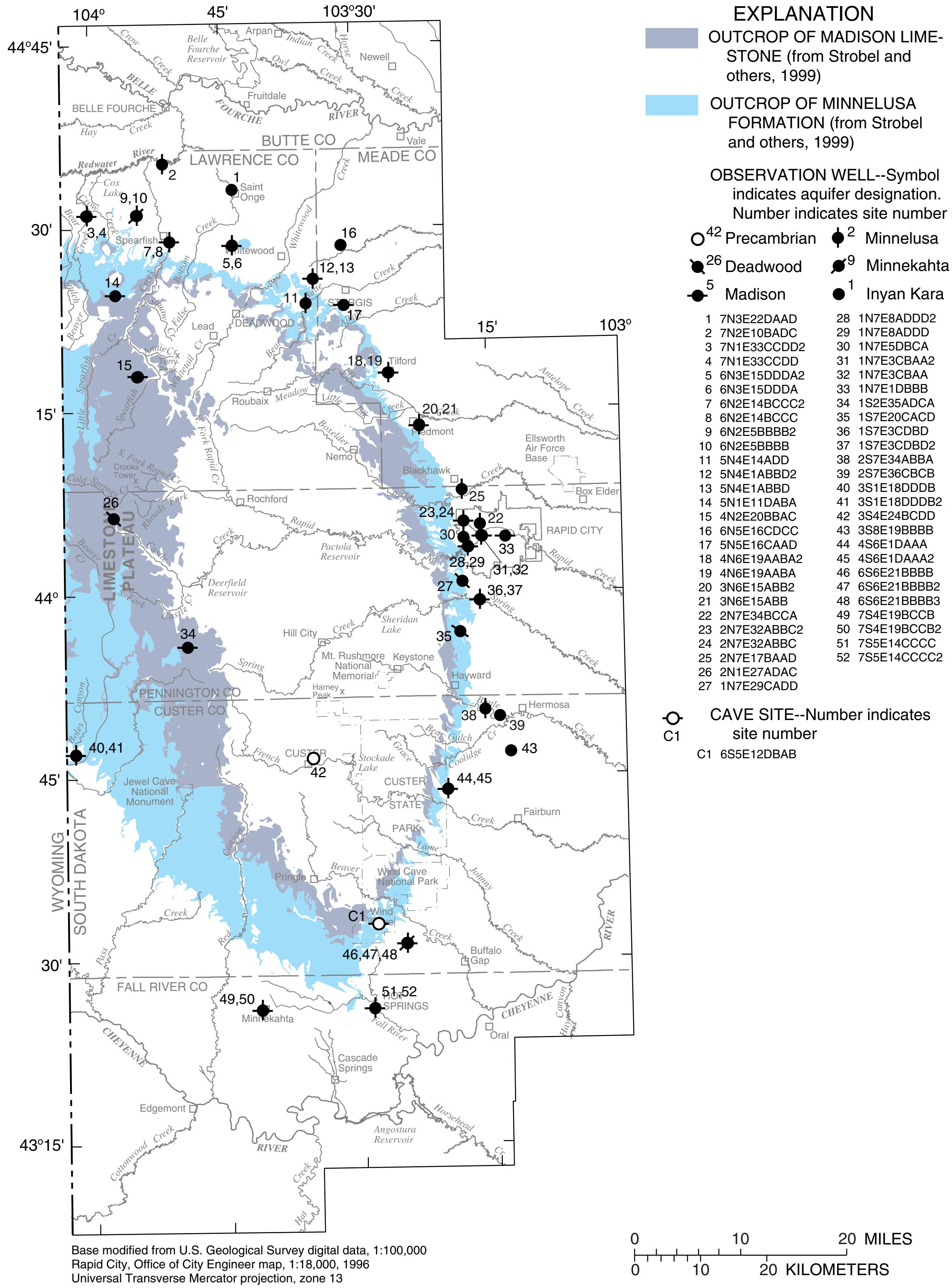

Figure 11. Location of observation wells and cave site for which hydrographs are presented.

Hydrographs are presented for one Precambrian well (fig. 42F) and three Deadwood wells (figs. 41F, 41G, and 41O), all of which indicate general responsiveness to climatic influences. Hydrographs are presented for two Minnekahta wells (table 1). The record for the 7-11 Ranch well (fig. 42M) is very short and not very informative. Water levels in the Spearfish West Minnekahta well (fig. 39J) are very responsive to the general precipitation trend and also exhibit extreme response to recharge episodes, with an increase of almost 60 ft during 1993. Records for two other Minnekahta wells reported by Driscoll, Bradford, and Moran (2000) are not included in this report. These wells, which are colocated with the State line wells and the Tilford wells (table 1), both show large fluctuations in annual water levels.

Many of the hydrographs presented are for wells completed in the Madison and Minnelusa aquifers, most of which are colocated. Many wells in both aquifers (with sufficient records) show pronounced responsiveness to climatic influences, with declining water levels during the late 1980's and early 1990's, followed by increasing water levels. Notable exceptions are the Canyon Lake wells (figs. 41H and 41I), which are located very near a large artesian spring complex (Cleghorn and Jackson Springs). Naus and others (2001) identified the Madison aquifer as the primary spring source, which probably results in minimal water-level fluctuations for the Madison well (fig. 41H). Hydraulic head in the Minnelusa aquifer (fig. 41I) is about 50 to 60 ft lower than in the Madison aquifer, indicating probable upward leakage from the Madison aquifer. The Minnelusa aquifer apparently is hydraulically connected to Rapid Creek at this location, as evidenced by a sharp decline during a period when Canyon Lake was drained near the end of 1995. The largest overall water-level change is for the Reptile Gardens Madison well (fig. 41P), which increased by about 110 ft during 1990-98. Increases of about 80 ft have been recorded for the Tilford Madison and Minnelusa wells (figs. 40D and 40E).

Madison and Minnelusa wells in the southern Black Hills show a general tendency for smaller water-level fluctuations than wells in other areas. Water-level changes appear small and gradual (for the periods of record available) for Windy City Lake (fig. 42J), the 7-11 Ranch wells (figs. 42K and 42L), and the Minnekahta Junction and Vets Home well pairs (fig. 43). Several possible explanations are offered for this observation. Estimated recharge from infiltration of precipitation is much smaller than in other areas and streamflow recharge also is very small (Carter, Driscoll, and Hamade, 2001). Another contributing factor may be large storage capacity in unconfined parts of the aquifers, which are especially large in the southern Black Hills (Clawges, 2000a; 2000b). Caves, which probably are more prevalent in the southern Black Hills than in other areas, can provide large storage capacity especially in the Madison aquifer.

Hydrographs for many Madison and Minnelusa wells located north of Wind Cave (fig. 11) show large water-level fluctuations; however, a wide range of variability is apparent, which probably reflects a wide range in recharge, discharge, and hydraulic characteristics. General water-level declines through the late 1980's and early 1990's are associated with generally deficit precipitation (and recharge) conditions and also indicate sufficiently large ground-water movement for substantial reduction of ground-water storage. General water-level increases during the mid to late 1990's indicate much larger recharge rates, which is consistent with results of water-budget analyses (Carter, Driscoll, Hamade, and Jarrell, 2001). The episodic recharge characteristics for these aquifers is accentuated by streamflow recharge, which locally can increase recharge amounts considerably beyond that which would occur simply from infiltration of precipitation, especially in discrete locations.

Large short-term water-level fluctuations (timeframe of weeks and months) also are apparent for many Madison and Minnelusa wells, which could result from a variety of hydraulic influences. An important factor may be the dual-porosity characteristics of these aquifers, which can result from openings associated with secondary porosity within a matrix of lower permeability material (Long, 2000) and can contribute to rapid changes in hydraulic head.

Streamflow Response to Precipitation

Streamflow is affected by numerous climatic variables including timing, intensity, and amount of precipitation, as well as other variables affecting evaporative processes. This section of the report focuses on quantifying the response of streamflow to annual precipitation amounts because: (1) measurements of annual precipitation are abundant, relative to other climatic variables; and (2) annual precipitation generally is the most important explanatory variable, which probably results at least partially from interrelations with other climatic variables.

Streamflow also can be affected by numerous physical factors such as topography, land cover, and soil conditions, all of which may be affected by geologic conditions. Similarities in hydrogeologic characteristics allow identification of hydrogeologic settings that have distinctive influences on streamflow characteristics in the Black Hills area. Hydrogeologic settings are described in the following section, prior to addressing responses to precipitation.

Hydrogeologic Settings

A distinctive effect of hydrogeologic setting is on the timing and variability of streamflow (Miller and Driscoll, 1998), which results primarily from interactions between surface water (streamflow) and ground water. In this report, four areas that represent five hydrogeologic settings are identified, as shown in figure 12. The “limestone headwater” setting occurs within outcrops of the Madison Limestone and Minnelusa Formation along the Limestone Plateau area. In this area, direct runoff is uncommon; however, numerous springs along the eastern fringe of the Limestone Plateau contribute to streamflow within the headwaters of several drainages. The “crystalline core” setting is encircled by the outcrop band of the Madison Limestone and Minnelusa Formation and is dominated by Precambrian igneous and metamorphic rocks. Downgradient from the crystalline core area is the “loss zone” setting, where streamflow losses occur as streams cross outcrops of the Madison Limestone and Minnelusa Formation. The loss zone and “artesian spring” settings share a common area because many artesian springs are located along stream channels that are influenced by streamflow losses and several artesian springs are within outcrops of the Minnelusa Formation. The outer extent of this common area is bounded by the outcrop of the Inyan Kara Group, which approximates the outer extent of the Black Hills area. Areas downgradient from this outcrop are considered to be within the “exterior” setting. The “connected outcrop” areas of the Madison Limestone and Minnelusa Formation shown in figure 12 are slightly modified from figure 3 and exclude small areas isolated from the main outcrops (erosional remnants).

Locations of streamflow-gaging stations that are used to identify representative streamflow characteristics for the five hydrogeologic settings are shown in figure 12. Locations of selected “combination” gages where flows are affected by a combination of hydrogeologic settings or by diversions or regulation also are shown. Site information and selected flow characteristics are summarized (by hydrogeologic setting) in table 2. Selected site information also is included in table 2 for “other” gages that are used later for various other purposes. Annual flow data for the representative and combination gages are summarized in tables 19-24 in the Supplemental Information section, along with estimated annual precipitation amounts for the associated drainage areas.

One of the flow characteristics summarized in table 2 is the “base flow index” (BFI), which represents the estimated percentage of streamflow contributed by base flow, for any given gage. BFI’s were determined with a computer program described by Wahl and Wahl (1995), using coefficients of N=5 (5-day increments) and f=0.9 (90 percent minimum criterion for determination of turning points). This program uses daily mean streamflow to define a base-flow hydrograph, which is used to compute the percentage of streamflow volume contributed by base flow.

Table 2 also includes mean flow values for representative gages (for the periods of record shown) in cubic feet per second and mean values of annual basin yield, expressed in inches per unit area. Because basin yields are normalized, relative to surface drainage area, values are directly comparable among different gages. For example, the mean flow of 11.73 ft^3/s for Castle Creek (station 06409000) is about 2.7 times larger than the mean flow of 4.33 ft^3/s for Cold Springs Creek (station 06429500); however, the mean annual basin yield for Castle Creek (2.01 inches) is smaller than for Cold Springs Creek (3.10 inches).

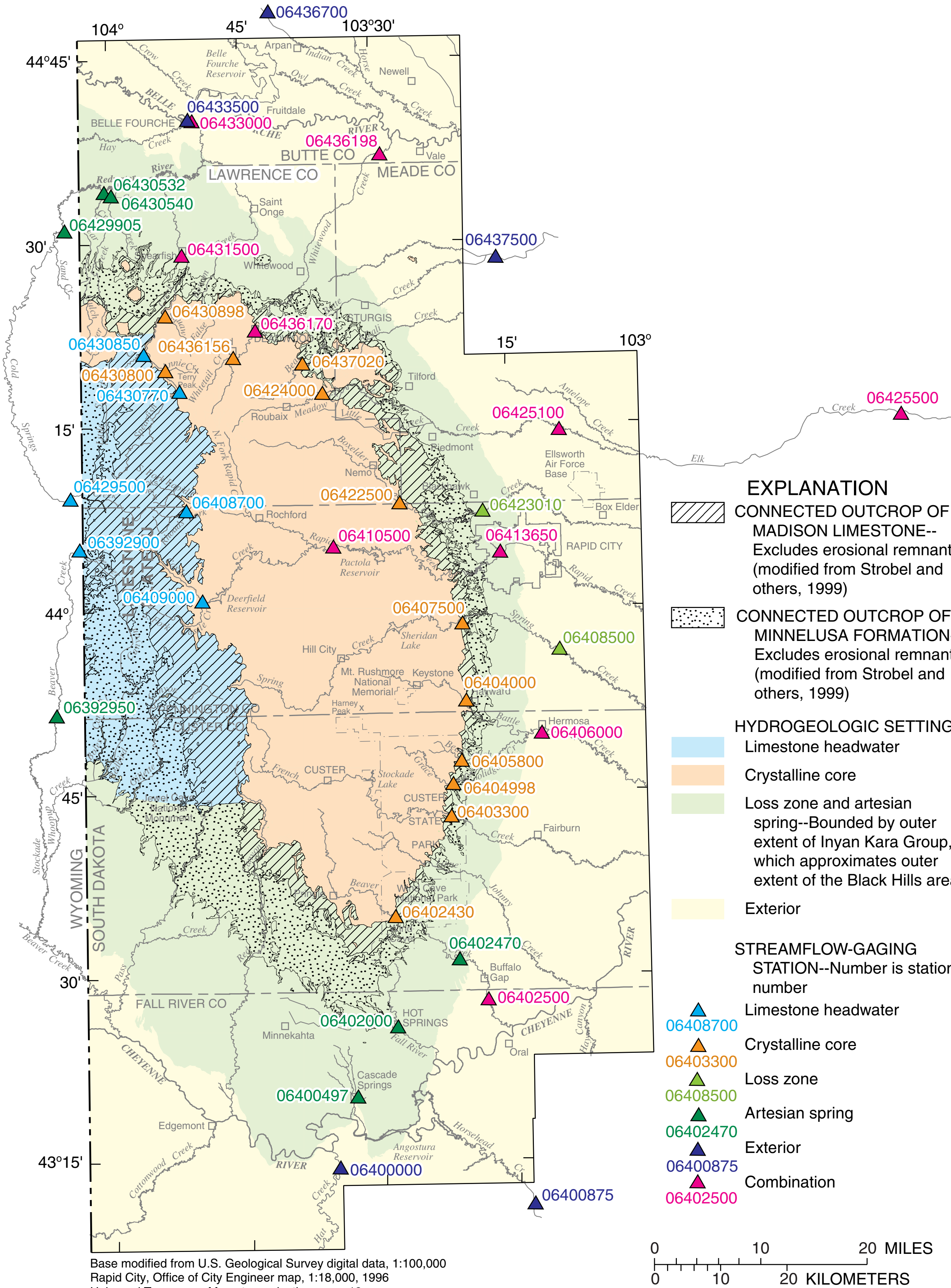

Figure 12. Streamflow-gaging stations used in analysis of streamflow characteristics, relative to hydrogeologic settings.

Table 2. Summary of selected site information and flow characteristics for streamflow-gaging stations representative of hydrogeologic settings

[NA, not applicable; --, not determined]

Station number	Station name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Drainage area (square miles)	Period of record used (water years)	Base flow index (percent)	Mean flow (cubic feet per second)	Annual basin yield: Mean (inches)	Annual basin yield: Standard deviation	Annual basin yield: Coefficient of variation (standard deviation/ mean)
	Limestone Headwater Basins									
06392900	Beaver Creek at Mallo Camp, near Four Corners, Wyo.	440506	1040336	10.3	1975-82, 1992-98	88.6	1.88	2.48	0.63	0.25
06408700	Rhoads Fork near Rochford	440812	1035129	7.95	1983-98	98.7	5.47	9.34	2.48	.27
06409000	Castle Creek above Deerfield Reservoir, near Hill City	440049	1034948	79.2	1949-98	87.1	11.73	2.01	.75	.37
06429500	Cold Springs Creek at Buckhorn, Wyo.	440915	1040437	19.0	1975-82, 1992-98	91.4	4.33	3.10	.68	.22
06430770	Spearfish Creek near Lead	441756	1035202	63.5	1989-98	[1]91.0	[1]25.43	[1]5.44	[1]2.59	[1].48
06430850	Little Spearfish Creek near Lead	442058	1035608	25.8	1989-98	97.0	16.59	8.74	2.31	.26
	Crystalline Core Basins									
06402430	Beaver Creek near Pringle	433453	1032834	45.8	1991-98	73.1	2.86	.85	.76	.89
06403300	French Creek above Fairburn	434302	1032203	105	1983-98	55.5	10.94	1.42	1.19	.84
06404000	Battle Creek near Keystone	435221	1032010	58.0	1962-98	45.4	9.39	2.20	1.59	.72
06404998	Grace Coolidge Creek near Game Lodge, near Custer	434540	1032149	25.2	1977-98	58.9	5.07	2.73	2.36	.86
06405800	Bear Gulch near Hayward	434731	1032049	4.23	1990-98	41.1	1.48	4.75	2.76	.58
06407500	Spring Creek near Keystone	435845	1032025	163	1987-98	54.1	25.06	2.09	1.73	.83
06422500	Boxelder Creek near Nemo	440838	1032716	96.0	1967-98	64.9	19.53	2.76	2.19	.79
06424000	Elk Creek near Roubaix	441741	1033547	21.5	1992-98	61.1	13.42	8.48	4.08	.48
06430800	Annie Creek near Lead	441937	1035338	3.55	1989-98	51.1	1.72	6.55	4.42	.67
06430898	Squaw Creek near Spearfish	442404	1035335	6.95	1989-98	52.5	3.76	7.34	4.44	.60
06436156	Whitetail Creek at Lead	442036	1034557	6.15	1989-98	63.0	4.79	10.57	6.01	.57
06437020	Bear Butte Creek near Deadwood	442008	1033806	16.6	1989-98	58.3	8.35	6.84	4.07	.60

Table 2. Summary of selected site information and flow characteristics for streamflow-gaging stations representative of hydrogeologic settings–Continued

[NA, not applicable; --, not determined]

