montana Creek, Deception Creek and the Deshka River were omitted from analysis because they could not be adequately correlated to any long-term index station for the entire study period (table 2). The daily patterns in these lower-elevation, snowmelt-and-rainfall-driven streams did not match the patterns of the available index stations, which had stronger influences from glacier melt and snowmelt.

Limited record availability dictated the selection of index stations in the early and late parts of the study period, and correlation and length of extension winnowed choices during the 1960–80s. Eight streamgages were used as index stations for at least one other station (fig. 7). Table 4 lists the dates and index stations used for each subperiod. Although as many as four index stations were available to extend records for a single site of interest, no more than two index stations were used for any single subperiod of record extension. Little Susitna River near Palmer served as an index station only for Willow Creek near Willow because an earlier breakup and stronger decrease in flow after snowmelt at the Little Susitna River created a lack of seasonal hydrologic similarity to otherwise reasonably correlated glacier-melt

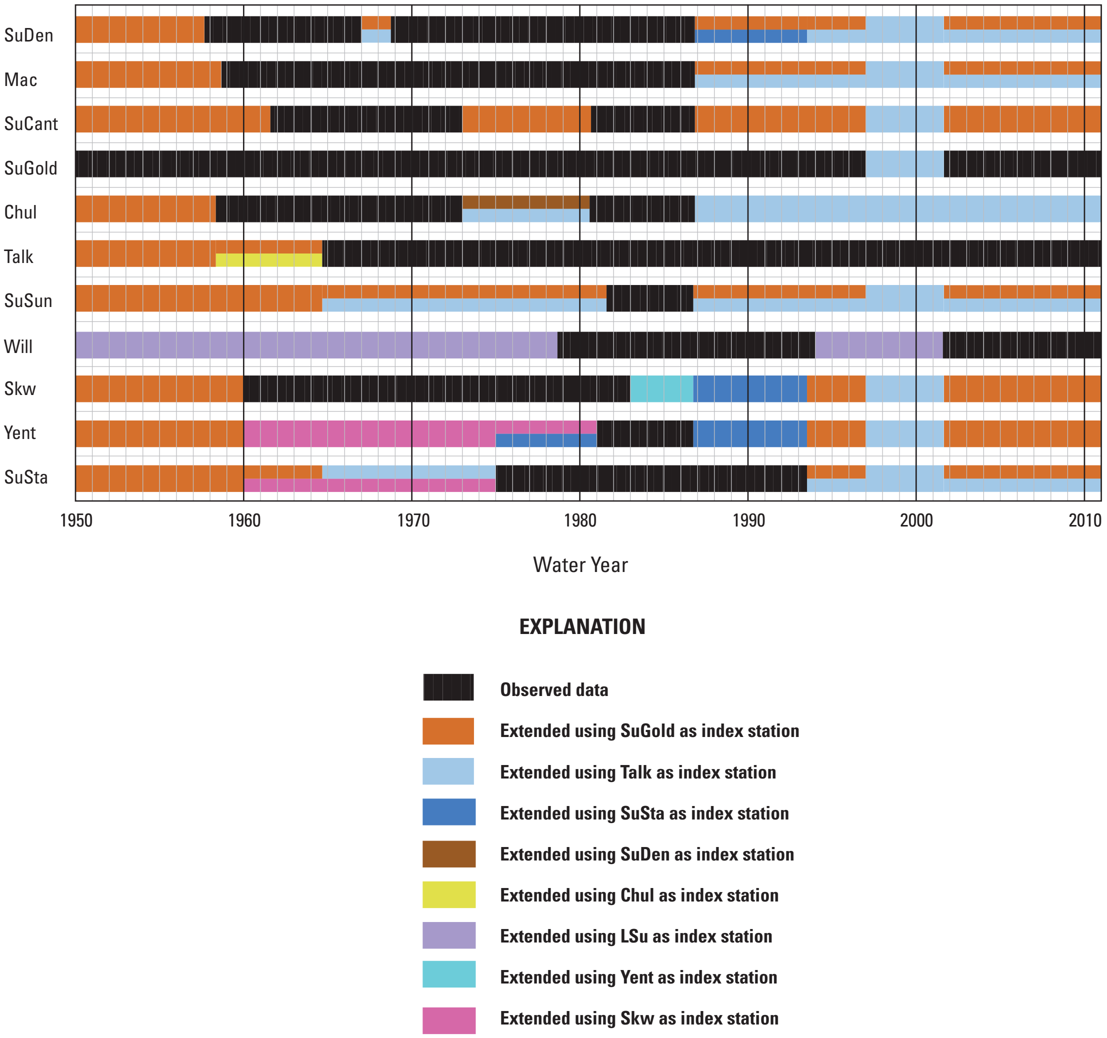


Figure 7. Index stations used to extend streamflow records in the Susitna River Basin, Alaska. Locations, full station names, numbers, and map identifiers are shown in figure 1.

and snowmelt-driven sites. For all sites other than Willow Creek near Willow, Susitna River at Gold Creek served as the primary index station, partly because it had the only record available for many subperiods and partly because of good correlation of daily discharge values. For the period October 1, 1996, to May 24, 2001, when no record was available for the Susitna River at Gold Creek, the Talkeetna River near Talkeetna served as a substitute index station. The combination of Susitna River at Gold Creek and Talkeetna River near Talkeetna also was commonly used in record extensions because it matched streamflows better than either station individually. The record for the Susitna River at Susitna Station was used to extend the record for the Susitna River near Denali for their subperiod of overlap despite the distance between the sites because no closer sites offered a better correlation.

Table 4. Periods of observed and extended streamflow records and index stations used for record extension for selected streamgages, Susitna River Basin, Alaska.

[LSu, Little Susitna River near Palmer, Alaska. –, measured values available]

Index stations	Date used for record extension	
	From	To
Susitna River near Denali, Alaska (SuDen)		
SuGold	10-01-1949	05-29-1957
–	05-30-1957	09-30-1966
SuGold, Talk	10-01-1966	06-30-1968
–	07-01-1968	07-31-1986
SuGold, SuSta	08-01-1986	03-31-1993
SuGold, Talk	04-01-1993	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold, Talk	05-25-2001	09-30-2010
Maclaren River near Paxson, Alaska (Mac)		
SuGold	10-01-1949	05-31-1958
–	06-01-1958	07-31-1986
SuGold, Talk	08-01-1986	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold, Talk	05-25-2001	09-30-2010
Susitna River near Cantwell, Alaska (SuCant)		
SuGold	10-01-1949	04-30-1961
–	05-01-1961	09-30-1972
SuGold	10-01-1972	05-28-1980
–	05-29-1980	07-31-1986
SuGold	08-01-1986	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold	05-25-2001	09-30-2010
Susitna River at Gold Creek, Alaska (SuGold)		
–	10-01-1949	09-30-1996
Talk	10-01-1996	05-24-2001
–	05-25-2001	09-30-2010
Chulitna River near Talkeetna, Alaska (Chul)		
SuGold	10-01-1949	01-31-1958
–	02-01-1958	09-30-1972
Talk, SuDen	10-01-1972	04-30-1980
–	05-01-1980	07-31-1986
Talk	08-01-1986	09-30-2010
Talkeetna River near Talkeetna, Alaska (Talk)		
SuGold	10-01-1949	01-31-1958
SuGold, Chul	02-01-1958	05-31-1964
–	06-01-1964	09-30-2010
Susitna River at Sunshine, Alaska (SuSun)		
SuGold	10-01-1949	05-31-1964
SuGold, Talk	06-01-1964	04-30-1981
–	05-01-1981	06-30-1986
SuGold, Talk	07-01-1986	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold, Talk	05-25-2001	09-30-2010
Willow Creek near Willow, Alaska (Will)		
LSu	10-01-1949	05-31-1978
–	06-01-1978	09-30-1993
LSu	10-01-1993	04-30-2001
–	05-01-2001	09-30-2010
Skwentna River near Skwentna, Alaska (Skw)		
SuGold	10-01-1949	09-30-1959
–	10-01-1959	09-30-1982
Yent	10-01-1982	06-30-1986
SuSta	07-01-1986	03-31-1993
SuGold	04-01-1993	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold	05-25-2001	09-30-2010
Yentna River near Susitna Station, Alaska (Yent)		
SuGold	10-01-1949	09-30-1959
Skw	10-01-1959	09-30-1974
Skw, SuSta	10-01-1974	09-30-1980
–	10-01-1980	06-30-1986
SuSta	07-01-1986	03-31-1993
SuGold	04-01-1993	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold	05-25-2001	09-30-2010
Susitna River at Susitna Station, Alaska (SuSta)		
SuGold	10-01-1949	09-30-1959
SuGold, Skw	10-01-1959	05-31-1964
Talk, Skw	06-01-1964	09-30-1974
–	10-01-1974	03-31-1993
SuGold, Talk	04-01-1993	09-30-1996
Talk	10-01-1996	05-24-2001
SuGold, Talk	05-25-2001	09-30-2010

Extended Record Data and Statistics

Extended daily streamflow records for WY 1950–2010 that were computed for the 11 streamgages are presented in appendix B. The observed data available for the same period can be obtained from this file for convenience or from the NWIS website for the most current version. Extended-record data can be merged with data for observed periods to create a continuous composite record for WY 1950–2010.

The composite record of observed and extended values was compiled and used to compute monthly mean and annual statistics for the period WY 1950–2010. Mean monthly discharge for the composite record is presented in table 5 and the percent difference relative to the mean monthly discharge for all available years of the observed record is presented in table 6. Annual mean discharge for the composite record for each year in the period WY 1950–2010 is shown in table 7. Mean annual discharge, a long-term metric computed as the mean of all annual means for a given period, is shown for the composite record for WY 1950–2010 for each streamgage in table 8, which also shows the percent difference from the observed mean annual discharge.

Differences Between Extended and Observed Records

The difference in values between most composite (observed and extended) records for the study period and the available observed records in the study period followed the pattern expected from the amount of extended record relative to the length of the study period (table 6, fig. 7) and the proportion of years added to the record from the PDO cool phase relative to the warm phase (fig. 2). Table 6 quantifies the differences by month, but plots of the mean daily discharge for the composite record for WY 1950–2010 compared to the available observed record during the same period (fig. 8) highlight the systematic differences in streamflow timing. Monthly discharge at stations whose records gained more PDO warm phase years than cool phase years during streamflow record extension (the Susitna River near Denali and near Cantwell, and the Maclaren River, Chulitna River, and Skwentna River streamgages) increased 7.9–46.3 percent in April and May as a result of earlier breakup. A corresponding delay in freeze-up and associated increased streamflows occurs during autumn (September or October) for these stations. The reverse is true for stations whose records gained more PDO cool phase years than warm phase years during extension. Mean monthly discharge at the Yentna River near Susitna Station and at the Susitna River at Susitna Station decreased about 10 percent in April because of a delayed breakup relative to the observed record, and lower October flows corresponded to earlier freeze-up. The extended record for Willow Creek shows breakup beginning at about the same time as in the observed record, but the flow increases slower, resulting in a later snowmelt peak and a 25 percent decrease in mean May discharge. The extended record for the Susitna River at Sunshine gained more PDO cool phase years than warm phase years, which can account for the more than 15 percent decrease in monthly mean discharge in January–March, but breakup appears to be earlier at this site.

Although less prominent than the differences in spring streamflow values, the difference in summer values can be largely explained by the pattern of a lower snowmelt peak for extended records that gained mostly PDO warm phase years and a higher peak for those records that gained mostly PDO cool phase years. For glacier-melt dominated sites whose extended records gained PDO warm phase years, the lower flows persisted through June and July. For the glacier-melt dominated sites whose extended records gained PDO cool phase years, the greater flow was apparent only in June.

The period of extended record relative to the period of observed record for the two primary index stations, Susitna River at Gold Creek and Talkeetna River near Talkeetna, is much smaller than for the other streamgages in the basin (table 6). As expected, shifts in the composited observed and extended record for these sites are minor, never exceeding a 5 percent difference in monthly mean discharge.

Record extension projects variations in the index station record onto the extended record for the site of interest, which governs the distribution of outliers. This is apparent in the minimum and maximum daily mean values for the Susitna River Basin sites. A large mid-February maximum value and a large October maximum value appear in many records as a result of record extension made on the basis of the data for the Susitna River at Gold Creek record. A nearly flat line in some winter maximum daily mean hydrographs appears as a result of extension using the Talkeetna River near Talkeetna record. A spike on February 29 is typically an artifact of the less frequent occurrence of that date, which reduces the potential for long-term averaging.

Table 5. Mean monthly discharge for composite (observed and extended) records for selected streamgages in the Susitna River Basin, Alaska, water years 1950–2010.

[Streamgage locations and map identifiers are shown in figure 1]

Streamgage name	Mean observed and extended discharge for water years 1950–2010 (cubic feet per second)											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Susitna River near Denali, Alaska	1,332	503	326	263	229	212	293	3,124	7,402	8,584	7,305	3,639
Maclaren River near Paxson, Alaska	465	182	125	102	88	81	106	1,142	2,798	2,915	2,419	1,288
Susitna River near Cantwell, Alaska	3,798	1,601	1,126	938	820	755	1,032	8,629	16,860	15,840	13,910	8,625
Susitna River at Gold Creek, Alaska	6,319	2,672	1,893	1,593	1,420	1,303	1,743	13,790	26,290	23,990	21,430	13,770
Chulitna River near Talkeetna, Alaska	5,751	2,261	1,545	1,302	1,143	1,061	1,369	10,350	21,510	23,200	20,580	12,580
Talkeetna River near Talkeetna, Alaska	2,836	1,162	801	655	553	502	670	5,123	10,720	10,260	9,206	5,941
Susitna River at Sunshine, Alaska	15,910	6,491	4,494	3,721	3,257	2,957	4,028	33,190	63,680	60,460	54,200	34,860
Willow Creek near Willow, Alaska	332	153	105	84	71	60	79	487	1,043	745	666	573
Skwentna River near Skwentna, Alaska	4,781	2,023	1,396	1,162	1,017	916	1,331	9,278	17,390	16,720	14,230	9,321
Yentna River near Susitna Station, Alaska	13,400	5,349	3,642	3,021	2,655	2,402	3,484	26,940	50,640	49,870	43,070	27,940
Susitna River at Susitna Station, Alaska	36,000	14,390	9,513	7,909	7,082	6,512	8,995	66,060	120,000	121,600	109,000	72,810

Table 6. Difference in mean monthly discharge between composite (observed and extended) records and observed records for selected streamgages in the Susitna River Basin, Alaska, water years 1950–2010.

[Streamgage locations and map identifiers are shown in figure 1. **Difference in mean monthly discharge:** Positive values indicate that the values in the composite record are greater than the values in the observed record only]

Streamgage name	Difference in mean monthly discharge (percent)												Amount of composite record consisting of extended values (percent)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	
Susitna River near Denali, Alaska	12.8	-4.2	-3.8	0.2	3.9	6.4	25.8	46.3	1.7	-12.7	-10.5	10.4	55
Maclaren River near Paxson, Alaska	10.5	-5.2	-3.8	-2.9	-1.6	-1.2	18.7	34.4	-3.3	-10.0	-5.1	13.4	54
Susitna River near Cantwell, Alaska	12.9	1.7	0.8	-2.4	-1.2	-3.1	12.8	9.1	-7.5	-9.7	-6.8	8.7	71
Susitna River at Gold Creek, Alaska	-0.4	-0.3	0.1	0.2	0.4	0.5	-0.6	-2.5	-0.5	0.5	0.5	0.5	8
Chulitna River near Talkeetna, Alaska	10.9	4.2	-2.0	-4.8	1.0	6.0	16.9	26.7	0.2	-12.0	-8.6	6.3	66
Talkeetna River near Talkeetna, Alaska	-3.7	-3.2	-2.3	-1.7	-1.6	-1.2	-4.7	1.4	0.8	1.1	1.1	1.4	24
Susitna River at Sunshine, Alaska	-4.2	-4.4	-7.9	-14.9	-17.3	-15.4	2.0	18.7	12.8	-8.7	-11.1	-1.0	92
Willow Creek near Willow, Alaska	-22.2	-3.2	0.0	0.2	-2.3	-1.3	-17.5	-25.4	6.3	17.0	7.8	-9.5	59
Skwentna River near Skwentna, Alaska	5.7	4.0	5.2	3.8	6.6	9.4	21.6	7.9	-8.5	-5.2	6.2	10.1	62
Yentna River near Susitna Station, Alaska	-4.3	-8.1	-6.4	-7.5	-10.9	-6.8	-9.8	1.9	5.5	-6.6	-12.2	1.2	91
Susitna River at Susitna Station, Alaska	-9.0	-9.9	-4.7	-6.8	-8.5	-8.8	-10.2	1.9	1.3	-6.7	-3.6	-2.2	70

Table 7. Annual mean discharge for composite (observed and extended) records for selected streamgages in the Susitna River Basin, Alaska, water years 1950–2010.

[Streamgage locations and map identifiers are shown in figure 1]

Water year	Observed and extended annual mean discharge (cubic feet per second)										
	SuDen	Mac	SuCant	SuGold	Chul	Talk	SuSun	Will	Skw	Yent	SuSta
1950	2,198	816	5,078	8,032	7,412	3,393	19,600	277	5,516	16,340	42,430
1951	2,620	978	5,785	9,106	8,467	3,863	22,340	394	6,187	18,520	47,340
1952	2,572	962	6,060	9,529	8,189	4,033	22,950	423	6,279	18,330	46,820
1953	2,831	1,066	6,412	10,090	9,238	4,260	24,690	351	6,829	20,430	52,150
1954	2,812	1,037	6,146	9,681	8,894	4,087	23,740	308	6,557	19,570	49,750
1955	2,727	1,033	6,516	10,260	8,730	4,321	24,610	391	6,727	19,700	50,300
1956	3,179	1,192	7,315	11,450	9,790	4,876	27,600	343	7,424	21,790	55,220
1957	3,646	1,103	6,606	10,380	9,241	4,363	25,270	361	6,951	20,640	52,270
1958	2,514	1,106	5,995	9,476	8,765	3,969	22,990	271	6,420	18,880	48,680
1959	2,614	843	6,707	10,560	8,376	4,068	25,480	405	6,915	20,410	51,720
1960	2,896	1,184	6,145	9,690	8,363	3,917	23,570	340	6,387	17,910	47,690
1961	2,655	1,111	6,463	10,810	9,451	4,352	26,300	382	7,255	20,320	52,230
1962	3,191	1,011	7,995	11,570	8,818	4,365	27,540	431	5,699	15,990	47,930
1963	3,148	1,287	7,372	11,070	8,268	4,151	26,680	500	5,854	16,410	47,100
1964	2,604	960	6,615	9,774	9,312	3,952	22,590	352	6,266	17,540	42,660
1965	2,510	985	6,629	10,170	9,365	4,749	25,790	385	6,628	18,560	49,260
1966	2,411	816	5,190	9,432	8,648	4,221	23,630	327	6,427	18,010	46,260
1967	2,970	1,149	6,843	11,220	11,110	4,470	26,860	423	5,607	15,720	45,200
1968	3,430	896	6,131	9,789	9,172	4,468	24,560	379	6,438	18,030	46,830
1969	2,290	697	4,186	5,597	6,110	2,249	13,950	205	5,199	14,580	33,450
1970	2,243	735	4,548	7,591	8,736	3,500	19,690	308	7,241	20,260	46,630
1971	2,903	1,092	6,824	10,250	8,406	5,299	25,400	399	6,937	19,390	47,830
1972	2,937	1,059	6,907	10,860	8,340	4,479	26,460	402	5,998	16,810	46,730
1973	2,242	890	5,107	8,087	7,589	3,851	20,850	350	5,243	14,720	41,360
1974	2,960	846	4,822	7,630	7,910	3,325	19,530	337	5,156	14,480	39,990
1975	3,003	1,033	6,549	10,280	8,969	4,336	25,390	410	6,491	18,920	46,100
1976	2,578	920	5,166	8,169	7,589	3,398	20,500	311	5,823	17,200	42,990
1977	3,048	1,156	6,405	10,110	8,745	4,355	24,750	434	10,060	26,260	55,980
1978	2,683	925	5,155	8,194	7,659	3,301	20,420	256	6,372	17,760	42,000
1979	3,039	886	6,032	9,490	8,937	4,446	23,990	433	6,629	20,700	53,670
1980	2,912	1,015	6,772	10,720	9,650	4,345	26,100	511	9,053	26,010	61,920

Accuracy and Limitations of Extended Record

The accuracy of the estimates for daily discharge is indicated by two statistics, the root mean square error (RMSE) of the estimating equations for each index station, and the Nash Sutcliffe efficiency (NSE) statistics for the final values, which could include more than one index station. The regression equation model RMSE (table 3) indicates the fit of the multi-segment line to the plot of the logs of the concurrent daily values for every index station/site of interest pair. These model RMSEs ranged from 0.05 to 0.18. The NSE statistic provided a measure of the fit of the final predicted values (the weighted value when more than one index station was used) to the observed record. NSE coefficients for the final models ranged from 0.75 to 0.93 (table 9). Both of these statistics measure the strength of the fit during the concurrent period, but cannot evaluate the error in the values for the extended period.