Station number	Station name	Latitude	Longitude	Drainage area (square miles)	Period of record used (water years)	Base flow index (percent)	Mean flow (cubic feet per second)	Annual basin yield: Mean (inches)	Annual basin yield: Standard deviation	Annual basin yield: Coefficient of variation (standard deviation/mean)
		(degrees, minutes, seconds)								
	Loss Zone Basins									
06408500	Spring Creek near Hermosa	435631	1030932	199	1950-98	44.1	7.15	0.49	0.73	1.49
06423010	Boxelder Creek near Rapid City	440754	1031754	128	1979-98	14.4	5.88	.62	1.23	1.98
	Artesian Spring Basins									
06392950	Stockade Beaver Creek near Newcastle, Wyo.	435132	1040624	107	1975-82, 1992-98	93.5	12.15	1.54	.23	.15
06400497	Cascade Springs near Hot Springs	432010	1033307	.47	1977-95	99.2	19.53	564	40.34	.07
06402000	Fall River at Hot Springs	432550	1032833	137	1939-46, 1948-98	96.0	23.61	2.34	.25	.11
06402470	Beaver Creek above Buffalo Gap	433120	1032123	111	1991-97	97.4	10.21	1.25	.25	.20
06429905	Sand Creek near Ranch A, near Beulah, Wyo.	443107	1040457	267	1977-83, 1992-98	95.1	22.58	1.15	.22	.19
06430532	Crow Creek near Beulah, Wyo.	443414	1040019	40.8	1993-98	92.6	40.68	13.5	1.13	.08
06430540	Cox Lake outlet near Beulah, Wyo.	443356	1035937	.07	1991-95	99.3	4.22	819	9.16	.01
	Exterior Basins									
06400000	Hat Creek near Edgemont	431424	1033516	1,044	1951-98	15.5	16.61	.22	.26	1.18
06400875	Horsehead Creek at Oelrichs	431117	1031334	187	1984-98	12.6	6.75	.49	.70	1.43
NA[2]	Elk Creek (subbasin)	NA	NA	350	1980-98	--	16.16	.63	.74	1.17
06433500	Hay Creek at Belle Fourche	444001	1035046	121	1954-96	17.5	1.74	.20	.23	1.15
06436700	Indian Creek near Arpan	444851	1034122	315	1962-81	6.6	19.98	.86	.92	1.07
06437500	Bear Butte Creek near Sturgis	442835	1031550	192	1946-72	32.3	13.93	.99	1.04	1.05

Table 2. Summary of selected site information and flow characteristics for streamflow-gaging stations representative of hydrogeologic settings–Continued

[NA, not applicable; --, not determined]

Station number	Station name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Drainage area (square miles)	Period of record used (water years)	Base flow index (percent)	Mean flow (cubic feet per second)	Annual basin yield: Mean (inches)	Annual basin yield: Standard deviation	Annual basin yield: Coefficient of variation (standard deviation/ mean)
Combination Basins										
06402500	Beaver Creek near Buffalo Gap	432800	1031820	130	1939-98	78.0	7.24	0.76	0.18	0.24
06406000	Battle Creek at Hermosa	434941	1031144	178	1950-98	58.9	11.88	.91	.88	.97
06410500	Rapid Creek above Pactola Reservoir	440505	1033448	292	1954-98	--	[3]45.88	[3]2.13	[3]1.19	[3].56
06413650	Lime Creek at mouth, at Rapid City	440430	1031600	10.0	1988-98	76.3	2.08	2.83	1.82	.64
06425100	Elk Creek near Rapid City	441425	1030903	190	1980-98	24.0	13.88	.99	1.52	1.54
06425500	Elk Creek near Elm Springs	441454	1023010	540	1950-98	15.1	26.01	.65	.73	1.12
06431500	Spearfish Creek at Spearfish	442857	1035140	168	1947-98	85.6	53.87	4.36	1.27	.29
06433000	Redwater River above Belle Fourche	444002	1035020	920	1946-98	79.1	137.82	2.03	.70	.34
06436170	Whitewood Creek at Deadwood	442248	1034325	40.6	1982-95	69.8	27.01	9.04	4.06	.45
06436198	Whitewood Creek above Vale	443704	1032852	102	1984-98	63.8	32.22	4.29	2.18	.51
Other Streamflow-Gaging Stations (used for various water-budget purposes)										
06395000	Cheyenne River at Edgemont	431820	1034914	7,143	1950-98	--	--	--	--	--
06412500	Rapid Creek above Canyon Lake	440310	1031841	371	1950-98	--	--	--	--	--
06414000	Rapid Creek at Rapid City	440509	1031431	410	1950-98	--	--	--	--	--
06418900	Rapid Creek below Sewage Plant, near Rapid City	440124	1030543	452	1982-98	--	--	--	--	--
06421500	Rapid Creek near Farmingdale	435631	1025112	602	1950-98	--	--	--	--	--
06423500	Cheyenne River near Wasta	440452	1022403	12,800	1950-98	--	--	--	--	--
06428500	Belle Fourche River at Wyoming-South Dakota State line	444459	1040249	3,280	1950-98	--	--	--	--	--
06429997	Murray Ditch above headgate at Wyoming-South Dakota State line	443435	1040320	NA	[4]1954-98	--	--	--	--	--

Table 2. Summary of selected site information and flow characteristics for streamflow-gaging stations representative of hydrogeologic settings–Continued

[NA, not applicable; --, not determined]

Station number	Station name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Drainage area (square miles)	Period of record used (water years)	Base flow index (percent)	Mean flow (cubic feet per second)	Annual basin yield: Mean (inches)	Annual basin yield: Standard deviation	Annual basin yield: Coefficient of variation (standard deviation/mean)
Other Streamflow-Gaging Stations (used for various water-budget purposes)—Continued										
06430500	Redwater Creek at Wyoming-South Dakota State line	443426	1040254	920	1955-98	--	--	--	--	--
06434505	Inlet Canal above Belle Fourche Reservoir	444205	1034400	NA	[5]1950-98	--	--	--	--	--
06436000	Belle Fourche River near Fruitdale	444127	1034441	4,540	1950-98	--	--	--	--	--
06436180	Whitewood Creek above Whitewood	442632	1033744	56.3	1983-98	--	--	--	--	--
06436500	Horse Creek near Newell	444753	1033228	67.0	1962-69	--	--	--	--	--
06437000	Belle Fourche River near Sturgis	443047	1030811	5,870	1950-98	--	--	--	--	--
06438000	Belle Fourche River near Elm Springs	442211	1023356	7,210	1950-98	--	--	--	--	--
06439000	Cherry Creek near Plainview	444435	1020311	1,190	1950-98	--	--	--	--	--
06441500	Bad River near Fort Pierre	441936	1002302	3,107	1950-98	--	--	--	--	--
06447000	White River near Kadoka	434509	1013128	5,000	1950-98	--	--	--	--	--

[1]Flow characteristics affected by relatively consistent diversions of about 10 cubic feet per second.
[2]Consists of subbasin between two stations on Elk Creek—near Rapid City (06425100) and near Elm Springs (06425500).
[3]Affected by upstream reservoir; however, flow records have been adjusted for annual storage changes.
[4]Includes 1954-87 records for station 06430000, which was located immediately downstream.
[5]Includes 1950-94 records for station 06434500, which was located about 5 miles upstream.

The last flow characteristic summarized in table 2 is the coefficient of variation (standard deviation divided by mean) for annual basin yield, which provides an excellent measure of annual flow variability. This statistic is directly comparable among different gages, because the standard deviations are normalized relative to means. For example, standard deviations for Beaver Creek at Mallo Camp (06392900) and Rhoads Fork (06408700) are very different; however, coefficients of variation are nearly identical. A notable example is provided by two gages representative of the artesian spring setting—Cascade Springs (06400497) and Cox Lake (06430540), which have anomalously large values for annual basin yield (orders of magnitude higher than annual precipitation) because of extremely large artesian springflow that occurs in very small drainages. Standard deviations for these sites are the largest in table 2; however, the coefficients of variation are the smallest, which is consistent with the BFI's, which are the largest in the table and are indicative of extremely large contributions from base flow.

The previous discussion provides a good example of a generally inverse relation between BFI and coefficient of variation, with decreasing variability in annual flow generally indicative of increasing contributions from base flow, much of which is derived from ground-water discharge. Representative gages for each category of hydrogeologic setting typically have similar BFI's and coefficients of variation, resulting primarily from similarities in flow variability.

Graphs showing variability in daily, monthly, and annual flow are presented in figures 13-15, respectively. For the duration curves of daily mean flow (fig. 13), two graphs are provided for the crystalline core setting because of the large number of basins representative of this setting. Basin yields are used to summarize annual flow characteristics (fig. 15) for all hydrogeologic settings except the artesian spring setting, for which annual yield values can be unrealistically large (table 2), as discussed previously. Following are discussions of flow characteristics and physical settings for the five hydrogeologic settings. Detailed analyses of relations between precipitation and streamflow are presented in the next section.

Relative variability of daily, monthly, and annual flow is much smaller for gages representative of limestone headwater and artesian spring settings than for the other settings (figs. 13-15). Coefficients of variation for these settings are consistently smaller than for the other settings (table 2). BFI's are consistently larger, indicating large proportions of base flow, which results primarily from ground-water discharge in the form of springflow for these settings. All measures considered indicate much higher flow variability for the other three settings.

Gages representative of the limestone headwater setting are located near the Limestone Plateau (fig. 12), where large outcrops of the Madison Limestone and Minnelusa Formation occur in an area of generally low relief, along the South Dakota-Wyoming border. Two of the gages considered (06392900 and 06429500) are located in Wyoming within outcrops of the Minnelusa Formation. The remainder are located near the contact between the Madison Limestone and underlying geologic units (figs. 2 and 3), where headwater springs commonly occur. Most recharge for these headwater springs is from infiltration of precipitation on the Madison Limestone or Minnelusa Formation (Rahn and Gries, 1973; Carter, Driscoll, Hamade, and Jarrell, 2001). Ground-water discharge from the Deadwood aquifer also can contribute to springflow.

Sustained streamflow within the Madison and Minnelusa outcrops is very uncommon (Miller and Driscoll, 1998) and generally occurs only in limited areas where low-permeability "perching" layers occur. Such conditions probably exist in the vicinity of the two Wyoming gages, where streamflow is again lost to the Minnelusa Formation downstream from the gages. Small perched springs are common within outcrops of the Minnelusa Formation along the Limestone Plateau. Among the limestone headwater basins, the smallest variability in daily flow is for Rhoads Fork (06408700), where measured values have ranged almost exclusively between 3 and 10 ft^3/s (fig. 13). Measured daily flows generally vary by less than an order of magnitude for representative gages, which indicates that direct runoff is uncommon for this setting.

The four limestone headwater gages in South Dakota are downstream from the largest headwater spring areas and measure a large percentage of the springflow along the eastern side of the Limestone Plateau, most of which occurs within the Rapid and Spearfish Creek Basins. Large and sustained headwater springflow generally does not occur south of Castle Creek (06409000); however, several smaller springs of more intermittent nature occur in the Spring and French Creek drainages.

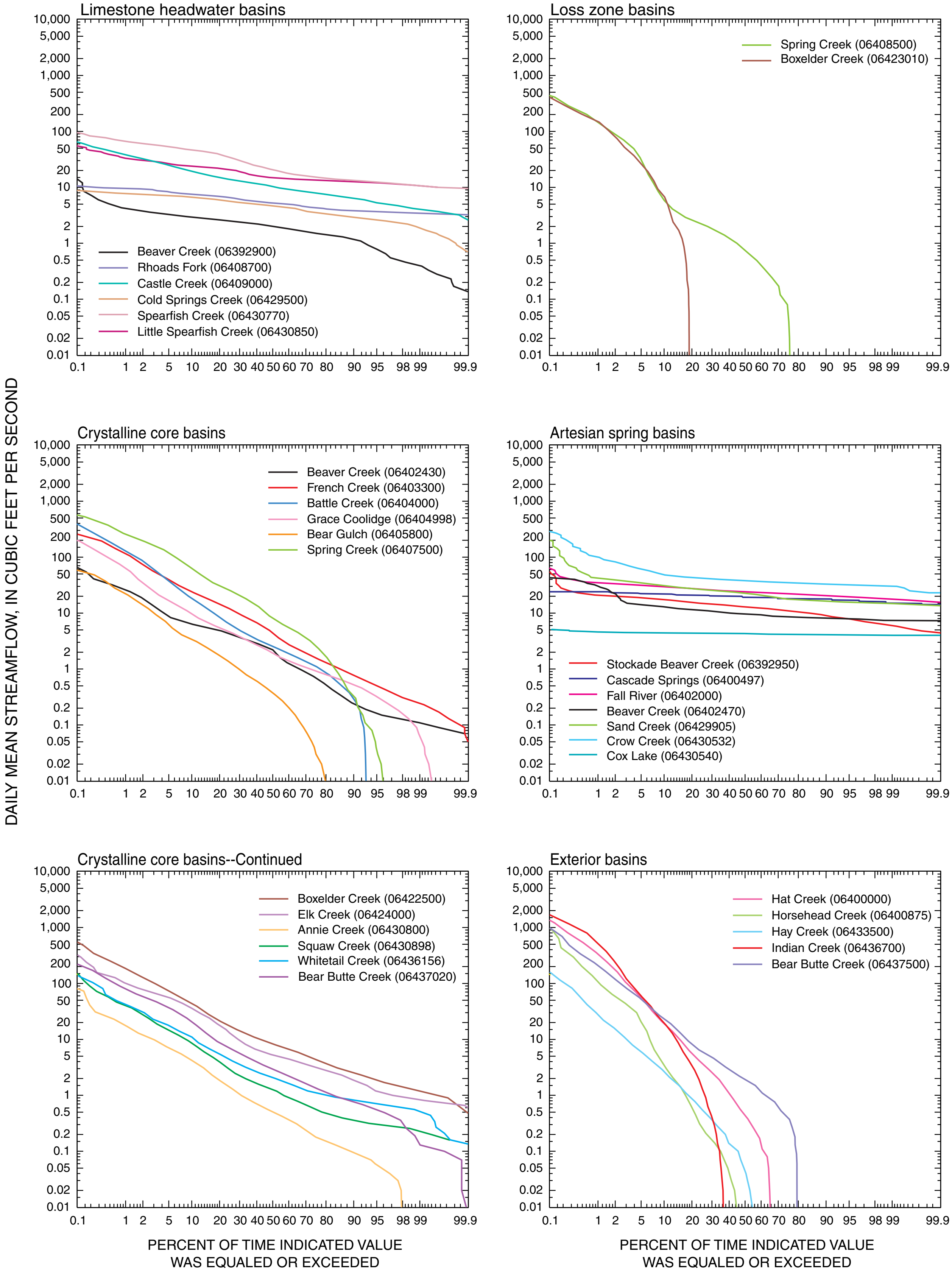

Figure 13. Duration curves of daily mean streamflow for basins representative of hydrogeologic settings.

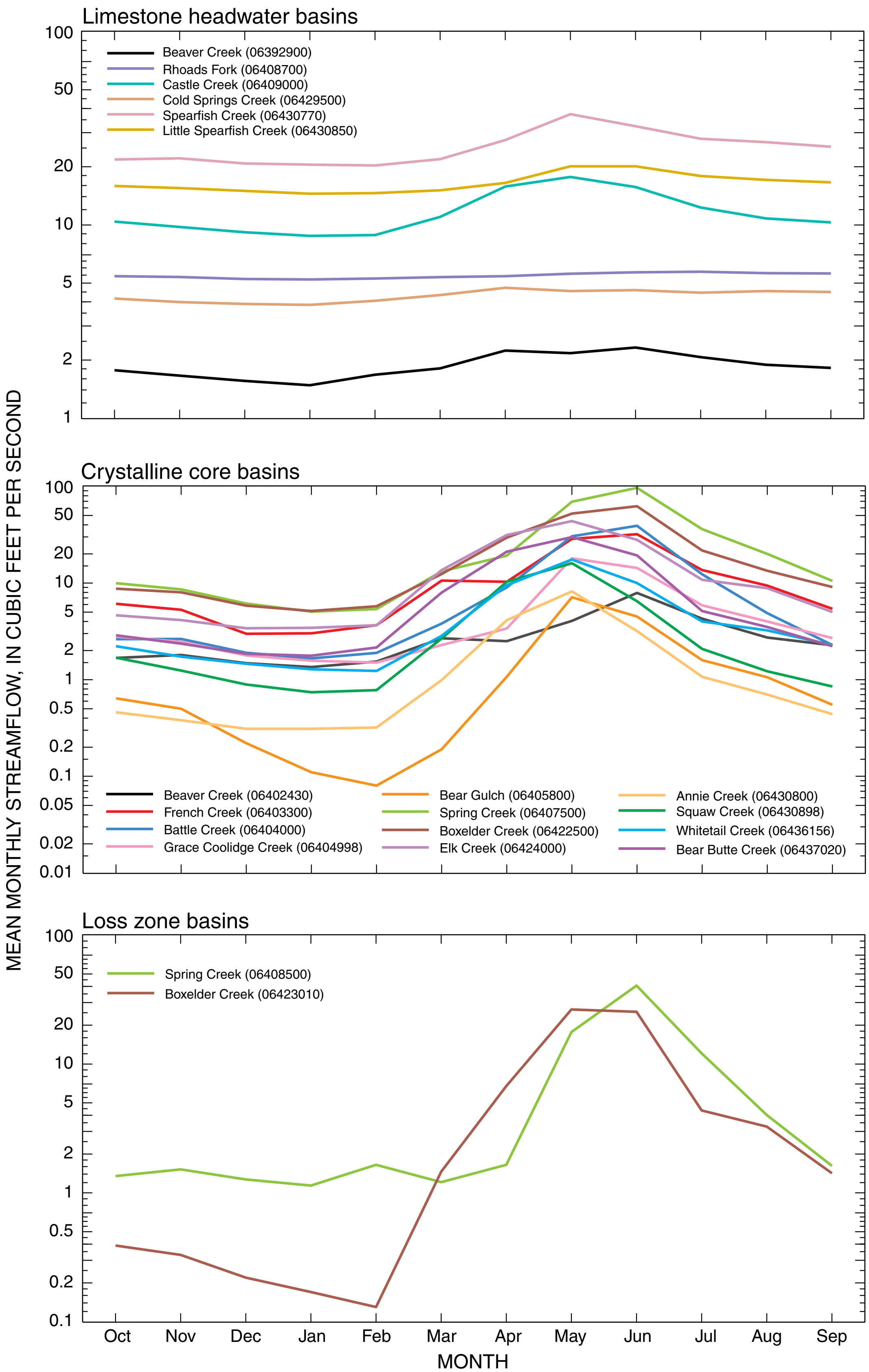

Figure 14. Mean monthly streamflow for basins representative of hydrogeologic settings.