Table 7. Annual mean discharge for composite (observed and extended) records for selected streamgages in the Susitna River Basin, Alaska, water years 1950–2010.—Continued

[Streamgage locations and map identifiers are shown in figure 1]

Water year	Observed and extended annual mean discharge (cubic feet per second)										
	SuDen	Mac	SuCant	SuGold	Chul	Talk	SuSun	Will	Skw	Yent	SuSta
1981	3,395	1,168	7,887	11,960	10,410	4,416	28,350	367	9,055	24,920	55,730
1982	2,622	806	6,019	9,668	8,455	4,204	24,080	427	6,132	18,640	47,080
1983	2,827	994	6,515	9,924	8,224	3,635	23,570	349	6,390	18,330	43,830
1984	2,927	938	6,648	9,578	8,457	3,635	23,490	331	6,952	19,970	45,370
1985	3,003	1,072	5,933	9,880	8,456	4,259	24,300	468	6,844	19,670	47,260
1986	2,969	1,062	5,773	8,531	7,472	3,352	20,620	320	6,481	19,680	46,350
1987	3,060	1,072	6,706	10,550	9,865	4,812	26,740	416	7,755	23,600	54,900
1988	3,046	983	6,501	10,220	8,077	3,736	24,840	349	7,521	22,850	53,570
1989	3,210	1,033	6,503	10,250	8,957	4,239	25,550	413	7,985	24,410	56,480
1990	3,698	1,286	8,308	13,020	10,940	5,389	31,770	536	8,609	26,380	61,190
1991	2,603	855	5,391	8,532	7,940	3,779	21,610	383	6,743	20,590	48,200
1992	2,425	863	5,514	8,720	7,512	3,525	21,590	335	6,081	18,370	43,900
1993	3,043	1,093	6,411	10,100	10,010	4,839	26,020	383	6,834	20,400	53,120
1994	2,772	990	6,302	9,960	9,169	4,344	25,070	413	6,709	19,810	51,770
1995	2,847	1,020	6,537	10,290	8,682	4,039	25,420	360	6,975	20,610	51,330
1996	1,855	648	4,260	6,800	6,789	3,115	17,700	245	4,750	13,810	38,290
1997	2,435	827	5,514	8,800	7,667	3,581	23,140	317	6,049	18,440	44,550
1998	2,666	907	5,886	9,382	8,233	3,854	24,550	336	6,379	19,480	47,080
1999	2,519	864	5,808	9,294	8,078	3,850	24,370	326	6,361	19,510	46,590
2000	2,745	963	6,397	10,230	8,900	4,447	26,620	429	6,913	21,100	50,260
2001	2,506	901	6,026	9,539	7,845	3,703	23,790	355	6,379	19,170	46,930
2002	2,421	865	5,364	8,483	8,095	3,801	21,680	315	5,800	17,110	45,130
2003	2,819	1,002	6,514	10,280	9,083	4,248	25,630	338	6,927	20,330	52,430
2004	2,574	912	5,955	9,396	7,899	3,606	23,320	268	6,401	18,920	47,740
2005	3,656	1,330	7,821	12,210	11,700	5,856	30,880	607	7,973	23,600	61,390
2006	2,706	983	6,552	10,310	8,285	4,014	24,940	434	6,800	20,040	49,470
2007	2,548	917	6,102	9,649	7,838	3,588	23,750	313	6,636	19,780	48,520
2008	2,357	844	5,626	8,905	7,458	3,424	22,010	314	6,115	18,040	45,280
2009	2,525	904	6,022	9,499	7,731	3,558	23,390	289	6,472	19,210	47,690
2010	2,724	983	6,442	10,140	8,178	3,765	24,850	293	6,870	20,500	50,300

In addition to the accuracy of the estimates, users should consider limitations inherent in the data or introduced by the streamflow extension methods. The quality of the flow records for periods of estimated streamflow (including ice-affected winter periods, and periods of likely estimated data in 1954, 1956, 1958, and 1961–63 at Susitna River at Gold Creek) are categorized by the USGS as poor, indicating that the values may diverge from the actual values by more than 8 percent.

The effect of establishing multi-segment regression lines on the basis of magnitude of streamflow, rather than by seasons, is that annual estimates will be more accurate than monthly or daily estimates. For example, for Susitna River near Denali, the index stations generally slightly overestimated early-season peaks (similar to the case in fig. 6*B*) and slightly underestimated mid-summer peaks. The extended records are less appropriate for analyzing specifics of the distribution of flows across a season (such as the date of occurrence of the highest flows within the high flow season) than for computing statistics that synthesize streamflow over a month or longer.

Predicted low flows generally did not match observed low flows as well as predicted high flows matched observed high flows. Under-ice low flow is estimated, and can be driven by hydrologic basin conditions not shared by other basins. Conclusions about patterns in low flows should consider the greater uncertainty in these values.

Table 8. Mean annual discharge for composite (observed and extended) records and difference from observed records for selected streamgages in the Susitna River Basin, Alaska, water years 1950–2010.

[Streamgage locations and map identifiers are shown in figure 1. **Difference in mean annual discharge between composite and observed records:** Positive values indicate that the values in the composite record are greater than the values in the observed record only. **Abbreviations:** ft^3/s, cubic feet per second; WY, water year]

Streamgage name	Mean annual discharge for composite record, WY 1950–2010 (ft^3/s)	Difference in mean annual discharge between composite record (WY 1950–2010) and observed record (period varies) (percent)
Susitna River near Denali, Alaska	2,785	0.4
Maclaren River near Paxson, Alaska	982	0.1
Susitna River near Cantwell, Alaska	6,192	-3.1
Susitna River at Gold Creek, Alaska	9,724	-0.2
Chulitna River near Talkeetna, Alaska	8,601	-1.8
Talkeetna River near Talkeetna, Alaska	4,055	0.6
Susitna River at Sunshine, Alaska	24,060	0.8
Willow Creek near Willow, Alaska	368	-3.9
Skwentna River near Skwentna, Alaska	6,663	0.8
Yentna River near Susitna Station, Alaska	19,470	-4.1
Susitna River at Susitna Station, Alaska	48,560	-3.6

Table 9. Nash Sutcliffe efficiency (NSE) coefficients comparing observed and predicted discharge values at selected streamgages in the Susitna River Basin, Alaska.

[Streamgage locations and map identifiers are shown in figure 1. NSE, modified Nash Sutcliffe efficiency coefficient (Legates and McCabe, 1999)]

Streamgage name	USGS station identification No.	Index stations used for predicted values	NSE for full period of observed values
Susitna River near Denali, Alaska	15291000	SuGold, Talk, SuSta	0.78
Maclaren River near Paxson, Alaska	15291200	SuGold, Talk	0.80
Susitna River near Cantwell, Alaska	15291500	SuGold, Talk	0.86
Susitna River at Gold Creek, Alaska	15292000	Talk	0.81
Chulitna River near Talkeetna, Alaska	15292400	SuGold, Talk, SuDen	0.85
Talkeetna River near Talkeetna, Alaska	15292700	SuGold, Chul	0.82
Susitna River at Sunshine, Alaska	15292780	SuGold, Talk	0.93
Willow Creek near Willow, Alaska	15294005	LSu	0.75
Skwentna River near Skwentna, Alaska	15294300	SuGold, Yent, SuSta, Talk	0.78
Yentna River near Susitna Station, Alaska	15294345	SuGold, Skw, SuSta, Talk	0.88
Susitna River at Susitna Station, Alaska	15294350	SuGold, Skw, Talk	0.86