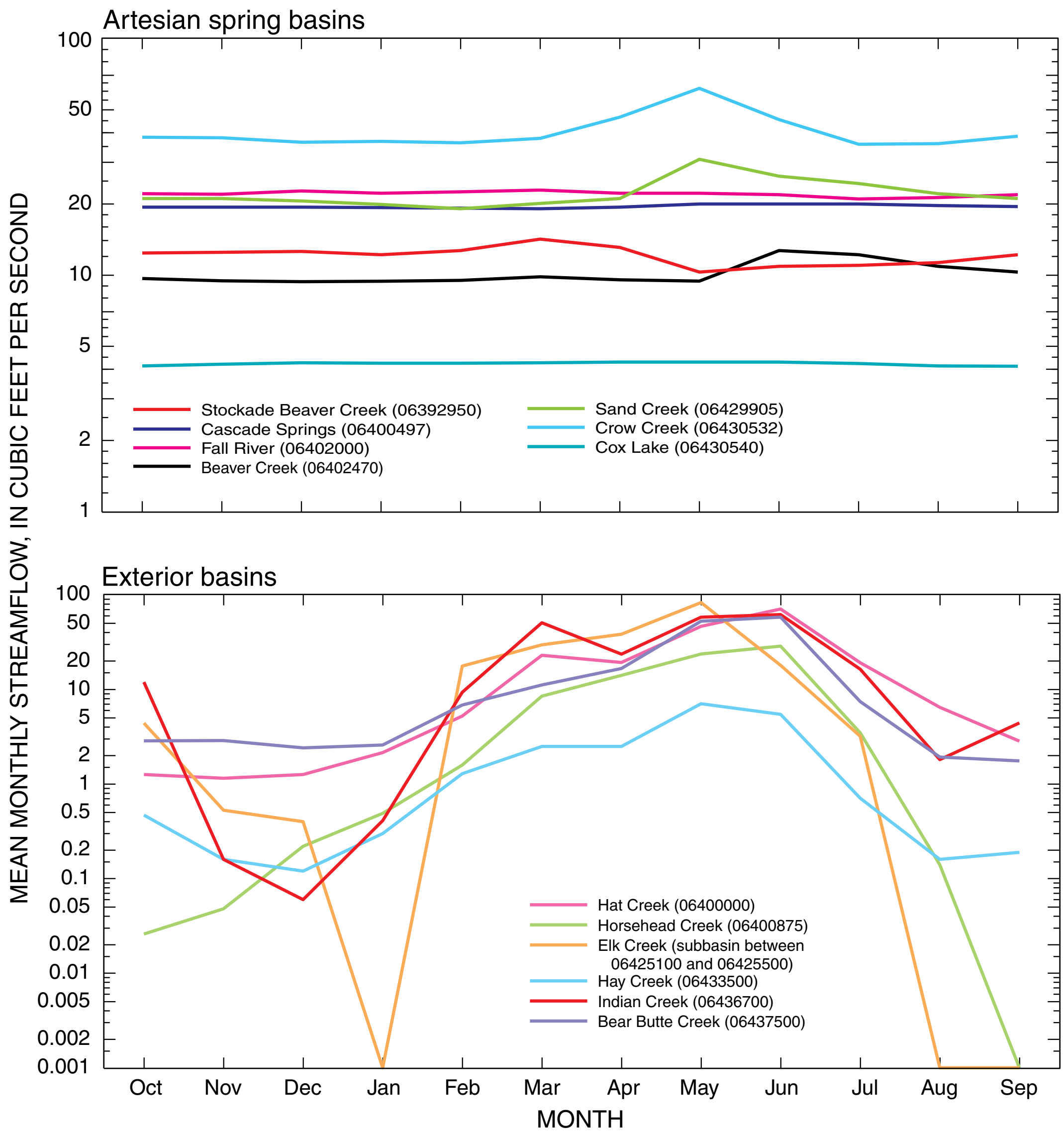

Figure 14. Mean monthly streamflow for basins representative of hydrogeologic settings.--Continued

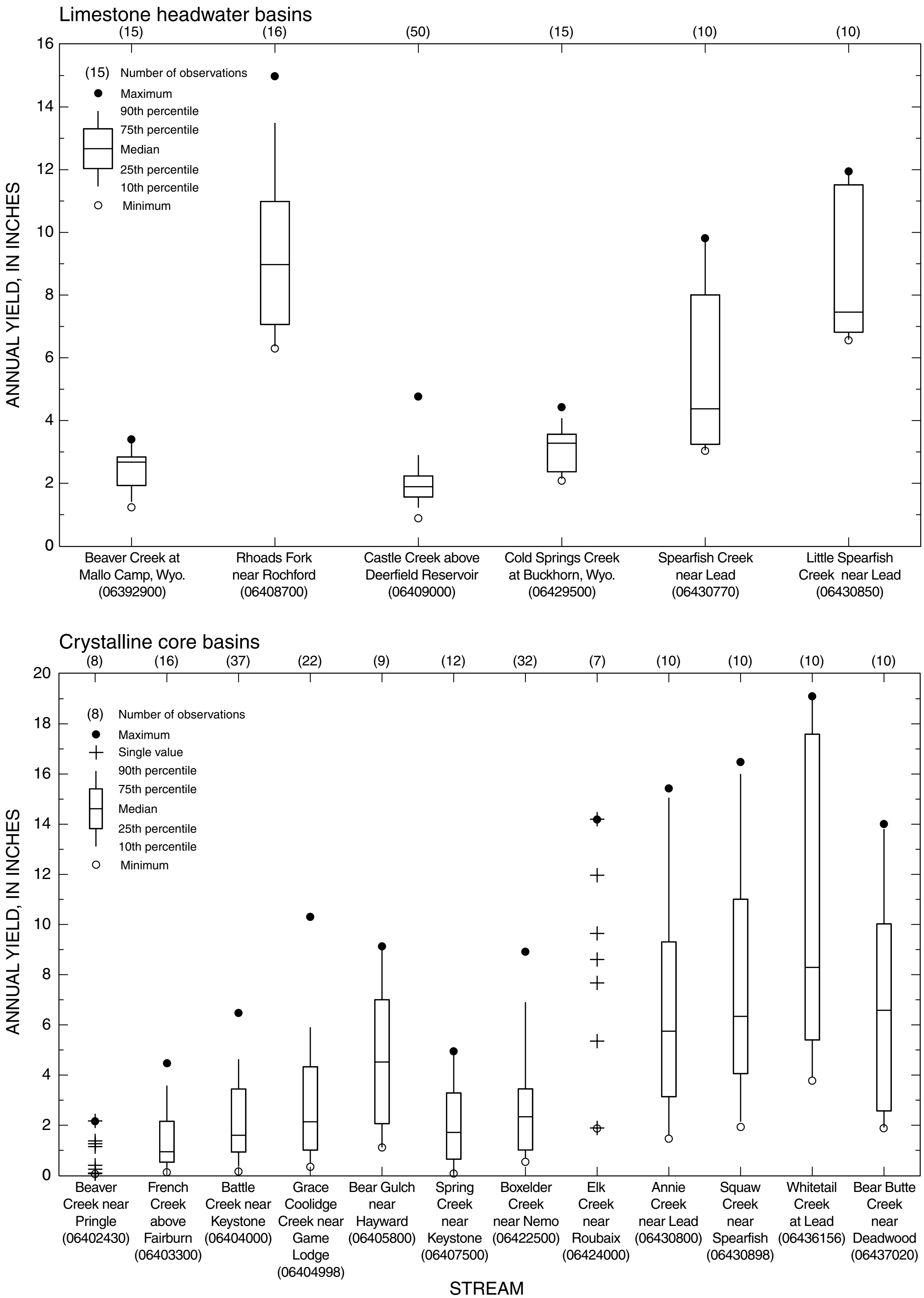

Figure 15. Distribution of annual yield for basins representative of hydrogeologic settings.

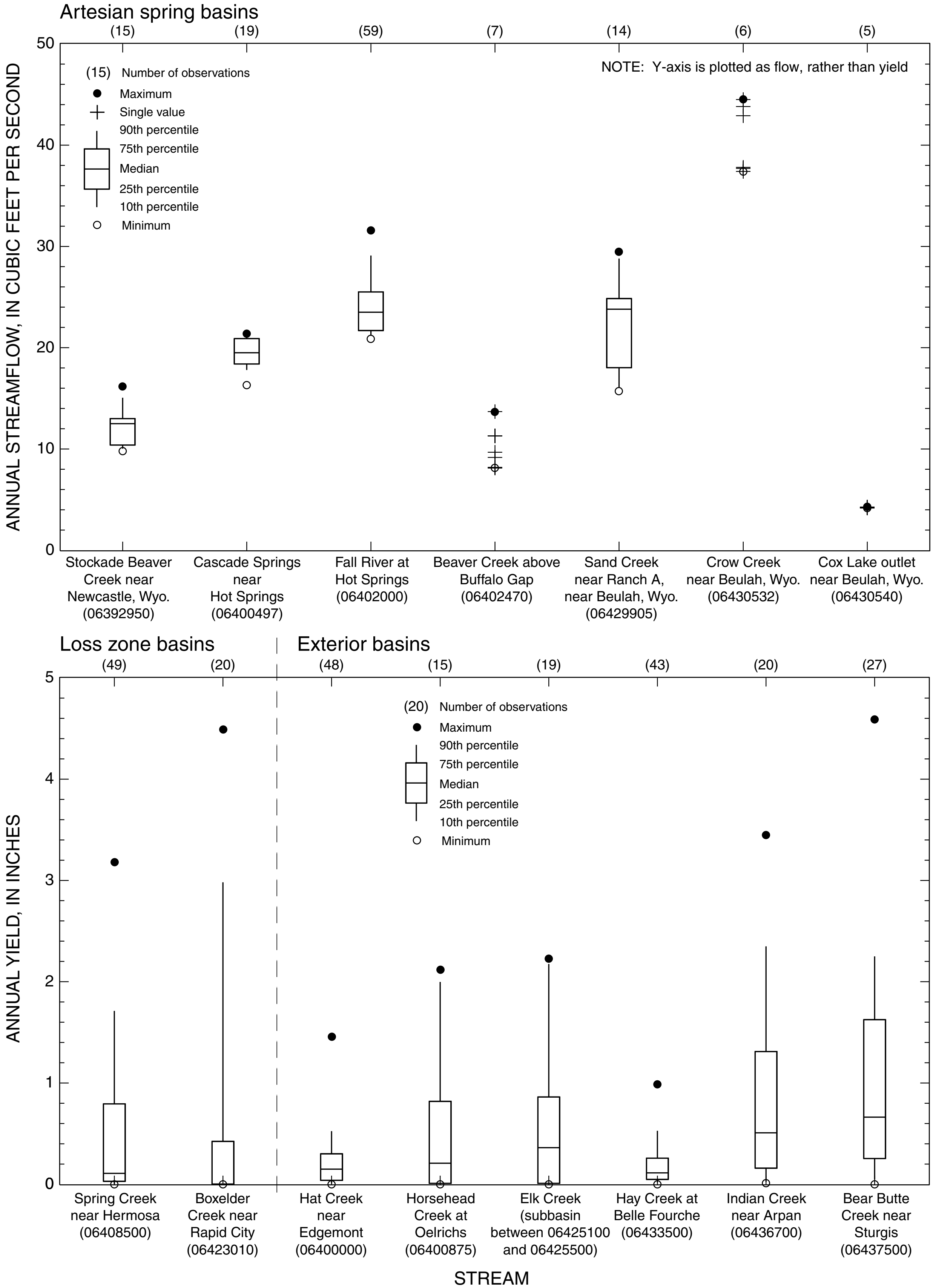

Figure 15. Distribution of annual yield for basins representative of hydrogeologic settings.--Continued

Similar contributions to base flow can occur in other areas around the periphery of the uplift, especially where outcrops of the Deadwood, Madison, Minnelusa, and Minnekahta Formations occur along incised channels of generally easterly flowing streams. Numerous outcrops that are erosional remnants of these formations occur in the northern Black Hills (fig. 3) and also can contribute to base flow of various streams (most notably Boxelder, Elk, Bear Butte, and Whitewood Creeks). Small erosional remnants are not shown in figure 12, which includes only connected outcrops of the Madison and Minnelusa Formations.

Most gages representative of the crystalline core setting are located along the eastern and northern flanks of the uplift, immediately upstream from the outcrop of the Madison Limestone (fig. 12). The crystalline core is dominated by igneous and metamorphic Precambrian rocks, but also includes numerous Tertiary intrusives in the northern Black Hills (fig. 3). Unconsolidated Quaternary and Tertiary deposits also occur in various locations.

BFI's for the crystalline core basins generally approach or slightly exceed 50 percent (table 2). Monthly flow characteristics (fig. 14), however, indicate a short-term response to precipitation patterns (fig. 8), which probably indicates a relatively large component of interflow contributing to base flow. This interpretation is supported by the general physical characteristics of the crystalline core basins, where large relief and steep planar surfaces provide mechanisms for non-vertical flow components in the unsaturated zone. Contributions from ground-water discharge presumably also occur; however, ground-water storage available for contribution to streamflow apparently is quickly depleted, as evidenced by the lower end of the range of annual yield values for the crystalline core basins (fig. 15). Daily flow values span two or more orders of magnitude for all crystalline core basins (fig. 13).

Gages representative of the loss zone setting are uncommon, because sustained flow is uncommon downstream from outcrop areas where large streamflow losses provide recharge to the Madison and Minnelusa aquifers (Hortness and Driscoll, 1998). The only two representative loss zone gages (fig. 12) are located on Spring Creek (06408500) and Boxelder Creek (06423010). Annual basin yields for these gages (table 2) are much smaller than for gages located upstream (stations 06407500 on Spring Creek and 06422500 on Boxelder Creek) and relative variability in flow is larger (figs. 13-15). Spring Creek does have relatively consistent base flow (table 2, BFI = 44 percent) from alluvial springs that occur a short distance upstream from the gage.

Data are presented for seven gages representative of the artesian spring setting (table 2). The loss zone and artesian spring settings are grouped together in figure 12 because many artesian springs are located along stream channels that are influenced by streamflow losses upstream. Of the artesian springs, daily flow variability (fig. 13) is smallest for Cox Lake (06430540) and Cascade Springs (06400497), which are located in extremely small drainages with no influence from streamflow losses. Four of the gages are located in larger drainages downstream from loss zones, and one gage (Fall River, 06402000) heads predominantly within the loss zone setting. All five of these gages show minor influences from occasional storm flows (fig. 13). The influence of minor irrigation diversions along Stockade Beaver Creek (06392950) during late spring and summer months can be discerned in the monthly hydrographs (fig. 14).

The exterior setting is considered to be the area beyond the outer extent of the outcrop of the Inyan Kara Group, which coincides with the outer extent of the area for the loss zone/artesian spring setting (fig. 12). One of the exterior basins consists of a subbasin on Elk Creek (table 2) located between stations 06425100 and 06425500 (fig. 12), with flow characteristics determined (when possible) using calculated flow differences between the two gages. For the exterior setting, daily flows for representative gages vary by more than four orders of magnitude (fig. 13) and zero-flow conditions are common, which is consistent with BFI's that typically are small (table 2). Large variability in monthly and annual flows also is characteristic for this setting (figs. 14 and 15). Annual basin yields are smaller than for most other settings (table 2), which is consistent with smaller precipitation and larger evaporation rates at lower altitudes. Many of these sites also are affected by minor irrigation withdrawals.

Responses to Precipitation

This section primarily addresses responses of streamflow to precipitation, including quantification of relations between streamflow and precipitation and examination of annual yield characteristics, which are heavily influenced by precipitation patterns. Long-term trends are examined first, however, to evaluate potential for bias resulting from short-term streamflow records.

Long-Term Trends

The potential for bias in analysis of streamflow data exists because many streamflow records for the Black Hills area have relatively short periods of record (table 2) that are biased towards wet climatic conditions that have prevailed since about 1990 (fig. 10). A perspective on long-term trends is provided by figure 16, which shows comparisons between annual streamflow and basin precipitation for three long-term gages on Battle, Castle, and Spearfish Creeks. It is apparent that flows during the 1990's are considerably larger than the long-term averages for these streams. Thus, readers are cautioned that flow data and characteristics for some gages (especially those with short periods of record) may not necessarily be representative of long-term conditions.

Relations between streamflow and precipitation, which are examined in the following section, also can be heavily influenced by short-term data sets. Many of the data sets considered are for short periods of record during recent years that may be biased towards wet climatic conditions. Relations between streamflow and precipitation are well defined for many sites, however, because relatively dry conditions also are well represented in most data sets. This is apparent from examination of table 18, which presents annual precipitation and ranks for the study area and those parts of the six counties within the study area. For the period 1985-98, during which many gages were operational, 1985, 1988, and 1994 were particularly dry for all counties. For 1931-98, drier conditions generally have occurred only during 1949-61 or during the 1930's.

The shortest streamflow records considered (table 2) are for stations 06430532, Crow Creek (1993-98) and 06430540, Cox Lake (1991-95), both of which include water year 1994. Periods of record are longer for all other gages. Thus, although mean conditions for some gages may be slightly biased towards wet climatic conditions, the range of conditions represented generally includes both wet and dry periods.

Relations Between Streamflow and Precipitation

Relations between streamflow and precipitation are examined in this section for drainage basins representative of the five hydrogeologic settings. Relations also are examined for "combination" basins, where streamflow is affected by diversions, regulation, or a combination of hydrogeologic settings.

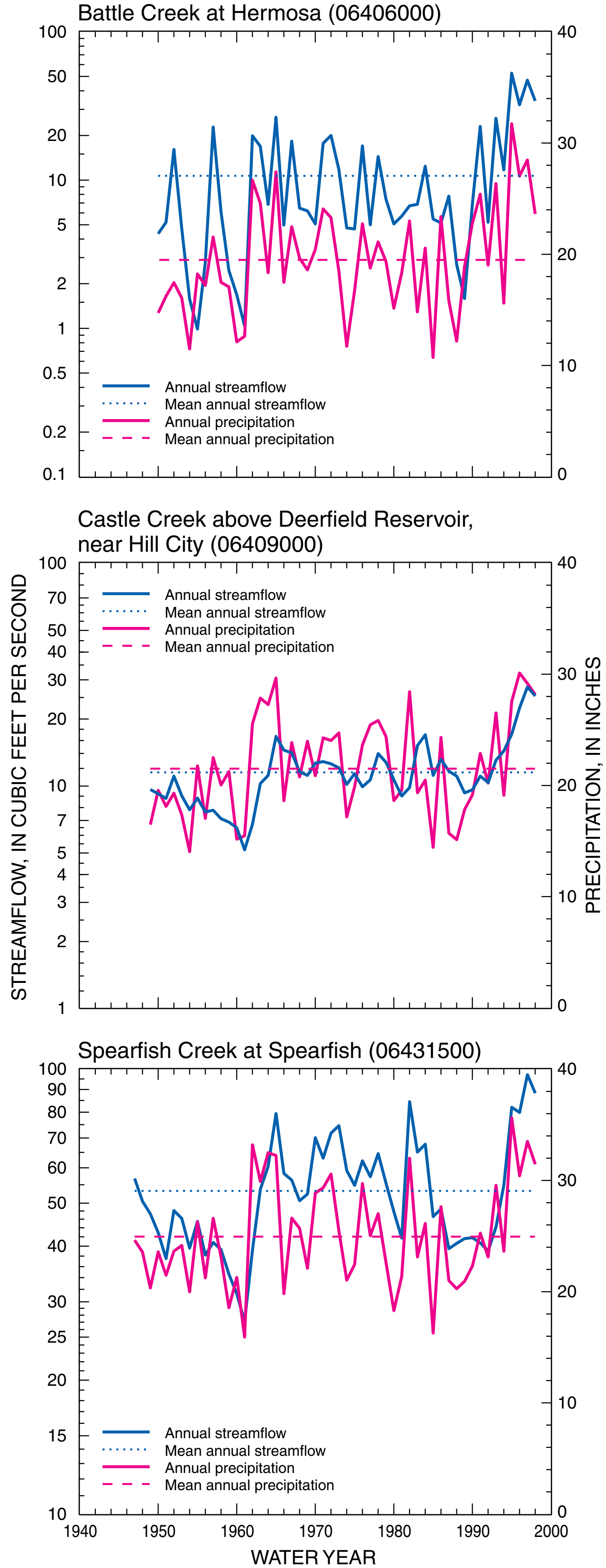

Figure 16. Long-term streamflow and precipitation trends for Battle, Castle, and Spearfish Creeks.