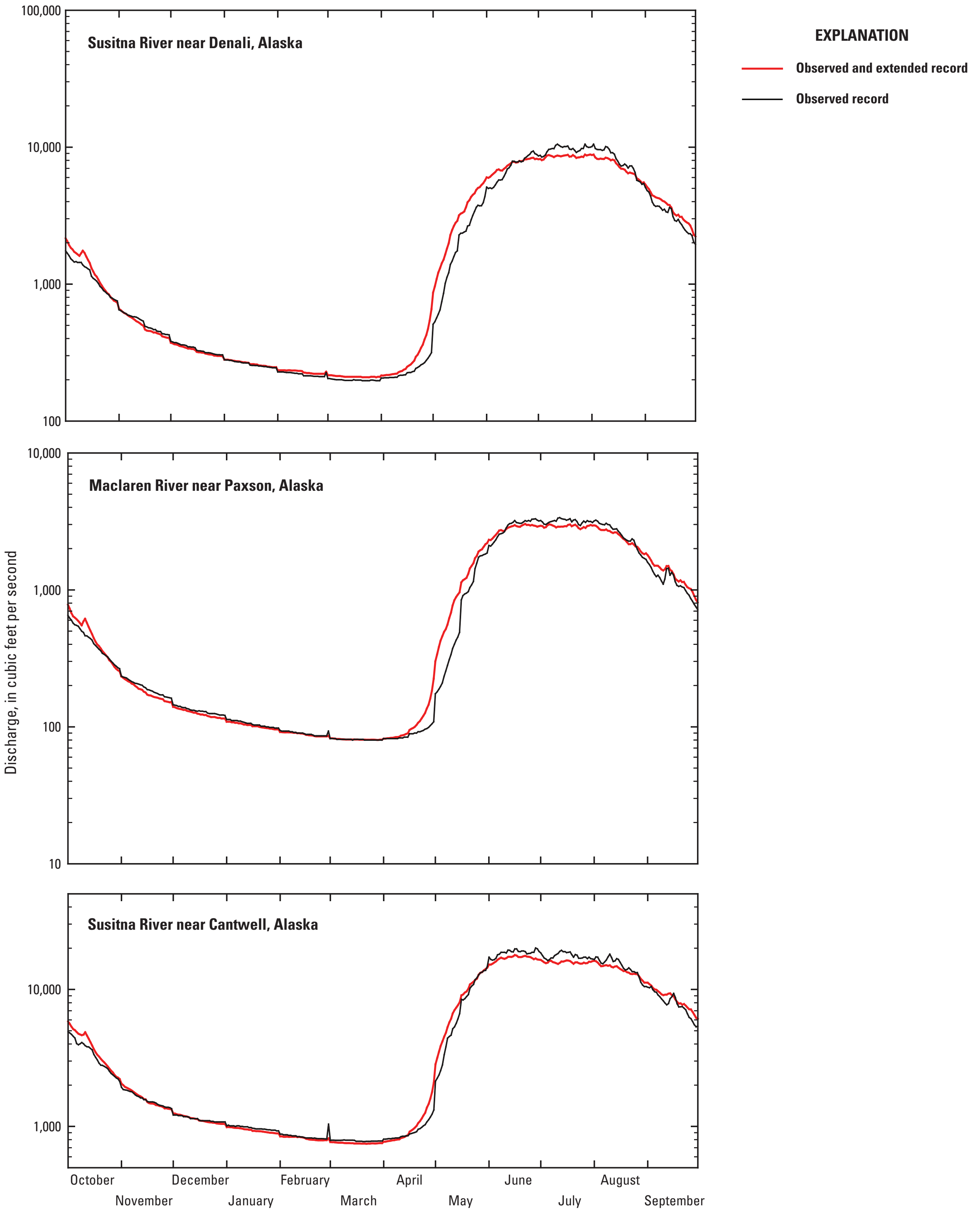


Figure 8. Mean daily discharge for composite (observed and extended) records for water year 1950–2010 and observed records for the available period of record for selected streamgages, Susitna River Basin, Alaska. Plots show the mean of all discharge values for each calendar day during the respective period of record. Locations, full station names, numbers, and map identifiers are shown in figure 1.

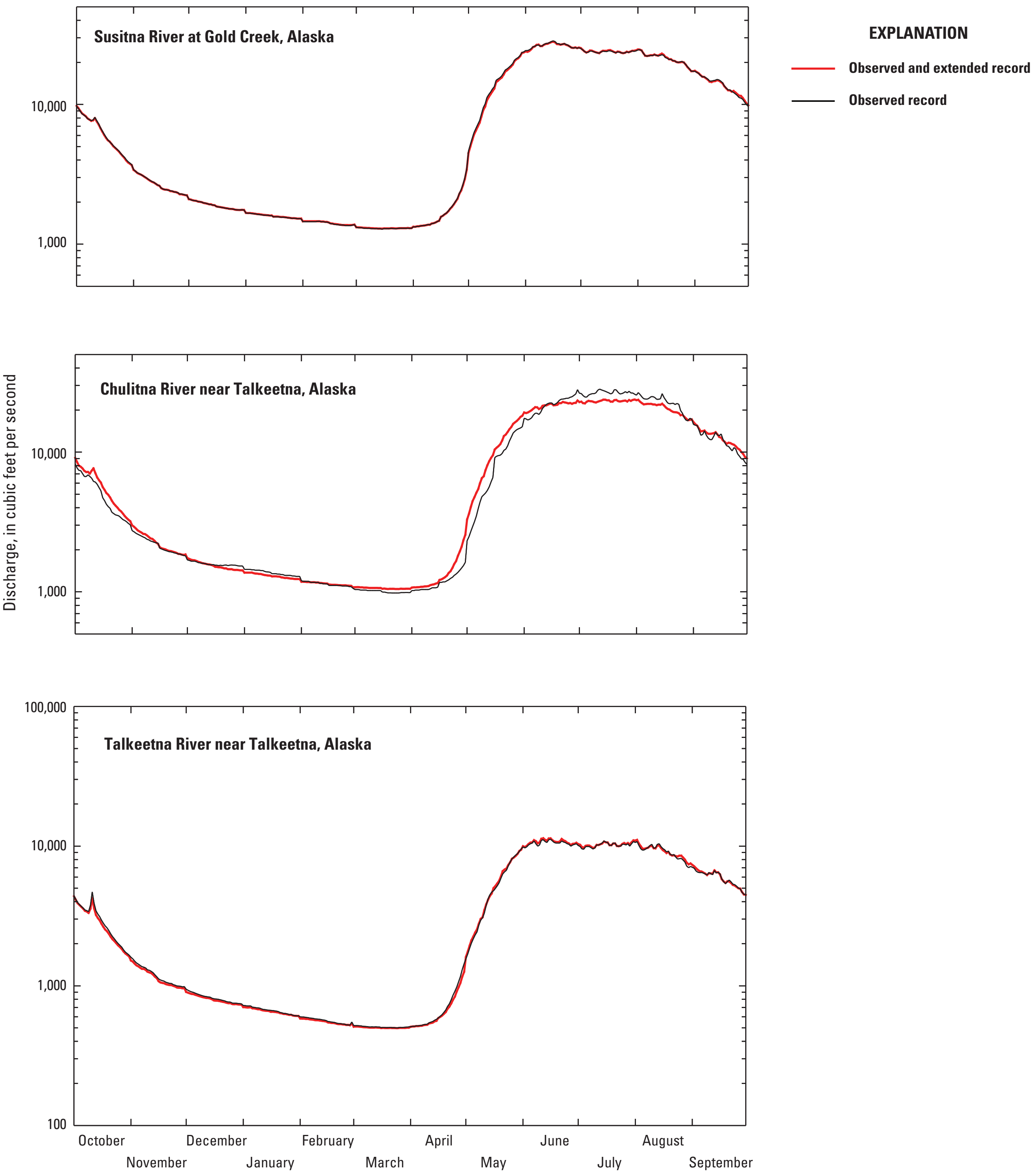


Figure 8.—Continued

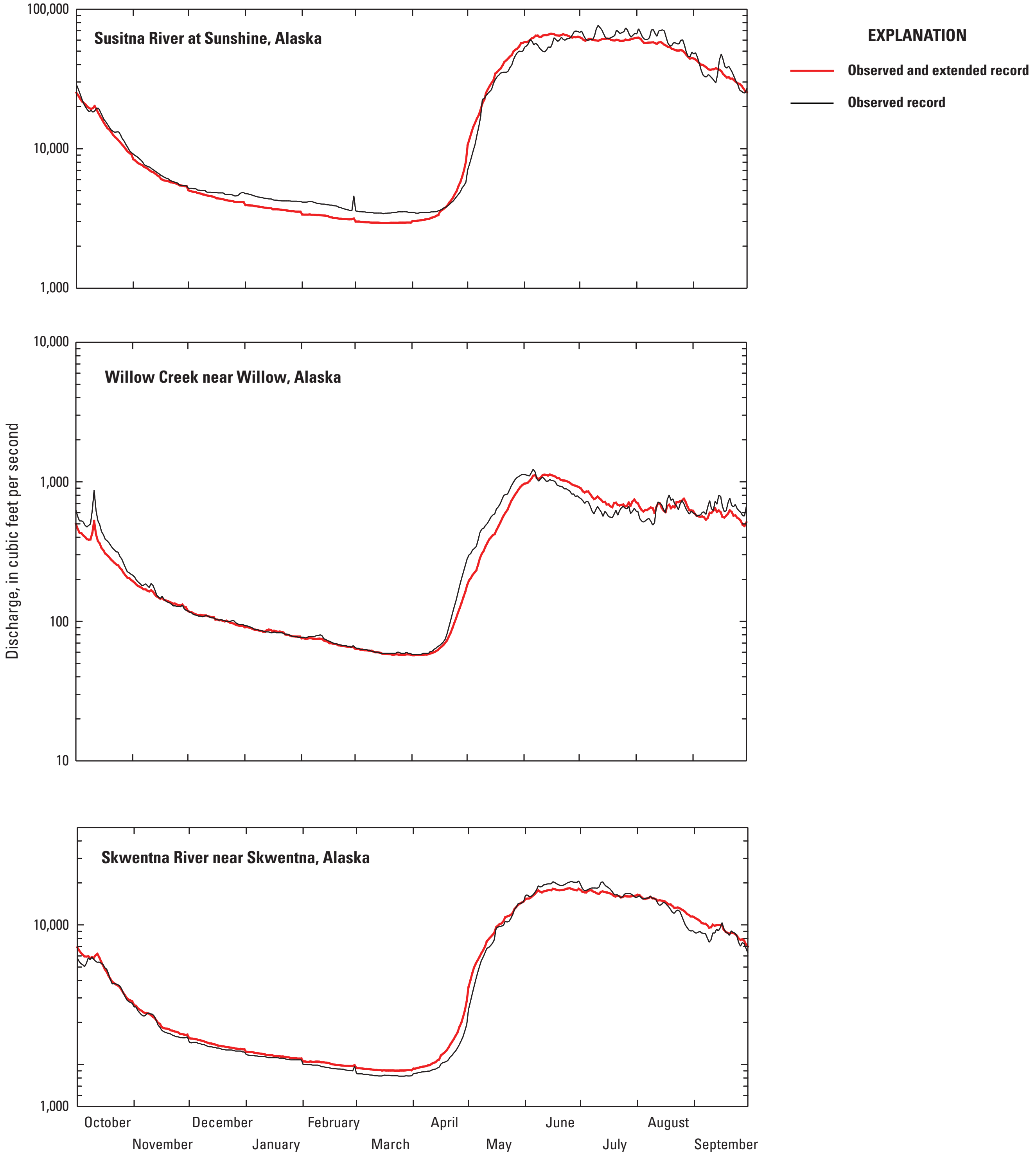


Figure 8.—Continued

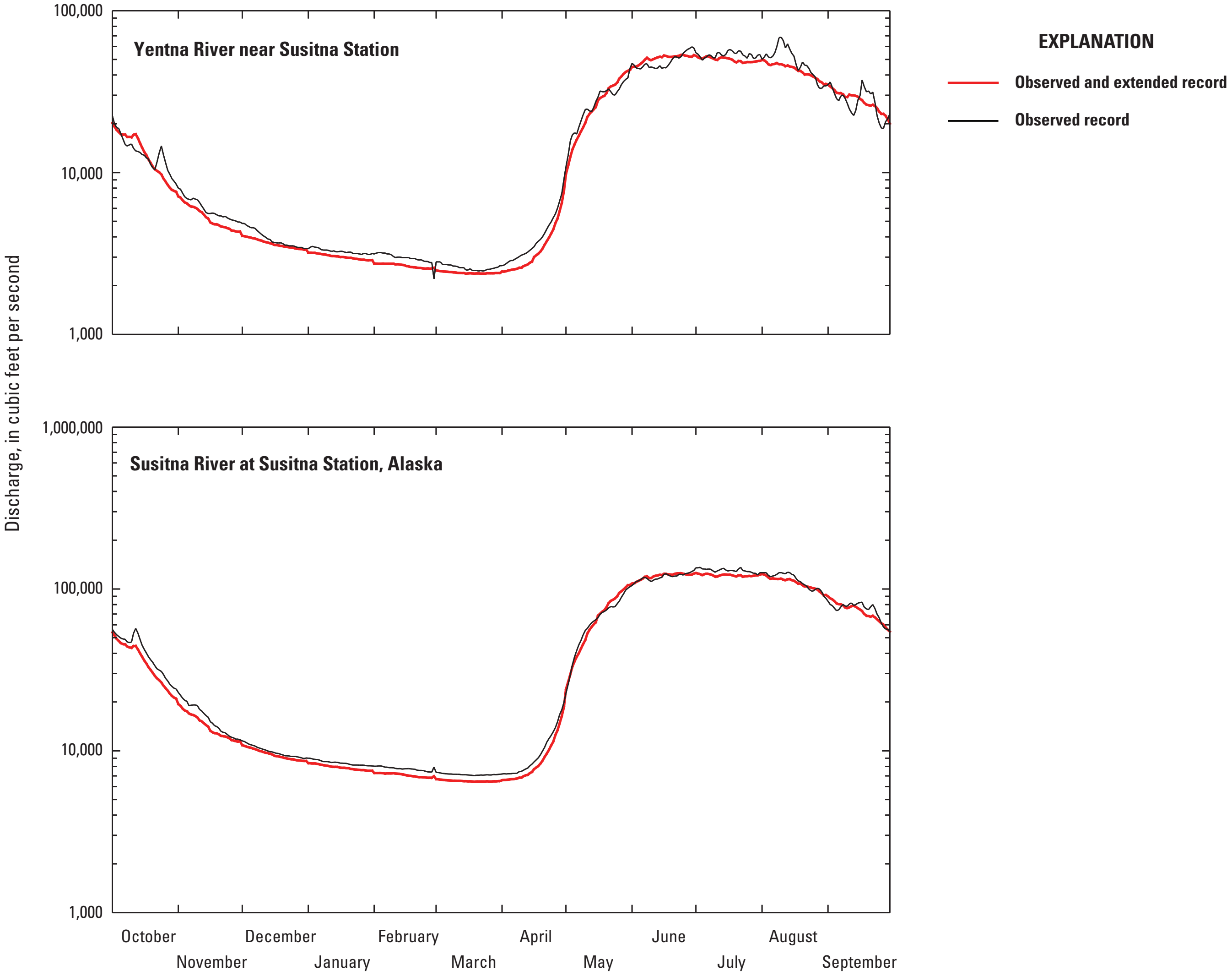


Figure 8.—Continued

Summary

Streamflow data in the Susitna River Basin include records from 14 streamgages during the period of water year 1950–2010, but no single streamgage collected data for the entire period. Additionally, many streamgages were operated for mostly one phase of the Pacific Decadal Oscillation (PDO), a climate pattern that affects streamflow timing, and thus may not represent long-term flow patterns. Streamflow records can be extended to estimate flow for a site of interest when daily discharge at an index station is well correlated with daily discharge at the site and available for the desired extended period. The extended streamflow records then provide a continuous string of daily discharge and can improve long-term streamflow statistics.

To examine the suitability of record extension for streams in the Susitna River Basin, the streams were sorted into glacier-melt, snowmelt-and-glacier-melt, snowmelt, and snowmelt-and-rainfall dominated groups on the basis of the relative magnitude of and trends in spring and summer streamflow. Correlation coefficients computed for all possible pairs of sites and index stations showed adequate correlation (*r* greater than 0.95) with one or more index stations for the study period for all but three lowland sites in the snowmelt-and-rainfall dominated group, Montana Creek, Deception Creek, and the Deshka River. Records for streams in which the flow showed at least a moderate mid-summer effect of glacier melt correlated better with the records for the long-term index stations, Susitna River at Gold Creek and Talkeetna River near Talkeetna, than did records for streams not affected by glacier melt.

The Kendall-Theil Robust Line method, a nonparametric approach to regression analysis, provided the most technically appropriate and computationally feasible method for extending streamflow records for the 11 well-correlated records. Multiple line segments addressed the variation in the relationship between stations for particularly high and low flows. Index stations were used singly or in pairs to compute extended records, and weighted by their respective error to produce final extended daily discharge values.

Resulting composited extended and observed records, when compared to the observed records only, show shifts in streamflow timing and magnitude largely as expected from the relative proportion of years in the PDO cool and warm phases added to the record. Monthly means for the months when breakup occurs, typically April or May, and for the typical freeze-up months of September or October, were higher for sites whose extended records were supplemented with warm phase PDO years and lower for those supplemented with cool phase PDO years. Monthly means were correspondingly lower through mid-to-late-summer (July and August) at sites whose extended records gained additional warm phase PDO years and in June for sites whose extended records gained additional cool phase PDO years.

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Appendix A. Plots of Daily Discharge and Best-Fit Multi-Segment Kendall-Theil Regression Lines for Sites of Interest and Index Stations for Concurrent Periods during Water Years 1950–2010, Susitna River Basin, Alaska

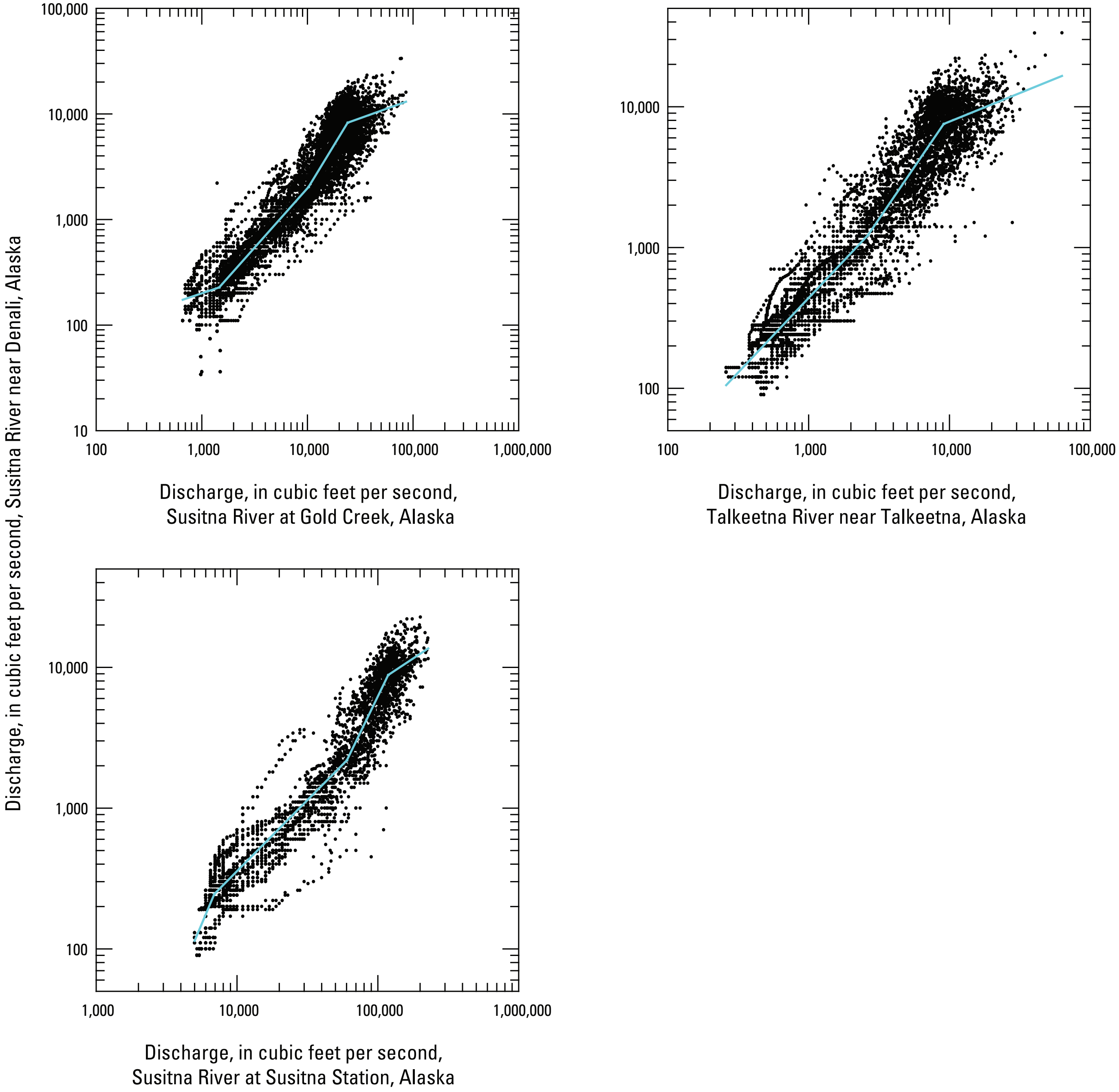

Figure A1. Correlation of concurrent daily mean discharge between Susitna River near Denali and Susitna River at Gold Creek, Talkeetna River near Talkeetna, and Susitna River at Susitna Station, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