Annual streamflow records for all gaging stations considered (table 2, fig. 12), along with estimated precipitation amounts for the associated drainage areas, are presented by hydrogeologic setting in tables 19-24. For some gages, additional years of precipitation data also are presented, for purposes described in subsequent discussions. Annual runoff efficiency (the ratio of annual basin yield to precipitation, expressed as a percent) also is presented with the exception of artesian spring basins, for which runoff efficiencies are not meaningful.

Four graphs showing relations between streamflow and precipitation for each of the six representative gages for the limestone headwater setting are presented in figure 17. The first graph for each gage is a scatter plot showing the linear regression between annual streamflow (dependent variable, in cubic feet per second) and precipitation (independent or explanatory variable, in inches). Regression equations (in the form of $y = mx + b$) are provided on each graph, along with the coefficient of determination (r^2), which represents the percentage of variability of the dependent variable explained by the independent variable. P-values also are provided, which indicate the statistical significance of the slopes (p-values $\leq$0.05 indicate a $\geq$95.0 percent probability of non-zero slopes). The r^2 values and p-values provide consistent indications of generally weak relations between annual streamflow and precipitation for this setting, which results primarily from the large influence of ground-water discharge, which responds very slowly to changes in precipitation patterns.

The second graph for each gage (fig. 17) shows r^2 values for a series of regression analyses using "moving-average" precipitation as an explanatory variable for annual streamflow. The 1-year averages are simply the current year's precipitation, with r^2 values that are identical to those for the first graphs. The 2-year averages are computed by averaging precipitation for 2 years (current and previous); the 3-year averages are computed by averaging precipitation for 3 years (current and 2 previous); and so on. For all gages, the r^2 values generally improve, to a point, as additional years are included in the averages.

The third graph for each gage (fig. 17) shows a scatter plot, regression equation, and statistics for the best-fit, moving-average regression. Using Castle Creek as an example, the best fit is for the 3-year moving average, for which r^2 has improved to 0.58 and the p-value is much less than 0.001, indicating a probability in excess of 99.9 percent that the slope of the regression line is not due to chance. The best-fit averages range up to 11 years for Beaver Creek and Cold Springs Creek. The p-value for Beaver Creek (0.063) indicates a marginally significant slope (about 94 percent probability of non-zero slope); however, slopes for best-fit averages for all other gages are highly significant.

The fourth graph for each gage (fig. 17) shows annual streamflow, precipitation, and the best-fit moving-average precipitation. Castle Creek shows more response to annual precipitation variability than the other gages, which is consistent with the 3-year best-fit moving average (the shortest among the limestone headwater gages). This probably results from the physical nature of this drainage basin, which includes a substantial area representative of the crystalline core setting (fig. 12), where response to changing precipitation patterns is relatively rapid.

Many of the limestone headwater gages have short periods of record, and numerical relations between streamflow and moving-average precipitation may change substantially if additional years of record become available for future analysis. It can be concluded, however, that cumulative, long-term precipitation patterns are much more important than short-term patterns for explaining streamflow variability in the limestone headwater setting. This concept is consistent with the hydrogeologic setting, where streamflow is dominated by headwater springflow.

Graphs showing relations between annual streamflow and precipitation for 12 gages representative of the crystalline core setting are presented in figure 18. Each graph includes a linear regression line, along with the corresponding equation and r^2 value. All of the slopes are highly significant; thus, p-values are not shown. The minimum r^2 value is for Beaver Creek (06402430), where 52 percent of the variability in annual streamflow can be explained by annual precipitation. The BFI (73 percent) for this gage is the largest among the crystalline core setting (table 2), which is consistent with the weak correlation between annual streamflow and precipitation.

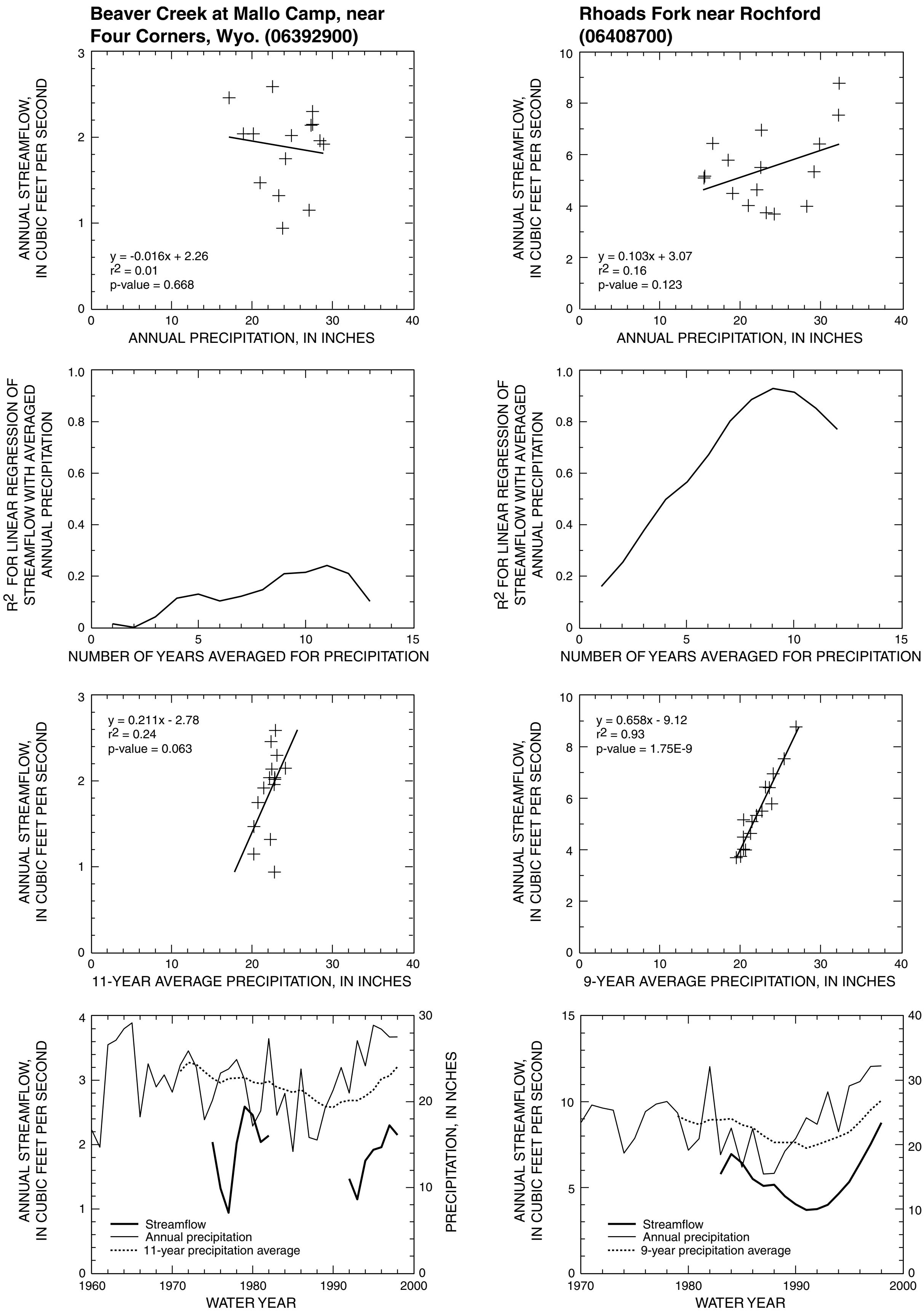

Figure 17. Relations between streamflow and precipitation for limestone headwater basins.

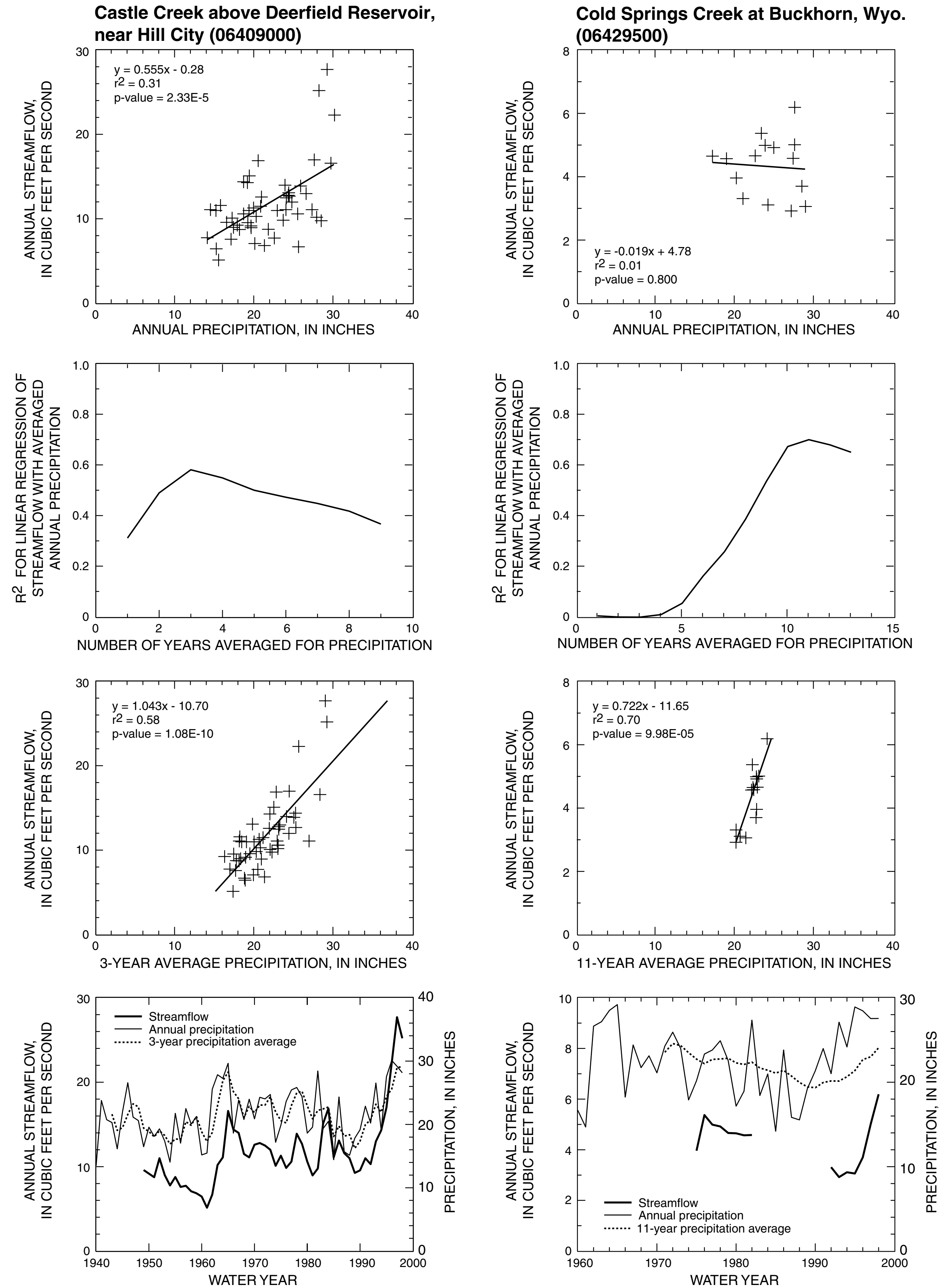

Figure 17. Relations between streamflow and precipitation for limestone headwater basins.--Continued

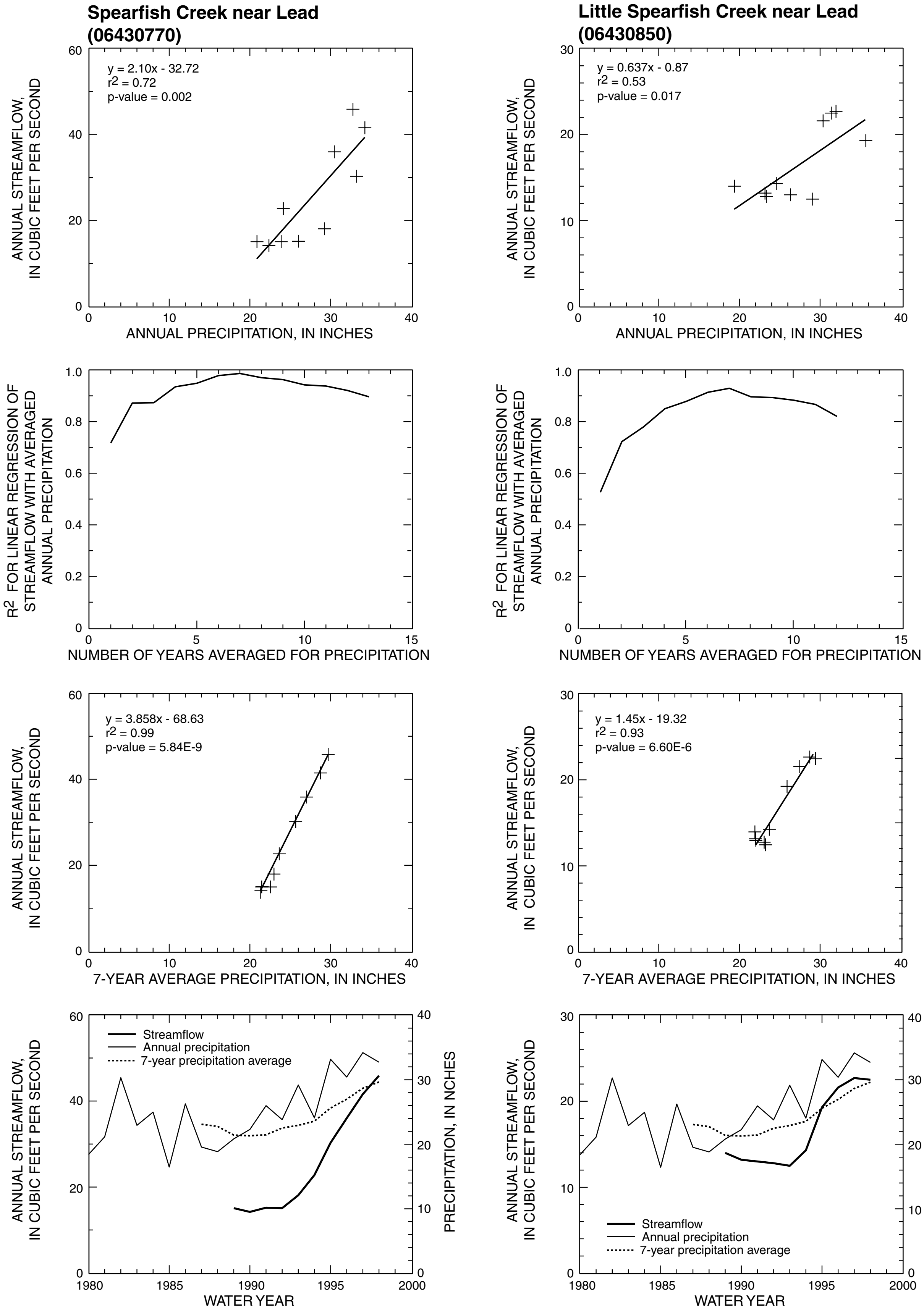

Figure 17. Relations between streamflow and precipitation for limestone headwater basins.--Continued

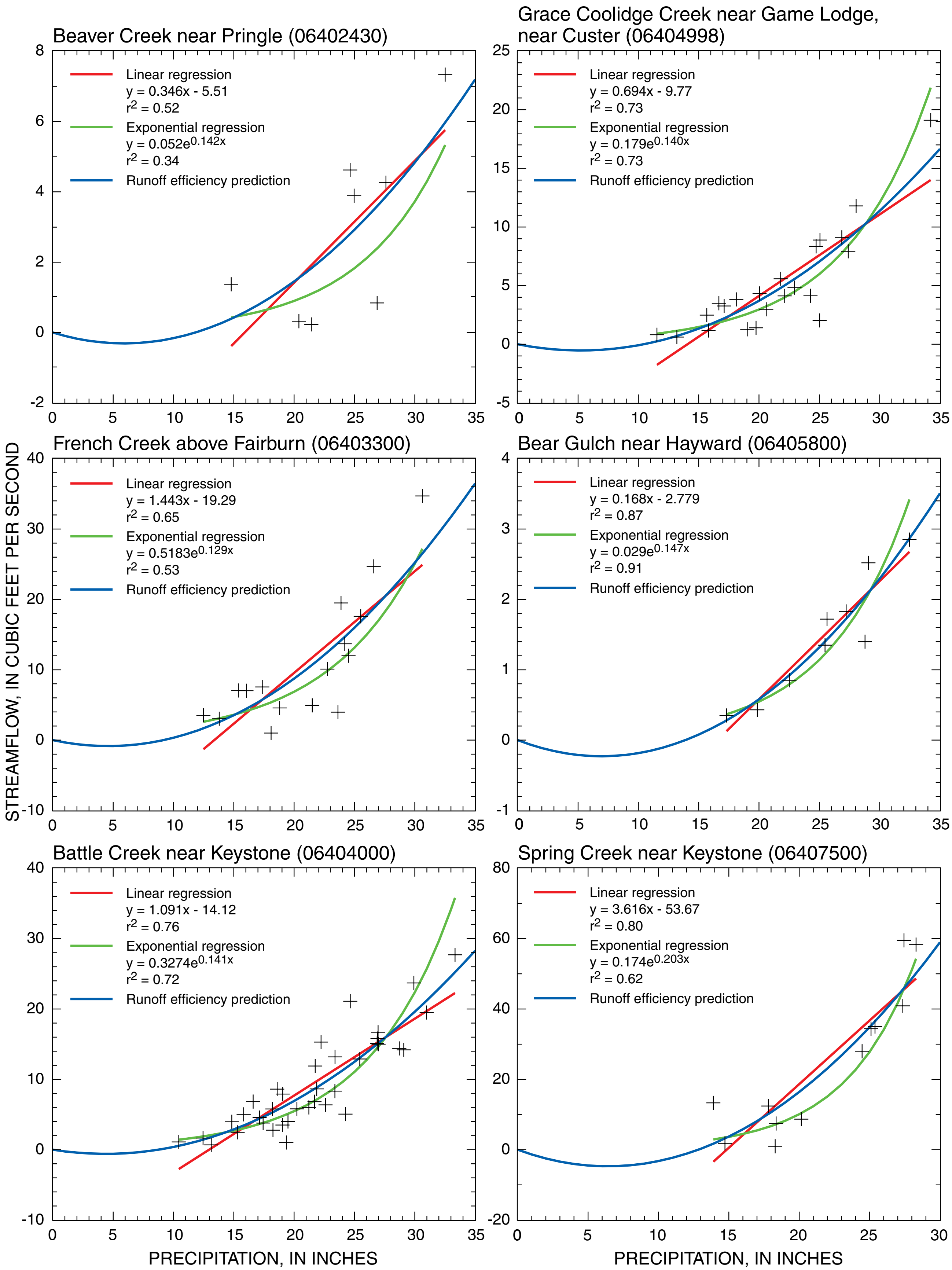

Figure 18. Relations between annual streamflow and precipitation for crystalline core basins.

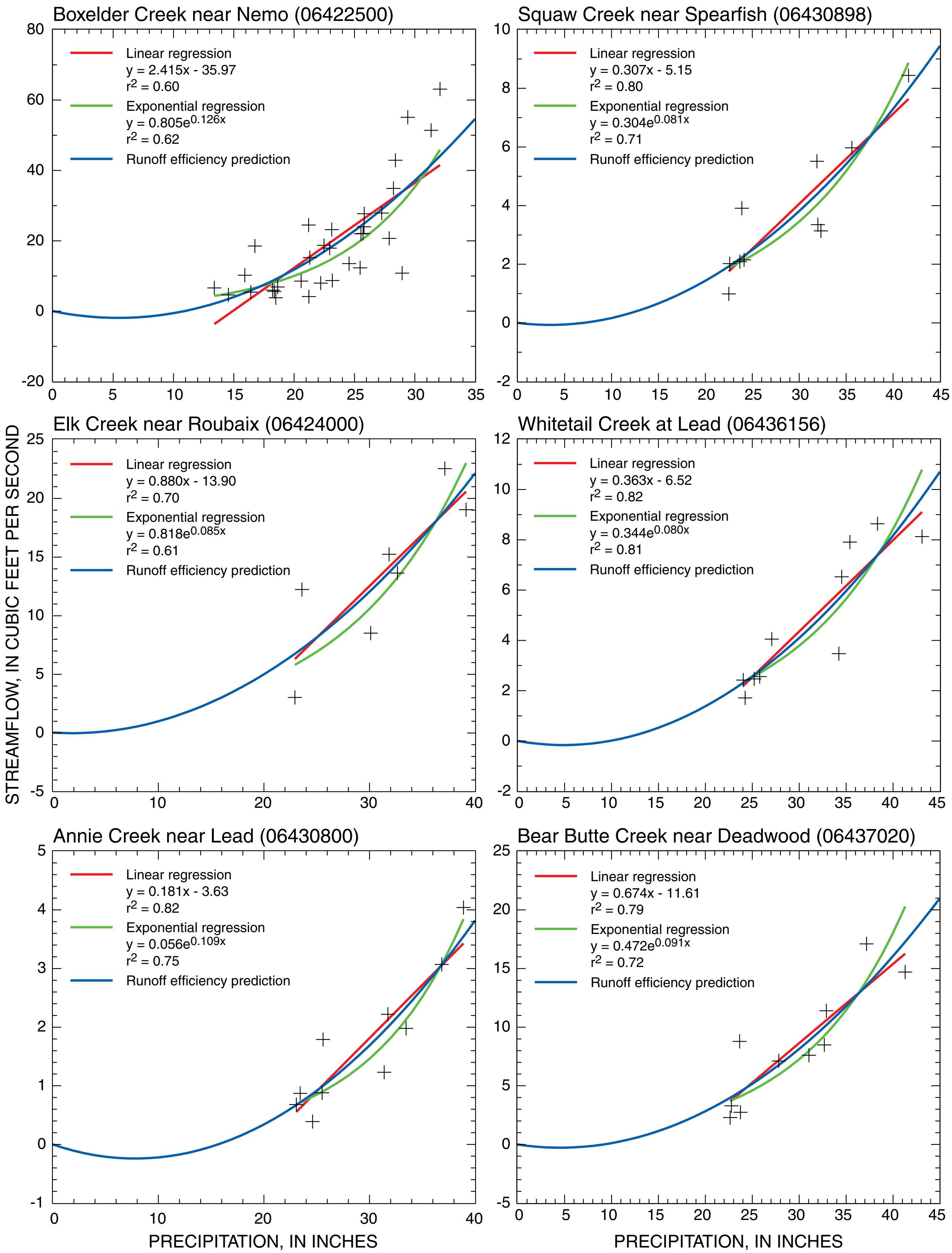

Figure 18. Relations between annual streamflow and precipitation for crystalline core basins.--Continued

An exponential regression curve, along with the corresponding equation and r^2 value, also is shown on each graph in figure 18. All of the linear regression equations have negative y-axis intercepts, which results in a general tendency to predict negative streamflow for small values of annual precipitation. All of the exponential equations would predict small, positive streamflow for zero precipitation (which is not realistic), but avoid prediction of negative streamflow in the lower range of typical annual precipitation. Predicted streamflow values for the linear equations slightly exceed the exponential predictions through most of the middle of the range of precipitation values; however, the exponential predictions generally become larger than the linear predictions near the upper end of the range of measured precipitation values.

Each graph in figure 18 also includes a curve labeled "runoff efficiency prediction," which is derived from linear regression equations of runoff efficiency as a function of precipitation. Regression lines for the 12 representative crystalline core basins are shown in figure 19; regression equations and r^2 values are provided in table 3. Correlations between runoff efficiency and precipitation are consistently positive and statistically significant; however, the r^2 values are consistently weaker than for the streamflow/precipitation regressions because of the use of precipitation as a divisor.

Figure 19 indicates that within each basin, runoff efficiency increases with increasing annual precipitation, and that basins with higher precipitation generally have higher efficiencies. Both scenarios are physically realistic. Given increasingly large precipitation, runoff efficiencies would eventually approach 100 percent as annual evapotranspiration was increasingly exceeded. The highest runoff efficiencies in the Black Hills area are in the highest altitudes, where evapotranspiration rates are smallest; however, total evapotranspiration can be larger than in lower altitudes, because of increased availability of water.

The equations in table 3 predict runoff efficiency as a percentage of precipitation, which requires additional manipulation for use in figure 18, where streamflow is plotted in cubic feet per second. Using 20.0 inches of precipitation for Beaver Creek (06402430) as an example, predicted runoff efficiency is 2.16 percent, which would produce 0.432 inch of runoff from the 45.8 mi^2 drainage basin (table 2), or the equivalent of 1.46 ft^3/s on an annual basis.

The runoff efficiency predictions generally are intermediate between the linear and exponential regression lines and tend to approximate the linear predictions very closely through most of the measured precipitation ranges (fig. 18). Runoff efficiency predictions are unrealistic (slightly negative) for very low precipitation values, but are consistently positive for the measured ranges of precipitation. The runoff efficiency predictions and exponential equations both impart a curvilinear characteristic that is apparent for the gages with longer records, such as Battle, Grace Coolidge, and Boxelder Creeks.

The linear and exponential equations are summarized in table 3, with streamflow expressed in inches, rather than cubic feet per second (fig. 18), which allows generic comparison of regression equations. The r^2 values for both equation types are independent of units and are the same for each gage, as are the exponents for the exponential regressions. For the exponential equations, the coefficients are inversely correlated with the exponents and tend to increase with increasing basin yield, as shown for selected basins (fig. 20). For the linear regression equations, increasing yields generally are associated with decreasing intercepts and increasing slopes.

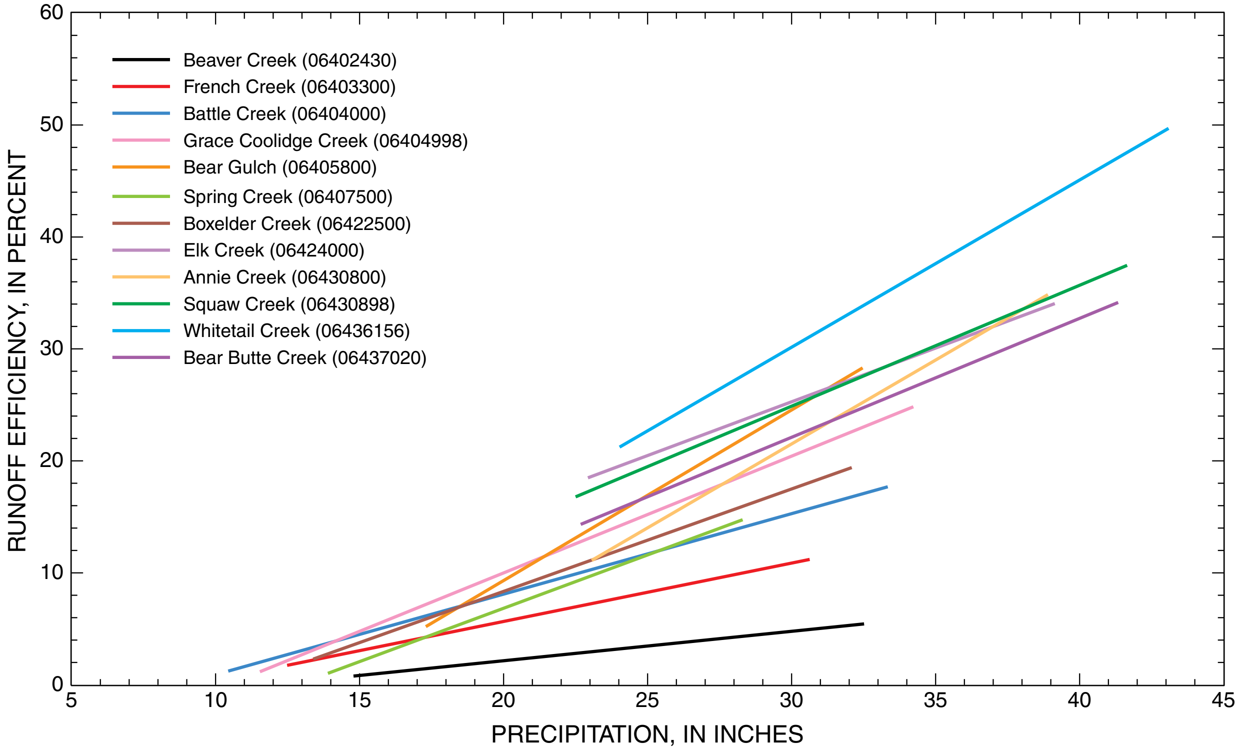

Figure 19. Relations between annual runoff efficiency and precipitation for crystalline core basins.

Table 3. Summary of selected regression information for crystalline core basins

[Runoff efficiencies in percent; all other units in inches. Int, Intercept; Coef, Coefficient; Exp, Exponent; <, less than]

Station number	Station name	Annual runoff efficiency versus precipitation			Annual streamflow versus precipitation (all variables in inches)											
					Exponential regression			Linear regression			Multiple linear regression					
												Current precipitation		Previous precipitation		
		r^2	Slope	Int	r^2	Coef	Exp	r^2	Slope	Int	R^2	Coef	p-value	Coef	p-value	Int
06402430	Beaver Creek near Pringle	0.32	0.263	-3.10	0.34	0.015	0.142	0.52	0.103	-1.63	0.61	0.122	0.037	0.046	0.327	-3.19
06403300	French Creek	.49	.521	-4.76	.53	.067	.129	.65	.187	-2.50	.72	.190	<.001	.059	.100	-3.82
06404000	Battle Creek	.61	.719	-6.28	.72	.077	.141	.76	.255	-3.30	.78	.254	<.001	.034	.152	-4.00
06404998	Grace Coolidge Creek	.64	1.043	-10.87	.73	.096	.140	.73	.374	-5.26	.76	.370	<.001	.068	.190	-6.60
06405800	Bear Gulch	.82	1.523	-21.14	.91	.093	.147	.87	.539	-8.93	.87	.532	<.001	-.039	.640	-7.79
06407500	Spring Creek	.70	.953	-12.22	.62	.014	.204	.80	.301	-4.47	.82	.297	<.001	.038	.447	-5.22
06422500	Boxelder Creek	.45	.915	-9.95	.62	.114	.126	.60	.342	-5.09	.67	.321	<.001	.119	.020	-7.32
06424000	Elk Creek	.34	.960	-3.52	.61	.518	.085	.70	.555	-8.77	.76	.547	.028	.158	.374	-13.28
06430800	Annie Creek	.68	1.498	-23.42	.74	.213	.109	.82	.693	-13.86	.82	.688	.002	.010	.940	-14.01
06430898	Squaw Creek	.52	1.080	-7.51	.71	.596	.081	.80	.599	-10.04	.81	.575	.001	.093	.428	-11.95
06436156	Whitetail Creek	.62	1.493	-14.64	.81	.756	.080	.82	.801	-14.42	.92	.671	<.001	.307	.018	-19.58
06437020	Bear Butte Creek	.50	1.062	-9.75	.72	.385	.091	.78	.552	-9.51	.82	.520	.002	.112	.293	-11.75

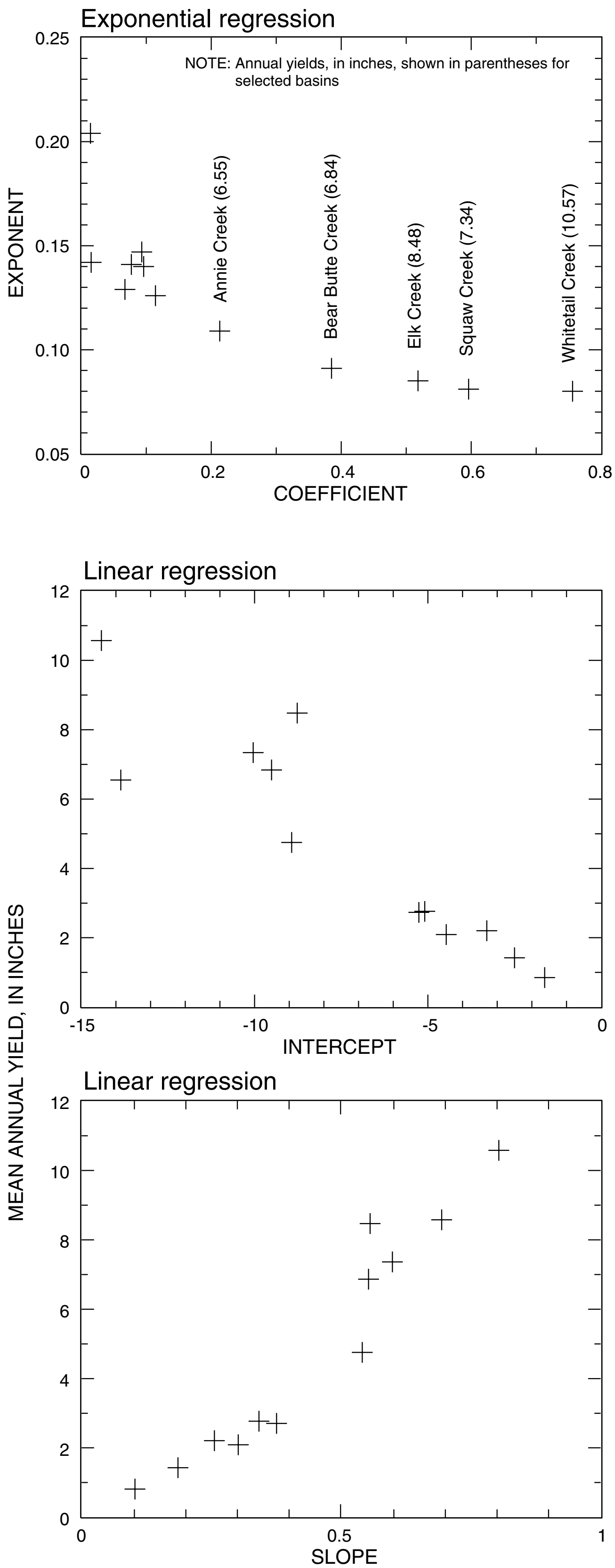

Figure 20. Relations among selected variables derived from exponential and linear regression analyses for crystalline core basins.

Regression information also is presented in table 3 for multiple linear regressions of annual flow (in inches) as a function of current and previous year's precipitation. Coefficients for previous precipitation are realistic (positive, indicating increased flow with increased precipitation) for all stations except Bear Gulch. Improvements in R^2 values generally are small, and previous precipitation is statistically significant at the 95-percent level ($p \leq 0.05$) only for Boxelder and Whitetail Creeks. Thus, it can be concluded that precipitation during the previous year generally has only minor influence on annual streamflow for crystalline core basins.

Antecedent precipitation and streamflow conditions would be useful for prediction of monthly flow for some crystalline core basins. As an example, R^2 values for three regression scenarios for monthly flow of Battle Creek are presented in figure 21. Monthly flow and precipitation data used in monthly regression analyses for Battle Creek are provided in table 25 in the Supplemental Information section. Using only monthly precipitation as an explanatory variable, R^2 values are very low for the winter months of November through February, when precipitation generally is minimal and may be stored as snow or ice. Including the previous month's streamflow as an explanatory variable improves R^2 values considerably for these and several other months because of high serial correlation values for these months (Miller and Driscoll, 1998). Including the previous month's precipitation also improves R^2 values for most months; however, improvements generally range from similar to much smaller than what could be obtained by using antecedent streamflow.

Graphs showing relations between streamflow and precipitation for the two gages representative of the loss zone setting are presented in figure 22. It is apparent that low-flow and zero-flow years are common, with substantial flows occurring only when upstream flows are sufficiently large to sustain flow through loss zones. A power equation and associated r^2 value is shown for each gage, which provide reasonable fits for the nonlinear data.

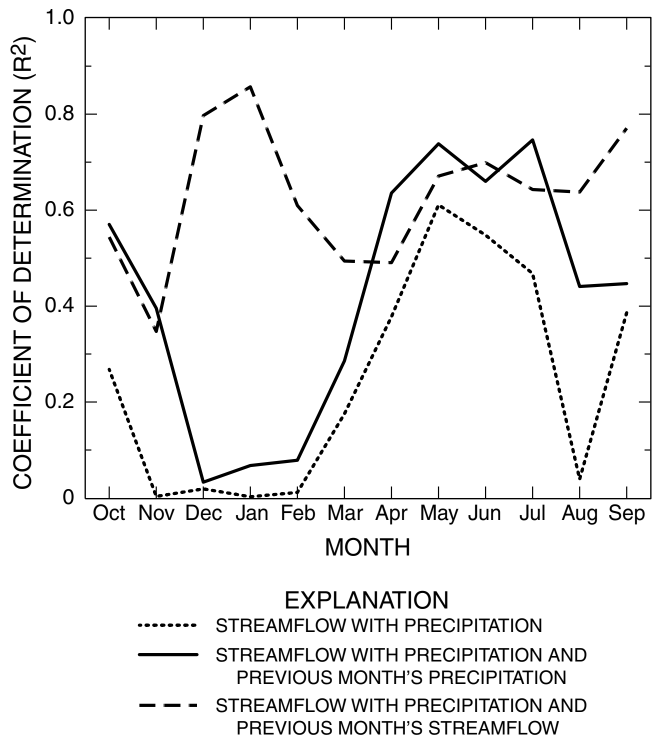

Figure 21. Coefficient of determination (R^2) values for selected regressions of monthly streamflow for Battle Creek near Keystone (06404000).