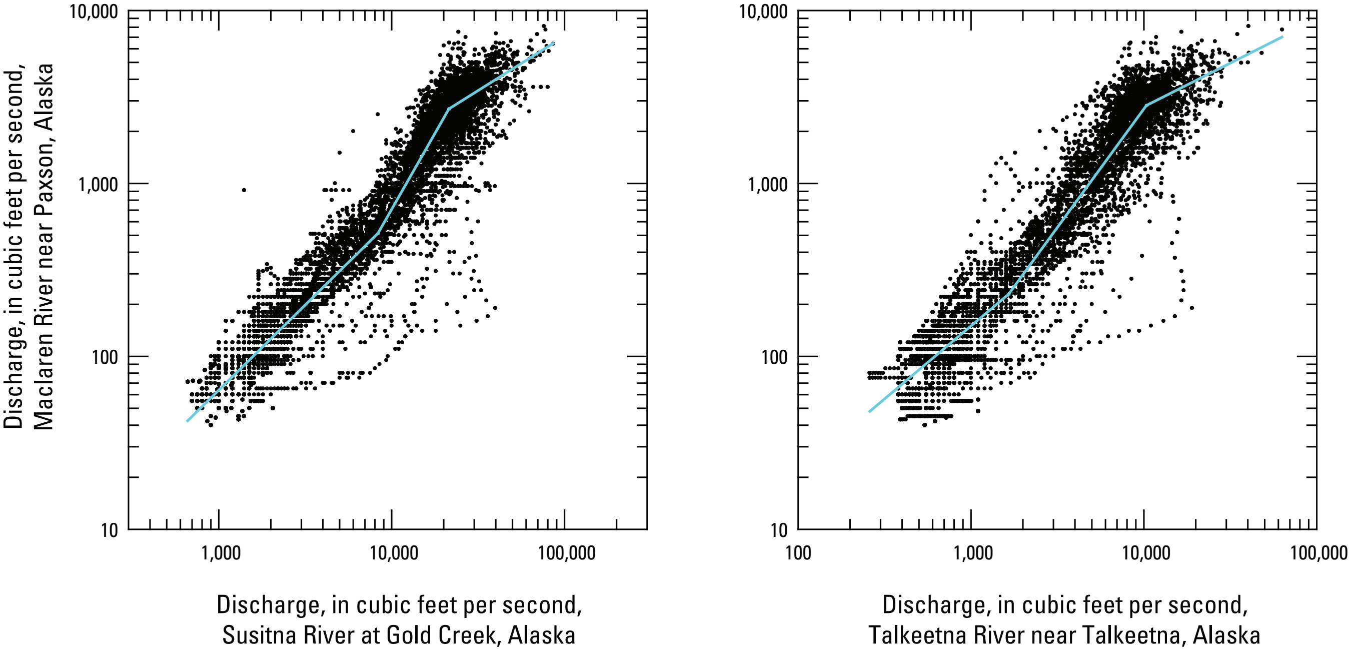

Figure A2. Correlation of concurrent daily mean discharge between Maclaren River near Paxson and Susitna River at Gold Creek and Talkeetna River near Talkeetna, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

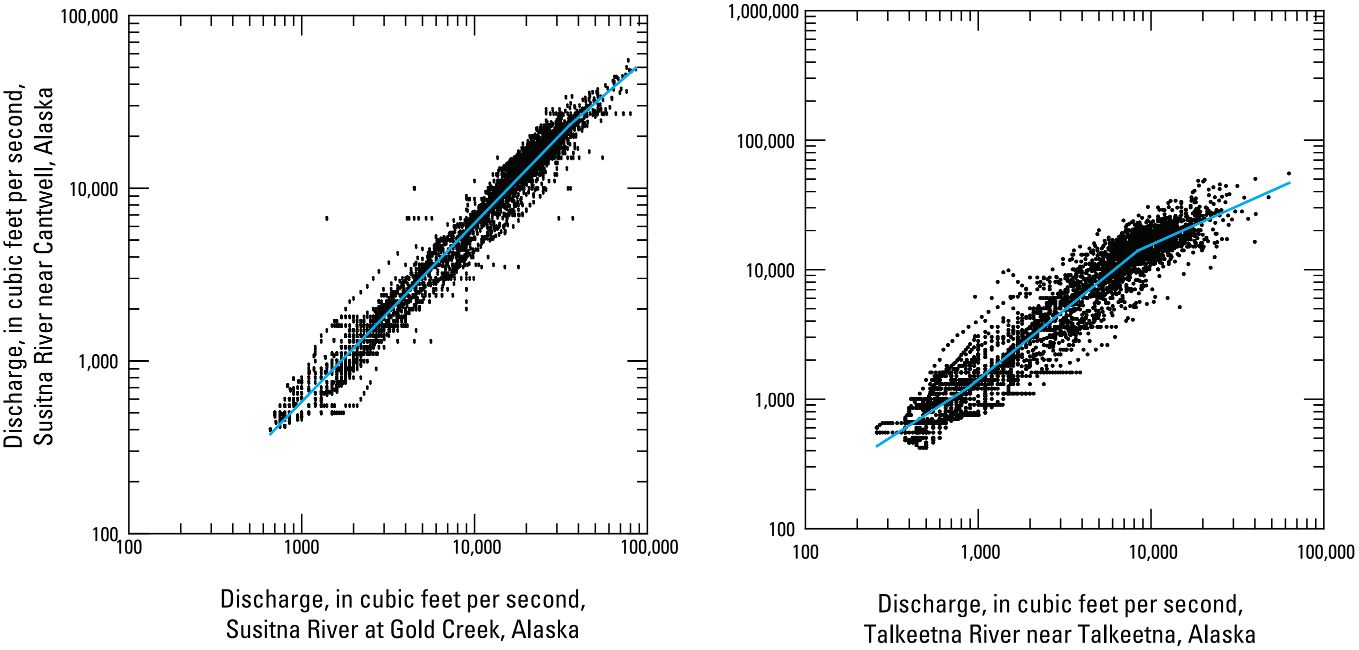

Figure A3. Correlation of concurrent daily mean discharge between Susitna River near Cantwell and Susitna River at Gold Creek and Talkeetna River near Talkeetna, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

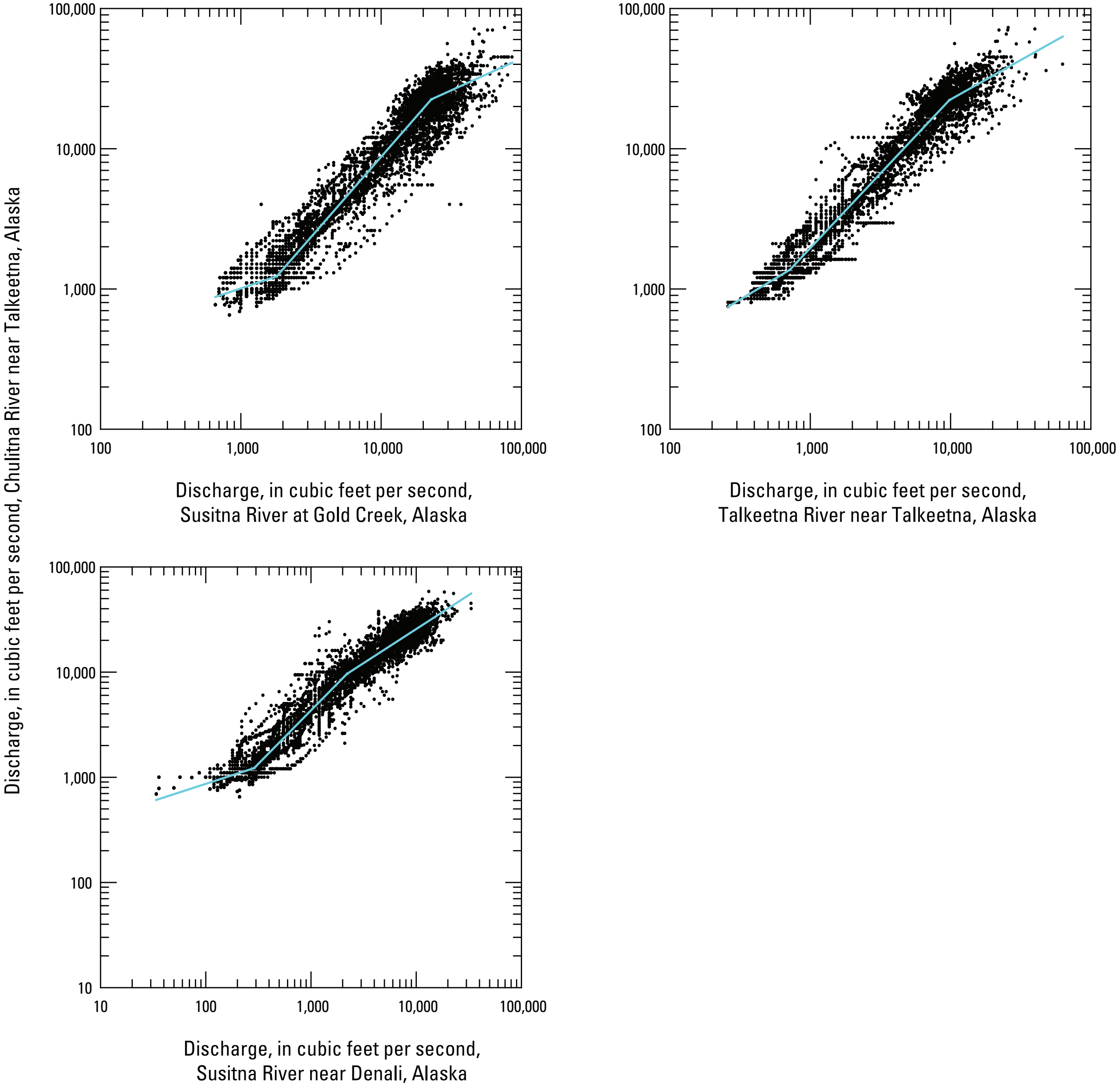

Figure A4. Correlation of concurrent daily mean discharge between Chulitna River near Talkeetna and Susitna River at Gold Creek, Talkeetna River near Talkeetna, and Susitna River near Denali, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