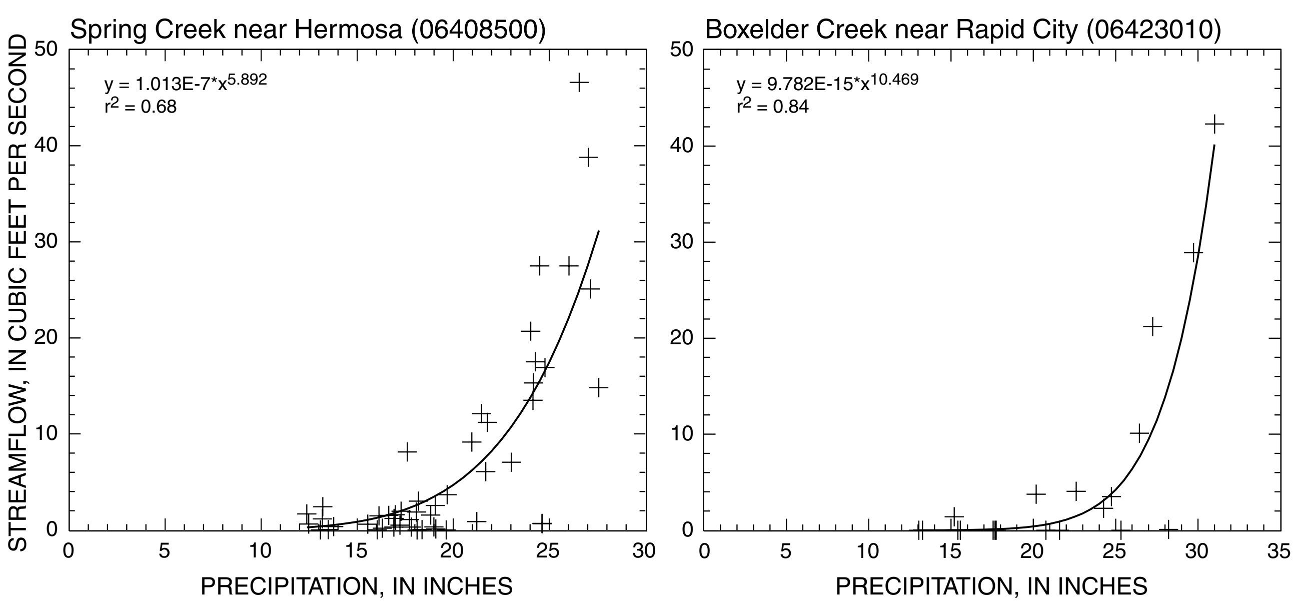

Figure 22. Relations between annual streamflow and precipitation for loss zone basins.

Two graphs showing relations between streamflow and precipitation for each of seven gages representative of the artesian spring setting are presented in figure 23. Surface drainage areas are very small for Cascade Springs (0.47 mi^2) and Cox Lake (0.07 mi^2) relative to annual flow (table 2). Thus, annual precipitation for these gages is arbitrarily represented by precipitation over Fall River and Lawrence Counties, respectively. Precipitation distributions were not performed for the two gages that are located in Wyoming (Stockade Beaver Creek and Sand Creek). For these gages, precipitation estimates were derived by averaging values for individual measurement sites presented by Driscoll, Hamade, and Kenner (2000, p. 7), which included sites 53 and 81 for Stockade Beaver Creek and sites 53, 61, and 89 for Sand Creek.

The first graph in figure 23 for each gage is a scatter plot showing the linear regression between annual flow and precipitation. Correlations between the two variables are very weak, with most r^2 values less than 50 percent and slopes of regression lines that are consistently nonsignificant, with all p-values greater than 0.05. Correlations between flow and moving-average precipitation might be stronger than annual relations for some sites, as indicated by time-trend plots of flow and precipitation that also are presented for each gage. Possible relations are not examined, however, because of generally short periods of record and inaccuracies associated with estimating precipitation over unknown contributing ground-water areas. Fall River had a declining trend for many years, but has shown recent response to the extremely wet climatic conditions during the 1990's. Peterlin (1990) investigated possible causes for the declining streamflow in Fall River that occurred during about 1940-70 (fig. 23), but was unable to conclusively determine causes.

Scatter plots showing linear regressions between annual flow and precipitation for six gages representative of the exterior setting are presented in figure 24. The r^2 values generally are weak; however, the p-values indicate that all slopes are statistically significant. Multiple linear regression analyses also were performed, with the previous year's precipitation tested as an additional explanatory variable. This improved relations significantly only for Hay and Bear Butte Creeks, as shown in table 4.

Relations between annual runoff efficiency and precipitation for exterior basins are shown in figure 25. Runoff efficiencies generally are lower than for the crystalline core basins (fig. 19) because of generally lower precipitation, increased evaporation potential, and minor irrigation withdrawals.

Table 4. Summary of regression information for exterior basins

[Multiple regression is for annual flow, in cubic feet per second, as a function of current and previous year's precipitation, in inches; simple regression is for runoff efficiency in percent, as a function of precipitation, in inches. NA, not applicable; Int, intercept; <, less than; --, no data]

Station number	Station name	Multiple linear regression						Annual runoff efficiency versus precipitation		
		R^2	Current precipitation		Previous precipitation		Intercept			
			Coefficient	p-value	Coefficient	p-value		r^2	Slope	Int
06400000	Hat Creek	--	--	--	--	--	--	0.10	0.126	-0.76
06400875	Horsehead Creek	--	--	--	--	--	--	.42	.487	-6.04
NA	Elk Creek (subbasin)	--	--	--	--	--	--	.36	.310	-3.68
06433500	Hay Creek	0.54	0.033	<0.001	0.011	0.052	-0.60	.41	.125	-1.37
06436700	Indian Creek	--	--	--	--	--	--	.19	.782	-6.64
06437500	Bear Butte Creek	.75	.148	<.001	.052	.022	-3.75	.56	.456	-7.15

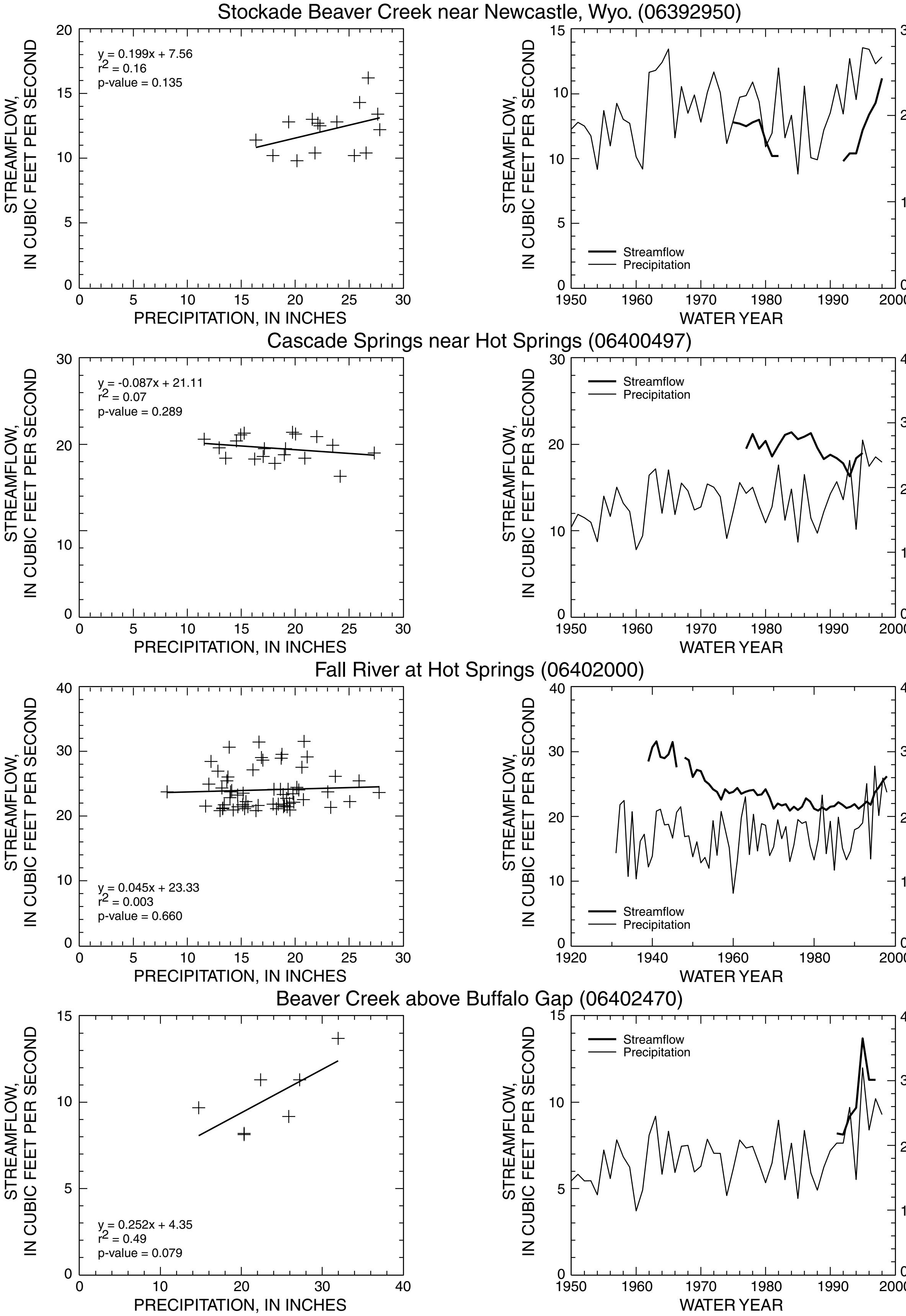

Figure 23. Relations between annual streamflow and precipitation for artesian spring basins.

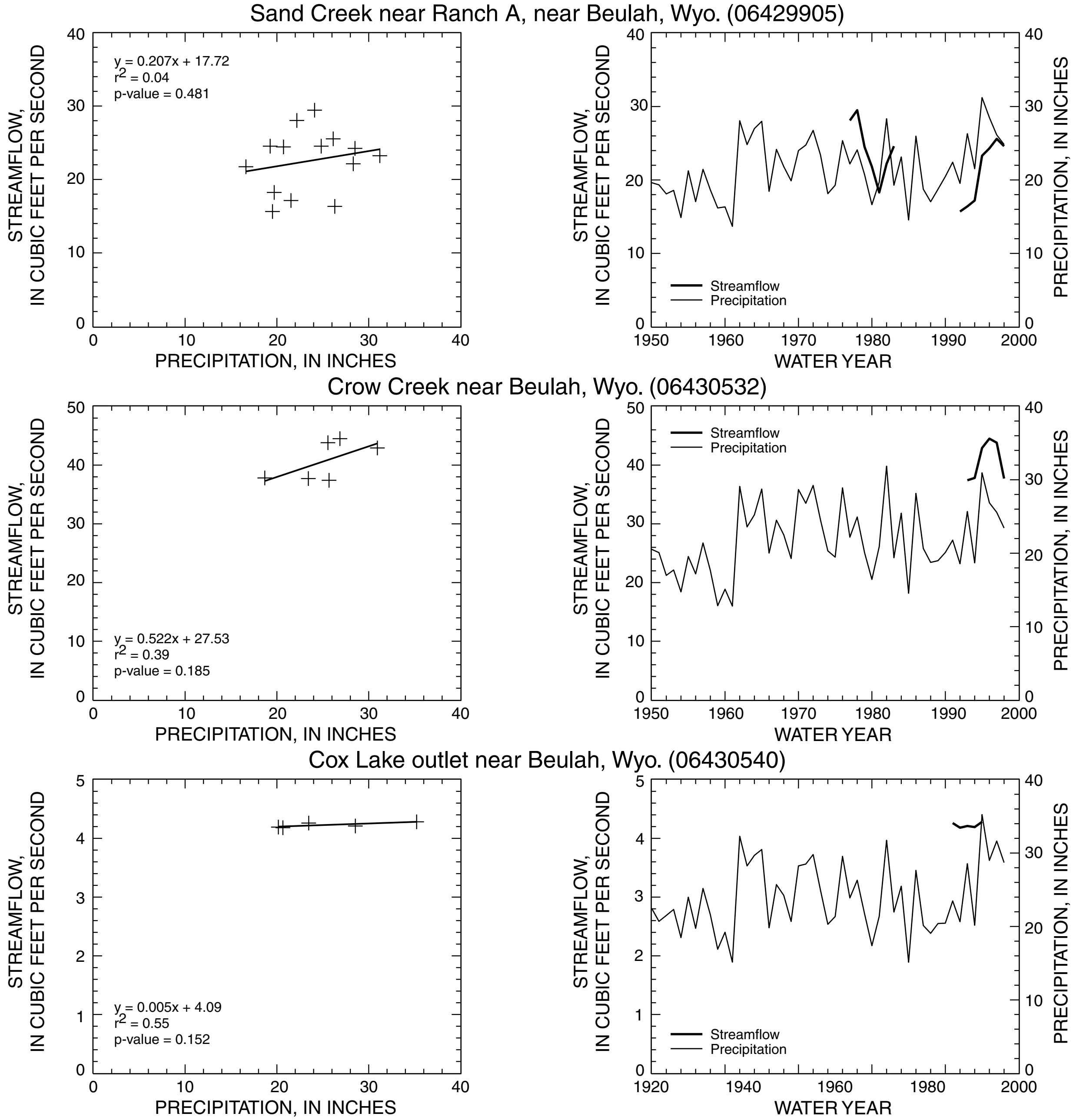

Figure 23. Relations between annual streamflow and precipitation for artesian spring basins.--Continued

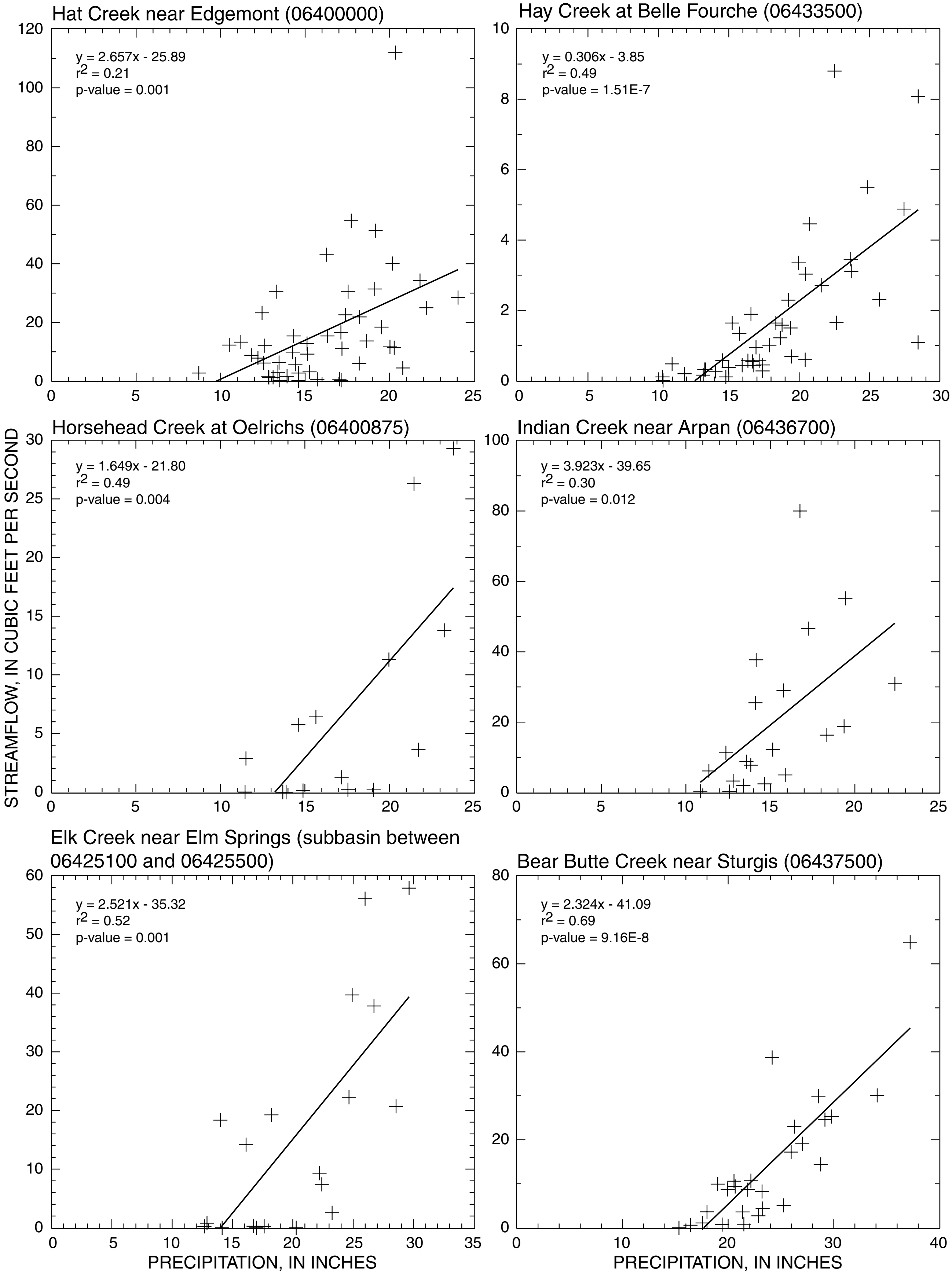

Figure 24. Relations between annual streamflow and precipitation for exterior basins.

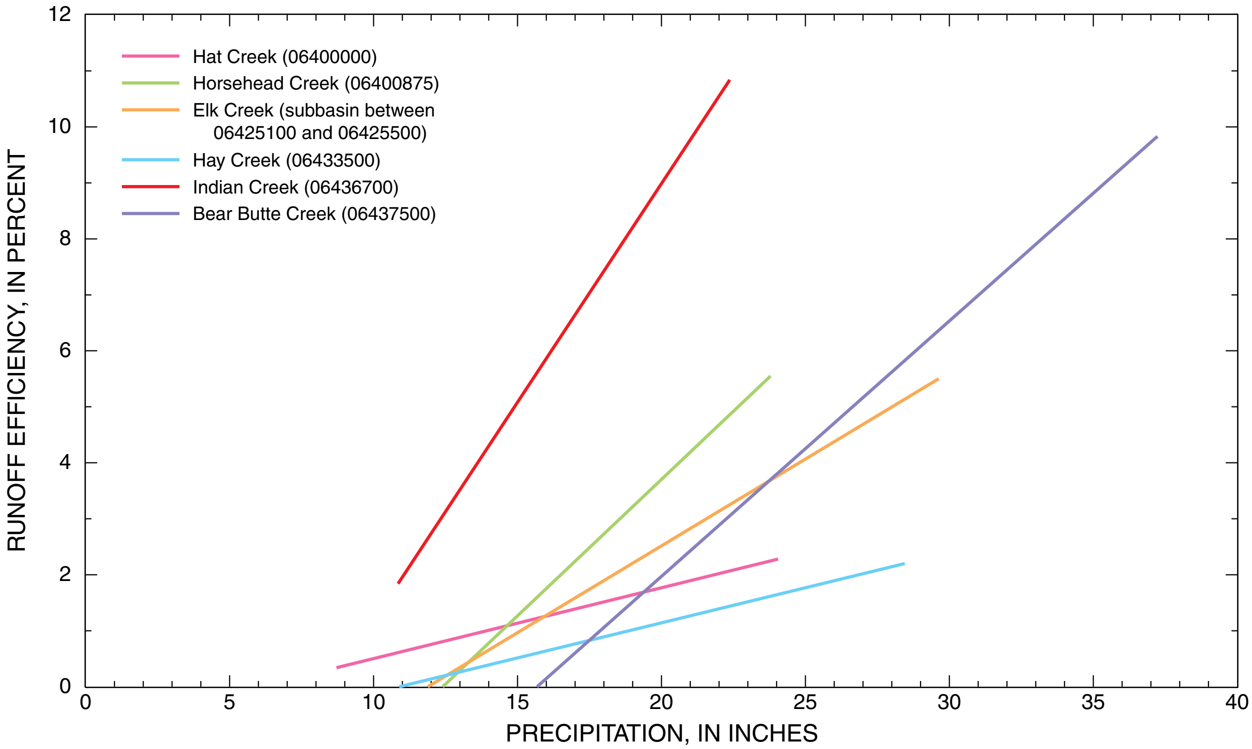

Figure 25. Relations between annual runoff efficiency and precipitation for exterior basins.

Scatter plots showing linear regressions between annual flow and precipitation for the 10 "combination" gages are presented in figure 26. Many of the gages are downstream from "representative" gages, but include a mix of hydrogeologic conditions (table 5). Many also are affected to some extent by regulation or diversions. Effects of regulation for Rapid Creek above Pactola Reservoir (06410500) have been accounted for by adjusting for annual storage changes in Deerfield Reservoir.

Correlations between streamflow and precipitation for many of the combination gages are stronger than for representative gages located upstream. In some cases this results from substantial diversions, which tend to be larger during drier years. An example is Beaver Creek near Buffalo Gap ($r^2 = 0.70$), which is downstream from Beaver Creek above Buffalo Gap where flow is influenced almost entirely by artesian springflow and the correlation with precipitation ($r^2 = 0.49$) is fairly weak (fig. 23). Redwater River also has relatively small variability in flow during base flow months (Miller and Driscoll, 1998); however, irrigation diversions during summer months contribute to variability in annual flow, which correlates fairly well with precipitation.

Multiple linear regression analyses also were performed (table 5), with the previous year's precipitation tested as an additional explanatory variable. The p-values indicate that previous precipitation is statistically significant at the 90-percent level ($p \leq 0.10$) for all but one gage (Elk Creek near Elm Springs) and most of the R^2 values show substantial improvements.

Correlations between annual streamflow and precipitation are fairly strong for Battle Creek ($r^2 = 0.64$), in spite of influence from loss zones and artesian springs, which generally weaken the correlations. Including previous precipitation improves predictability only slightly ($R^2 = 0.68$). In contrast, the annual correlation for Elk Creek near Rapid City, which has similar hydrogeologic influences, is fairly weak ($r^2 = 0.46$); however, predictability improves considerably by including previous precipitation ($R^2 = 0.64$).

Relations between streamflow and moving-average precipitation were not explored for the combination gages, but could improve predictability for gages that are strongly influenced by springflow. Similarly, curvilinear characteristics are apparent for several of the gages; however, curve-fitting techniques were not explored.

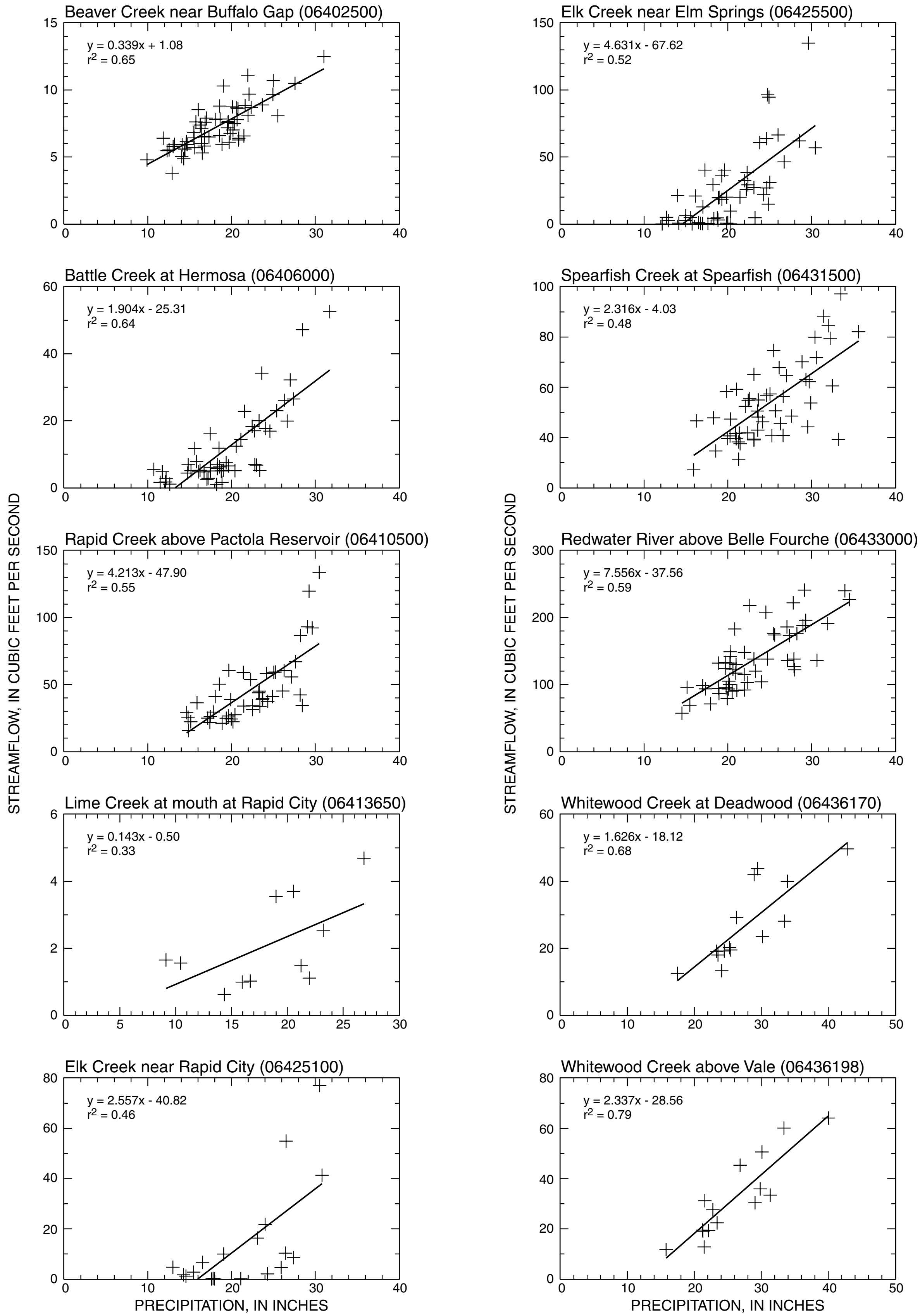

Figure 26. Relations between annual streamflow and precipitation for combination basins.

Table 5. Hydrogeologic influences and multiple regression information for combination basins

[Multiple regression is for annual flow, in cubic feet per second, as a function of current and previous year's precipitation, in inches. Coef, coefficient; Int, intercept; <, less than; --, no data]

Station number	Station name	Hydrogeologic influences		Multiple linear regression					
				R^2	Current precipitation		Previous precipitation		Int
		Major	Minor		Coef	p-value	Coef	p-value	
06402500	Beaver Creek near Buffalo Gap	Artesian, Diversions	Loss zone	0.70	0.323	<0.001	0.101	0.002	-0.48
06406000	Battle Creek at Hermosa	Loss zone, Artesian	Diversions	.68	1.821	<.001	.450	.032	-32.43
06410500	Rapid Creek above Pactola Reservoir	Headwater, Crystalline, Regulation[1]	Diversions	.68	3.581	<.001	2.210	<.001	-82.49
06413650	Lime Creek at mouth, at Rapid City	Artesian, Urban runoff, Diversions	--	.55	.144	.039	.114	.085	-2.56
06425100	Elk Creek near Rapid City	Loss zone, Artesian	Diversions	.64	2.605	<.001	1.627	.011	-76.27
06425500	Elk Creek near Elm Springs	Loss zone, Artesian, Exterior	Diversions	.54	4.623	<.001	1.010	.123	-87.87
06431500	Spearfish Creek at Spearfish	Headwater, Crystalline, Diversions	Loss zone	.64	2.033	<.001	1.312	<.001	-29.86
06433000	Redwater River above Belle Fourche	Headwater, Crystalline, Loss zone, Artesian, Exterior, Diversions	--	.77	6.854	<.001	4.251	<.001	-120.00
06436170	Whitewood Creek at Deadwood	Headwater, Crystalline, Diversions[2]	--	.83	1.767	<.001	1.095	.008	-50.84
06436198	Whitewood Creek above Vale	Headwater, Crystalline, Diversions[2], Exterior	Loss zone[3], Diversions[4]	.87	2.293	<.001	.753	.018	-46.77

[1]Flow affected by operation of Deerfield Reservoir; however, flow records have been adjusted to account for annual changes in storage.
[2]Flow affected by diversions into basin from Rapid, Elk, and Spearfish Creek Basins.
[3]Site located downstream from loss zone; however, losses are minimal (Hortness and Driscoll, 1998).
[4]Flow also affected by minor irrigation diversions.

Annual Yield Characteristics

Annual yield characteristics are highly variable throughout the study area, primarily because of orographic effects, which influence both precipitation and evapotranspiration. Evaluation of yield characteristics is complicated by the bias in some short-term streamflow records caused by wet climatic conditions during the 1990's. Relations between annual runoff efficiency and precipitation provide a basis, however, for a method of systematically estimating yield potential from annual precipitation, which was used for development of hydrologic budgets, as described in subsequent sections of this report.

Annual flow data for basins that are representative of hydrogeologic settings (table 2) are provided in tables 19-24. Yield data for selected gages that are used for analysis of yield characteristics are summarized in table 6. Selected gages include all of the limestone headwater and crystalline core gages except Bear Gulch, where yield characteristics were altered by effects of a large forest fire. Of the exterior basins, the Elk Creek subbasin and Indian Creek are excluded and all of the loss zone, artesian spring, and combination gages are excluded because yield characteristics are not necessarily representative of areal conditions. Station 06395000, Cheyenne River at Edgemont, which is listed with "other" streamflow-gaging stations in table 2, is included for analysis of yield characteristics.

Mean annual basin yields that are based on surface drainage areas for periods of measured record are shown in figure 27, along with estimated yield efficiencies for 1950-98 (table 6), which are taken from Carter, Driscoll, and Hamade (2001). For basins where contributing surface- and ground-water areas are assumed to be congruent, yield efficiency is considered equivalent to runoff efficiency. Yield efficiencies for 1950-98 could be calculated directly for only two gages (Cheyenne River and Castle Creek), which have sufficient periods of record. For most gages, precipitation records for 1950-98 were used in conjunction with relations between runoff efficiency and precipitation (determined from available streamflow and precipitation data), to derive estimates of annual yield, from which yield efficiencies were calculated. This method compensates for the climatic bias for short-term gages such as Elk Creek, where yield efficiency for 1950-98 is estimated as 21.5 percent (fig. 27, table 6), compared with 26.3 percent for 1992-98 (table 20), which is the period of streamflow record. Yield efficiencies for most of the limestone headwater gages are simply averages for the available periods of record, because relations between yield efficiency and precipitation for this setting generally are very weak or unrealistic.

It is apparent from examination of figure 27 that the largest yields are in the high altitudes of the northern Black Hills, where precipitation is largest (fig. 7). It also is apparent that calculated yields and efficiencies are highly variable along the Limestone Plateau, which results from incongruences between contributing ground- and surface-water areas. Carter, Driscoll, Hamade, and Jarrell (2001) presented estimates of contributing ground-water areas for the four limestone headwater gages in South Dakota (table 6). These estimates were derived from delineations of contributing areas (fig. 28) by Jarrell (2000), which were based primarily on dips of the underlying Ordovician or Cambrian strata.

Table 6 shows adjusted estimates of yield and yield efficiency for the four limestone headwater gages for which estimates of contributing ground-water areas are available. With these adjustments, yield efficiencies closely resemble those for nearby gages dominated by direct runoff. This was used as the basis of an assumption by Carter, Driscoll, and Hamade (2001) that the runoff efficiency of streams dominated by direct runoff can be used as a surrogate for the efficiency of precipitation recharge to the Madison and Minnelusa aquifers. This concept is schematically illustrated in figure 29. For areas where direct runoff is negligible, yield efficiency is considered equivalent to the efficiency of precipitation recharge. Precipitation recharge that occurs east of the ground-water divide (fig. 28) contributes to headwater springflow in generally easterly flowing streams; however, infiltration of precipitation west of the divide contributes to generally westerly ground-water flowpaths.

Table 6. Summary of information used in analysis of yield characteristics

[--, not applicable]

Site number (fig. 27)	Station number	Station name	Altitude of gage	Period of record (water years)	Contributing area (square miles)		Mean annual yield for period of record (inches)		Mean annual yield efficiency for water years 1950-98[3] (percent)	
					Surface water	Ground water[1]	Surface water	Ground water[2]	Surface water	Ground water[2]
1	06392900	Beaver Creek at Mallo Camp	6,030	1975-82, 1992-98	10.3	([4])	2.48	--	[5]10.6	--
2	06395000	Cheyenne River at Edgemont	3,415	1947-98	7,143	--	.15	--	[6].9	--
3	06400000	Hat Creek near Edgemont	3,296	1951-98	1,044	--	.22	--	1.3	--
4	06400875	Horsehead Creek at Oelrichs	3,320	1984-98	187	--	.49	--	2.1	--
5	06402430	Beaver Creek near Pringle	4,180	1991-98	45.8	--	.85	--	1.8	--
6	06403300	French Creek above Fairburn	3,850	1983-98	105	--	1.42	--	5.4	--
7	06404000	Battle Creek near Keystone	3,800	1962-98	58.0	--	2.20	--	8.3	--
8	06404998	Grace Coolidge Creek near Game Lodge	4,100	1977-98	25.2	--	2.73	--	9.9	--
9	06407500	Spring Creek near Keystone	3,885	1987-98	163	--	2.09	--	6.7	--
10	06408700	Rhoads Fork near Rochford	5,965	1983-98	7.95	13.1	9.34	5.67	[5]41.8	[5]25.4
11	06409000	Castle Creek above Deerfield Reservoir	5,920	1948-98	79.2	41.7	2.01	3.82	[6]9.3	[6]17.7
12	06422500	Boxelder Creek near Nemo	4,320	1967-98	96.0	--	2.76	--	10.8	--
13	06424000	Elk Creek near Roubaix	4,881	1992-98	21.5	--	8.48	--	21.5	--
14	06429500	Cold Springs Creek at Buckhorn	6,050	1975-82, 1992-98	19.0	([4])	3.10	--	[5]13.1	--
15	06430770	Spearfish Creek near Lead	5,310	1989-98	63.5	50.8	[7]7.58	9.48	[5, 7]25.1	[5, 7]31.4
16	06430800	Annie Creek near Lead	5,125	1989-98	3.55	--	6.55	--	16.4	--
17	06430850	Little Spearfish Creek near Lead	5,020	1989-98	25.8	25.4	8.74	8.88	[5]31.8	[5]32.3
18	06430898	Squaw Creek near Spearfish	4,480	1989-98	6.95	--	7.34	--	21.5	--
19	06433500	Hay Creek at Belle Fourche	3,005	1954-96	121	--	.20	--	1.0	--
20	06436156	Whitetail Creek at Lead	5,080	1989-98	6.15	--	10.57	--	27.2	--
21	06437020	Bear Butte Creek near Deadwood	4,750	1989-98	16.6	--	6.84	--	18.7	--
22	06437500	Bear Butte Creek near Sturgis	2,780	1946-72	[8]120	--	1.58	--	6.0	--

[1]Estimate of contributing ground-water area from Carter, Driscoll, Hamade, and Jarrell (2001).
[2]Yield estimates, where applicable, adjusted based on contributing ground-water area.
[3]Estimated using relations between runoff efficiency and precipitation from Carter, Driscoll, and Hamade (2001), unless otherwise noted.
[4]Contributing areas for surface water and ground water probably not congruent; however, no estimates available.
[5]Estimated using average runoff efficiency for the available period of record.
[6]Period of record sufficient for computation of yield efficiency.
[7]A flow of 10 cubic feet per second has been added to the measured streamflow to account for diverted flow.
[8]Approximate drainage area below loss zone. Actual drainage area is 192 square miles.