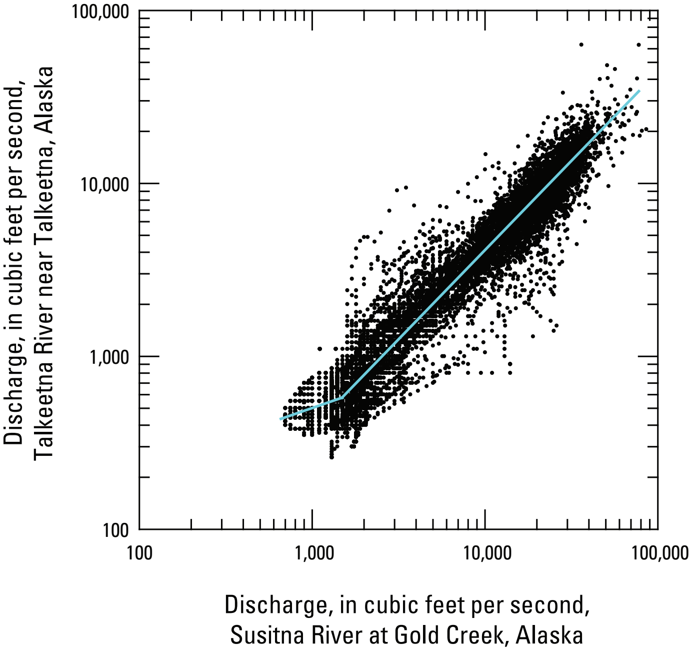

Figure A5. Correlation of concurrent daily mean discharge between Talkeetna River near Talkeetna and Susitna River at Gold Creek, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

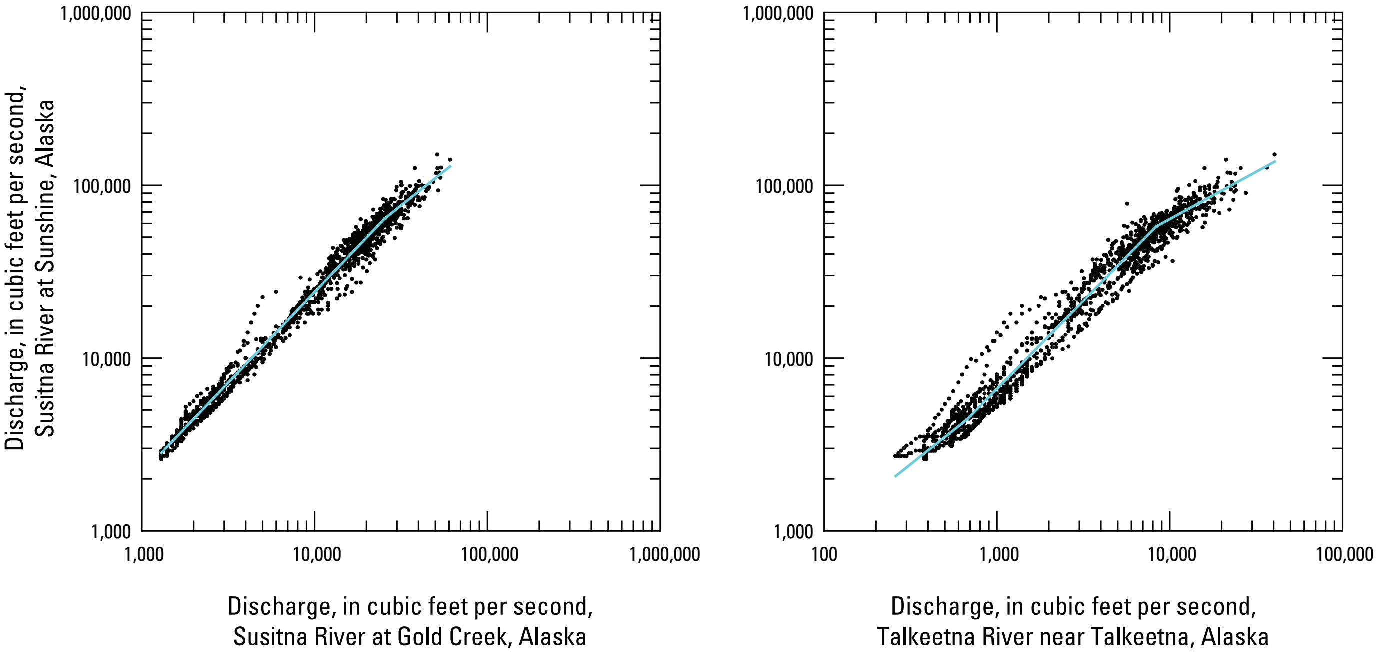

Figure A6. Correlation of concurrent daily mean discharge between Susitna River near Susitna and Susitna River at Gold Creek and Talkeetna River near Talkeetna, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

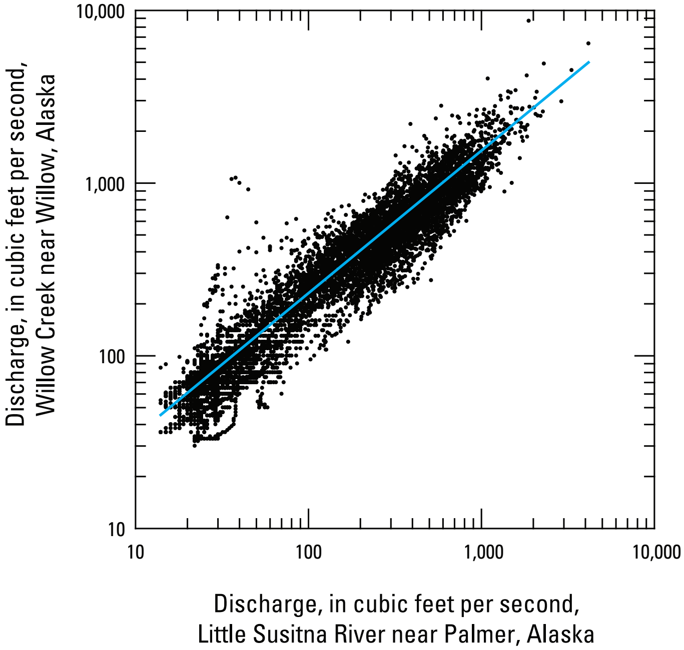

Figure A7. Correlation of concurrent daily mean discharge between Willow Creek near Willow and Little Susitna River near Palmer, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

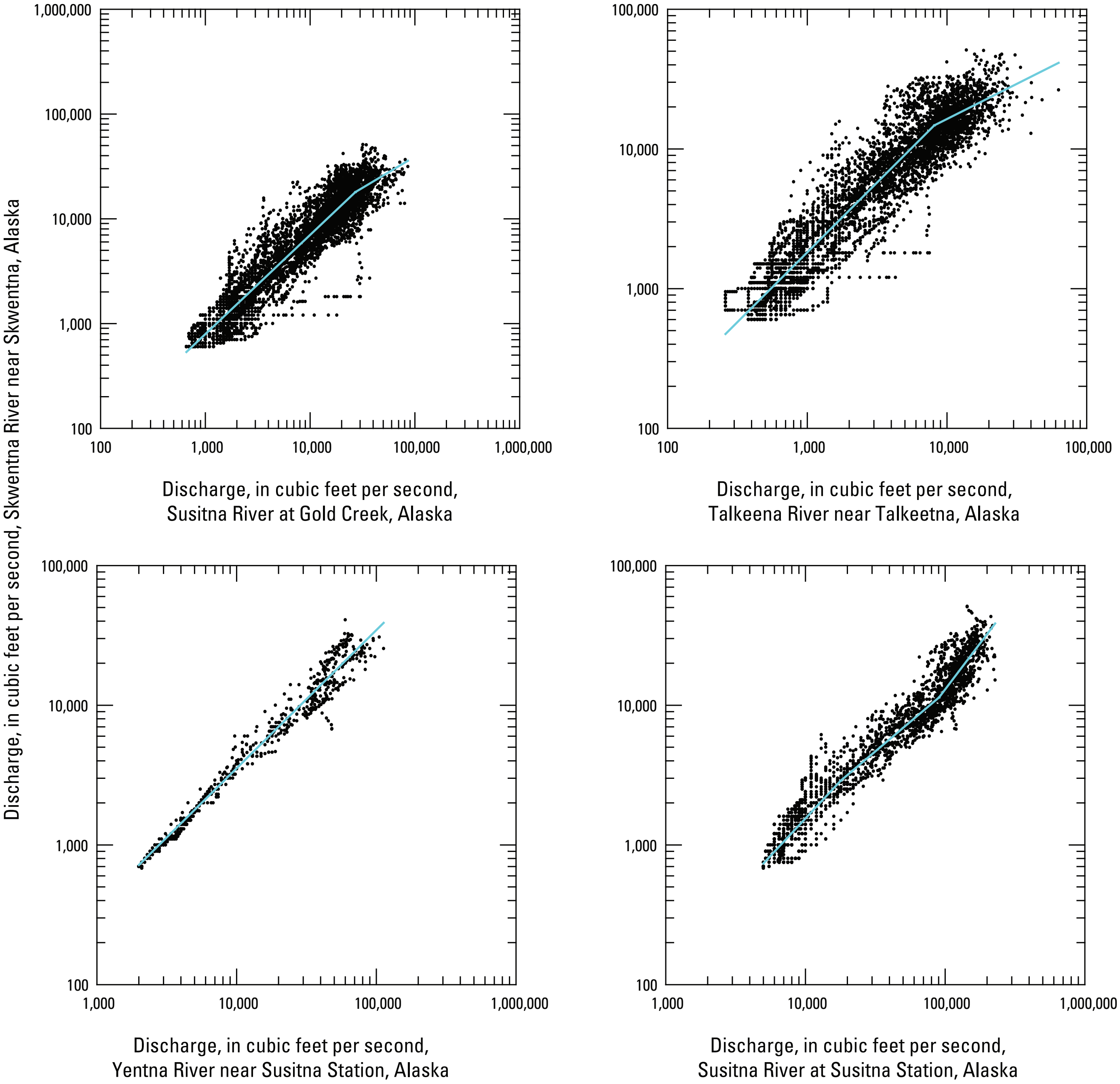

Figure A8. Correlation of concurrent daily mean discharge between Skwentna River near Skwentna and Susitna River at Gold Creek, Talkeetna River near Talkeetna, Yentna River near Susitna Station, and Susitna River at Susitna Station, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

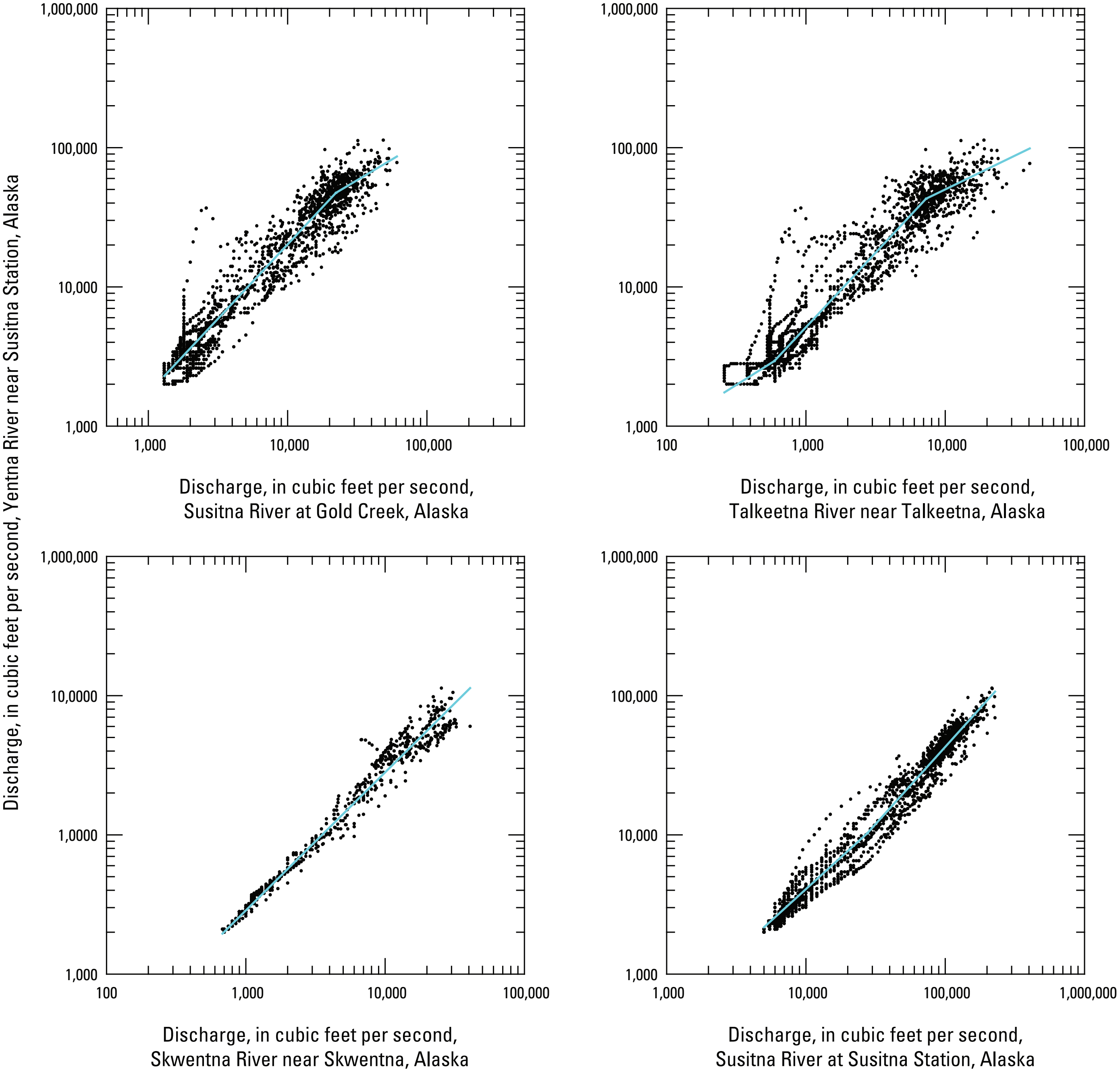

Figure A9. Correlation of concurrent daily mean discharge between Yentna River near Susitna Station and Susitna River at Gold Creek, Talkeetna River near Talkeetna, Skwentna River near Skwentna, and Susitna River at Susitna Station, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

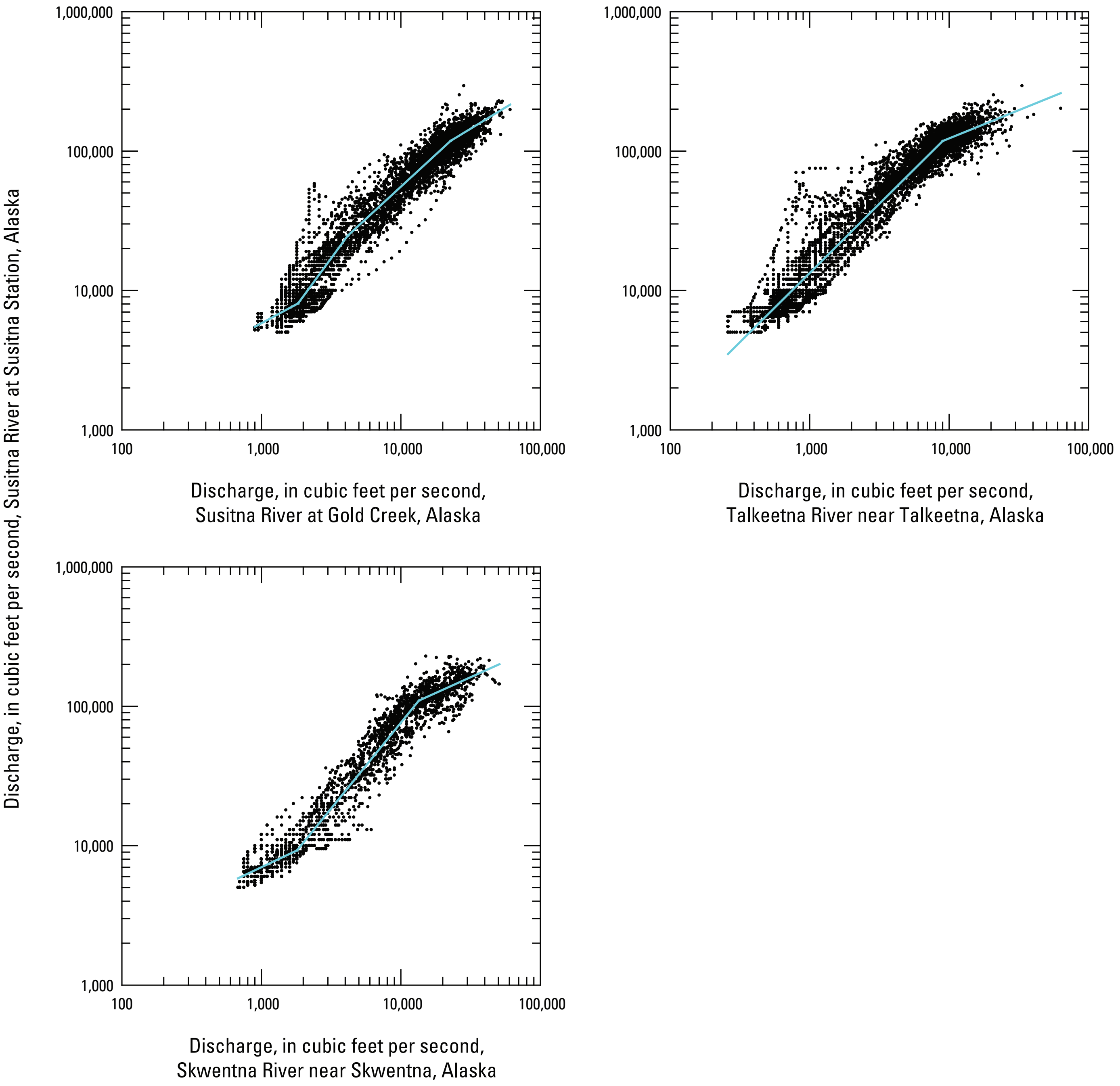

Figure A10. Correlation of concurrent daily mean discharge between Susitna River at Susitna Station and Susitna River at Gold Creek, Talkeetna River near Talkeetna, and Skwentna River near Skwentna, Susitna River Basin, Alaska, water years 1950–2010, and Kendall-Theil Robust Line regression line.

Appendix B. Extended and Observed Streamflow Records for Water Years 1950–2010 for Selected Streamgages, Susitna River Basin, Alaska

(Microsoft® Excel file available for download at http://pubs.usgs.gov/sir/2012/5210)

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Publishing support provided by the U.S. Geological Survey
Publishing Network, Tacoma Publishing Service Center

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Curran— **Streamflow Record Extension for Selected Streams in the Susitna River Basin, Alaska**—Scientific Investigations Report 2012–5210