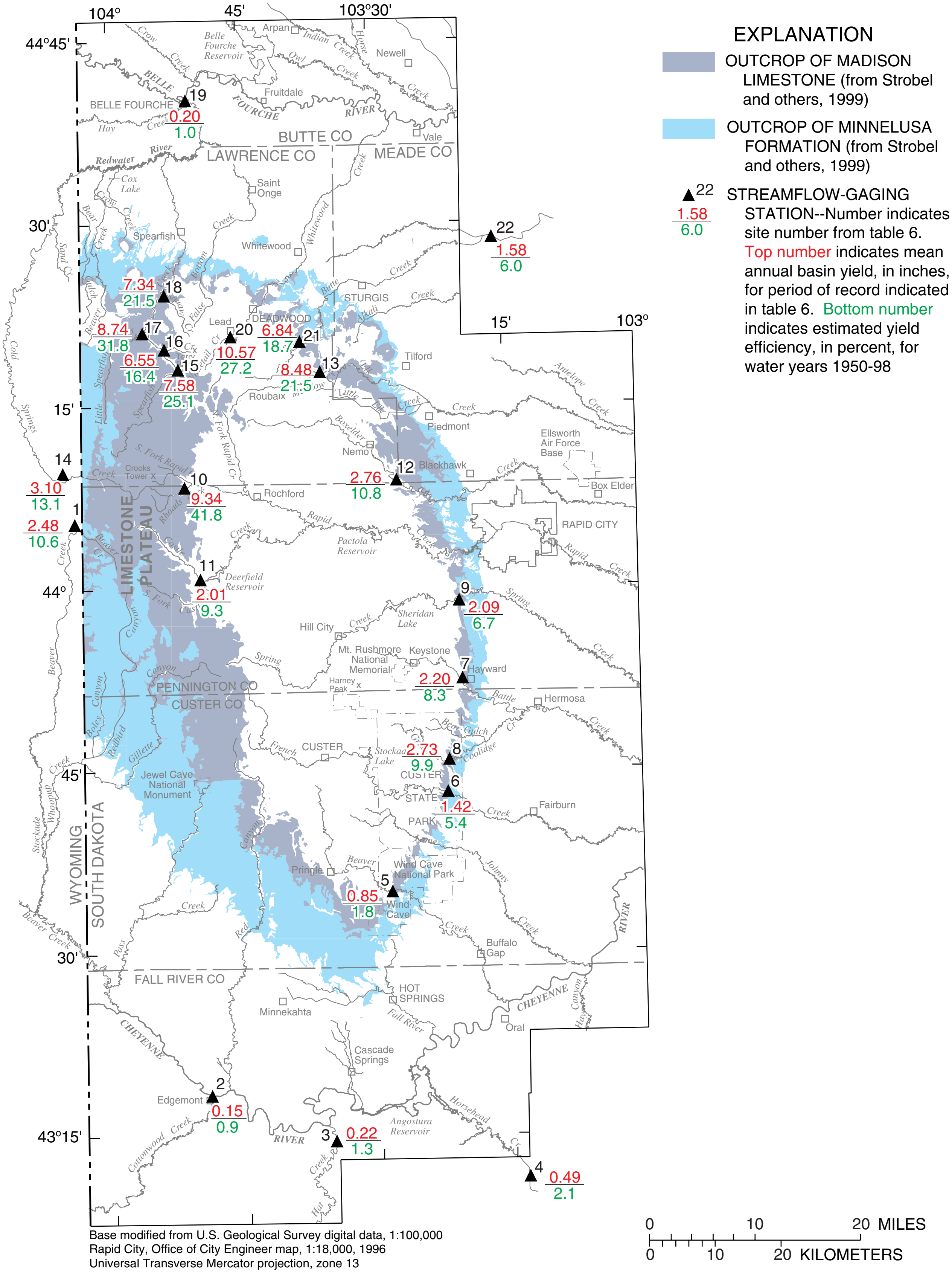

Figure 27. Basin yields and yield efficiencies for selected streamflow-gaging stations. Basin yields are for periods of actual record, which are not consistent. Yield efficiencies are for water years 1950-98, extrapolated using precipitation records.

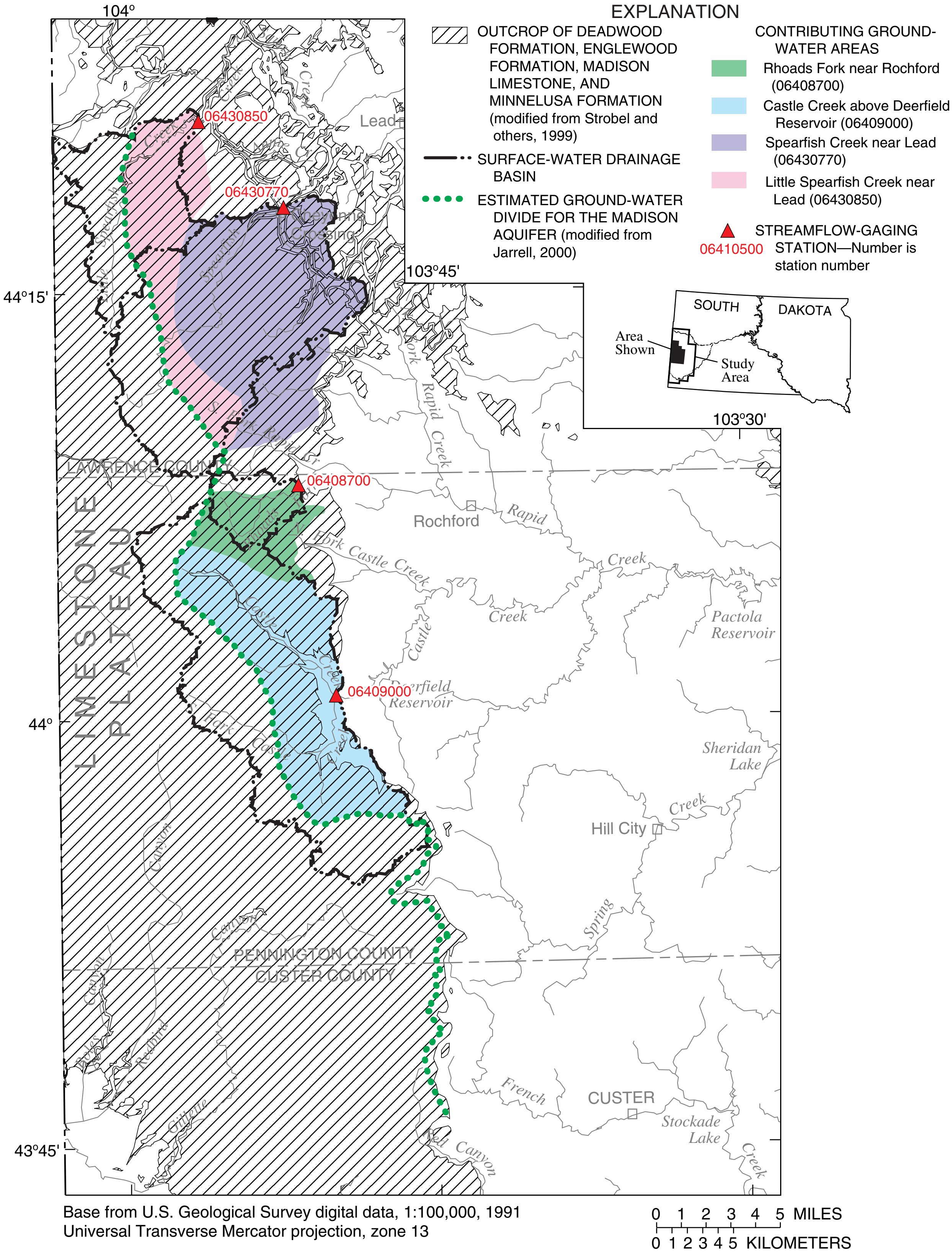

Figure 28. Comparison between contributing surface-water areas and ground-water areas for gaging stations in Limestone Plateau area (modified from Jarrell, 2000). Streamflow in the basins shown generally is dominated by ground-water discharge of headwater springs. Recharge occurring in areas west of the ground-water divide does not contribute to headwater springflow east of the divide.

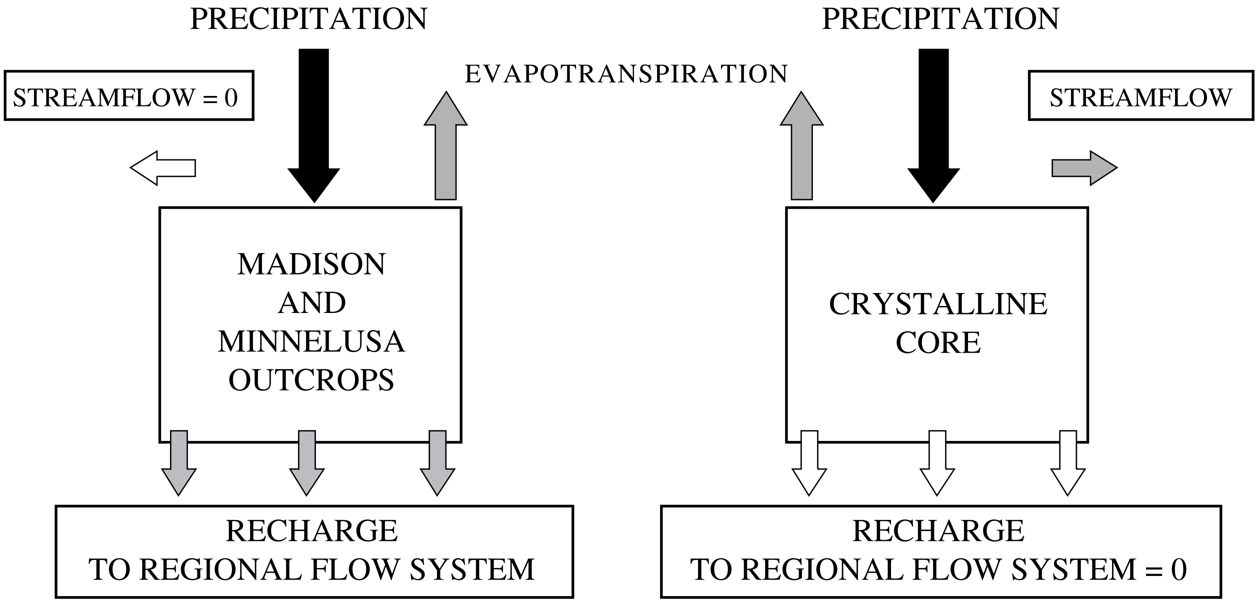

Figure 29. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types.

A contour map of generalized yield efficiency for the study area is presented as figure 30. Mapped contours are representative of estimated yield efficiencies for contributing surface- or ground-water areas (table 6) upgradient from gages. The map is taken from Carter, Driscoll, and Hamade (2001), who also considered precipitation patterns and topography in contouring. The generalized yield efficiency contours, with several minor exceptions, provide a reasonable fit with calculated efficiencies (table 6). Calculated efficiencies for the two limestone headwater gages in Wyoming (sites 1 and 14) are slightly lower than mapped efficiencies, which probably result from incongruences between contributing ground- and surface-water areas. For Annie Creek (site 16), the calculated yield efficiency (16.4 percent) is lower than for other nearby streams, which may result from extensive mining operations that utilize substantial quantities of water through evaporation for heap-leach processes. For Hay Creek (site 19), the calculated yield efficiency (1.0 percent) is notably lower than the mapped contours, which probably results from precipitation recharge to outcrops of the Inyan Kara Group (fig. 3).

Carter, Driscoll, and Hamade (2001) used relations between yield efficiency and precipitation in developing a GIS algorithm for systematically estimating annual recharge from infiltration of precipitation, based on annual precipitation on outcrop areas. Linear regression and best-fit exponential equations were determined for 11 basins, which include all of the representative crystalline basins (table 2), except Bear Gulch. Exponential equations were in the form of:

$$YE_{annual} = \left[\frac{P_{annual}}{P_{average}}\right]^n \times YE_{average} \qquad (1)$$

where

YE_{annual} = annual yield efficiency, in percent;
P_{annual} = annual precipitation, in inches;
$P_{average}$ = average annual precipitation for 1950-98, in inches;
$YE_{average}$ = average annual yield efficiency for 1950-98, in percent; and
n = exponent.

Best-fit exponents ranged from 1.1 for Elk Creek to 2.5 for Spring Creek. An exponent of 1.6 was chosen as best representing the range of best-fit exponents (Carter, Driscoll, and Hamade, 2001), which allowed a systematic approach to estimation of annual recharge. Scatter plots with the linear regression lines, best-fit exponential curves, and exponential curves using an exponent of 1.6 are shown in figure 44 in the Supplemental Information section. The three methods provide very similar results through the mid-range of measured precipitation values, with the largest differences occurring for the upper part of the range.

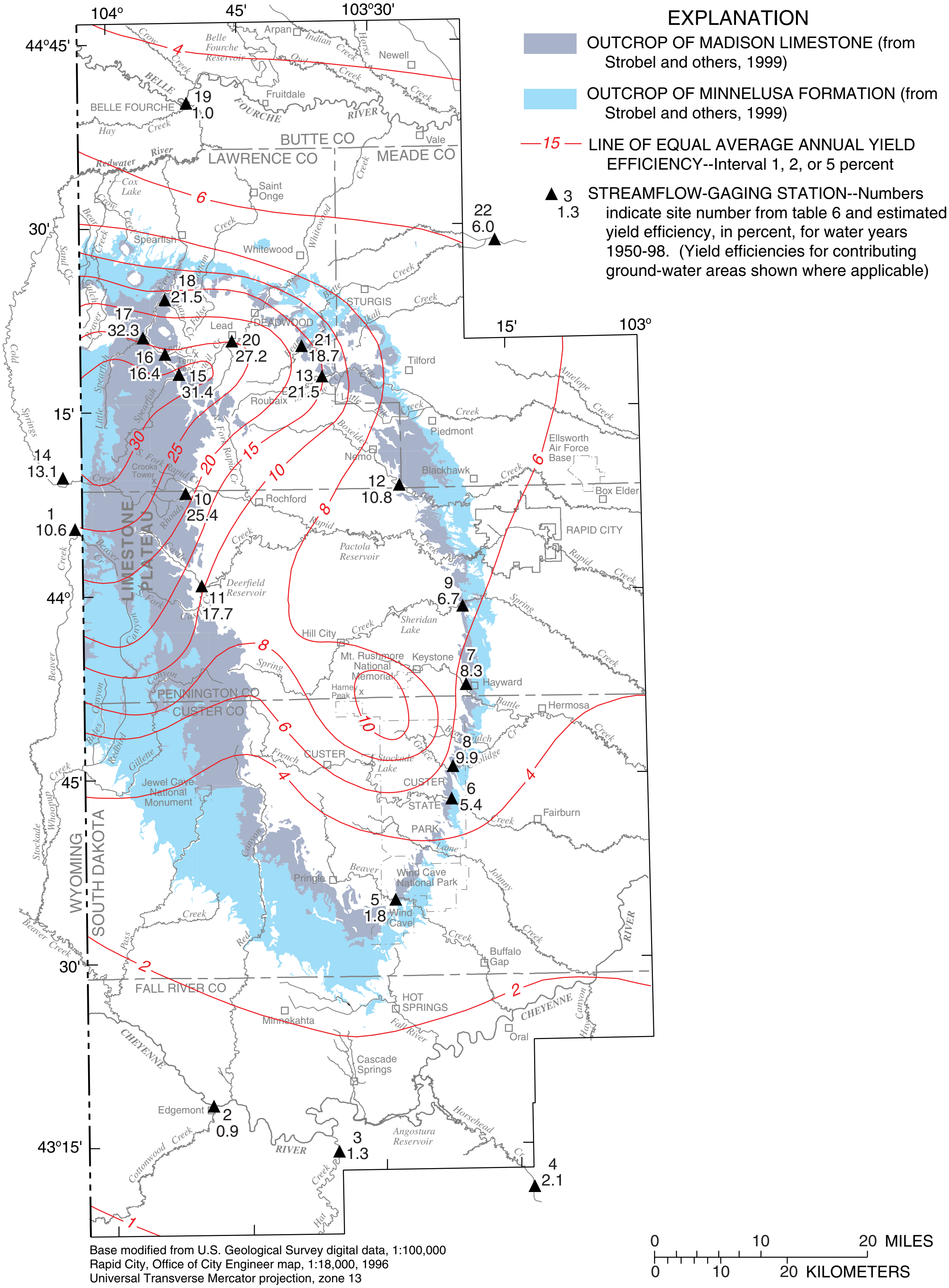

Figure 30. Generalized average annual yield efficiency (in percent of annual precipitation), water years 1950-98 (modified from Carter, Driscoll, and Hamade, 2001).

The spatial distribution of average annual yield potential for the Black Hills area is shown in figure 31. Average annual recharge from infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation is shown as an example. Estimates were derived by Carter, Driscoll, and Hamade (2001) using a GIS algorithm that compared digital grids (1,000-by-1,000 meters, including outcrop areas in Wyoming) for annual precipitation, average annual precipitation (fig. 7), and average annual yield efficiency (fig. 30). Annual recharge rates for individual grid cells ranged from 0.4 inch at the southern extremity of the outcrops to 8.7 inches in the northern Black Hills. Although this "yield-efficiency algorithm" was developed initially for estimating precipitation recharge for the Madison and Minnelusa aquifers, applications for estimating streamflow yield and recharge for other aquifers also are appropriate and are utilized later in this report.

HYDROLOGIC BUDGETS

Various hydrologic budgets are presented in this section, including ground-water budgets, surface-water budgets, and combined ground- and surface-water budgets for the entire study area. A general evaluation of budget estimates also is provided. The primary period for budgets is water years 1950-98; however, other periods are occasionally considered for selected purposes. All hydrologic budgets that are presented are developed from the following basic continuity equation, which states that for a designated volume:

$$\Sigma Inflows - \Sigma Outflows = \Delta Storage \qquad (2)$$

where:

$\Sigma Inflows$ = sum of inflows;
$\Sigma Outflows$ = sum of outflows; and
$\Delta Storage$ = change in storage.

Thus, a positive $\Delta Storage$ results when inflows exceed outflows.

Ground-Water Budgets

Ground-water budgets are developed for five major, sedimentary bedrock aquifers (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers) and for additional minor aquifers within the Jurassic-sequence semiconfining unit and Cretaceous-sequence confining unit. A ground-water budget also is provided for localized aquifers within the crystalline core area, which is dominated by Precambrian igneous and metamorphic rocks, but also includes Tertiary igneous rocks, erosional remnants of various sedimentary rocks, and minor, unconsolidated sedimentary deposits. These localized aquifers are subsequently referred to as the crystalline core aquifers. A combined budget is presented for the Madison and Minnelusa aquifers because most of the budget components cannot be quantified individually for these two aquifers. This budget is presented first because of the complexity and importance of the Madison and Minnelusa aquifers as an influence on the hydrology of the study area.

Budgets are for the period 1950-98, during which changes in ground-water storage are assumed to be negligible. As previously discussed, ground-water levels may fluctuate in response to precipitation patterns (figs. 39-43); however, major long-term trends are not apparent. In addition, annual changes in storage are small, when averaged for the period considered. The ground-water budgets generally are developed specifically for the study area; however, areas outside of the study area boundary are considered for selected purposes.

Various inflow and outflow components for ground-water budgets are schematically illustrated in figure 5. Inflow components can include recharge, vertical leakage from adjacent aquifers, and lateral ground-water inflow across the study area boundary. Recharge, which occurs at or near land surface, can include infiltration of precipitation on outcrops of the bedrock units and streamflow recharge resulting from streamflow losses that occur where streams cross aquifer outcrops. Streamflow recharge is quantified only for the Madison and Minnelusa aquifers. Streamflow recharge for other aquifers generally is small and cannot be quantified because of insufficient information.

Outflow components can include springflow, well withdrawals, vertical leakage to adjacent aquifers, and lateral ground-water outflow across the study area boundary (fig. 5). Springflow can include headwater springs and artesian springs. Headwater springs, which generally occur near the base of the Madison Limestone in the Limestone Plateau area, are considered an outflow component for only the Deadwood, Madison, and Minnelusa aquifers. Artesian springs, which constitute a form of leakage but are treated as a separate component because of magnitude and measurability, are considered an outflow component for only the Madison and Minnelusa aquifers.

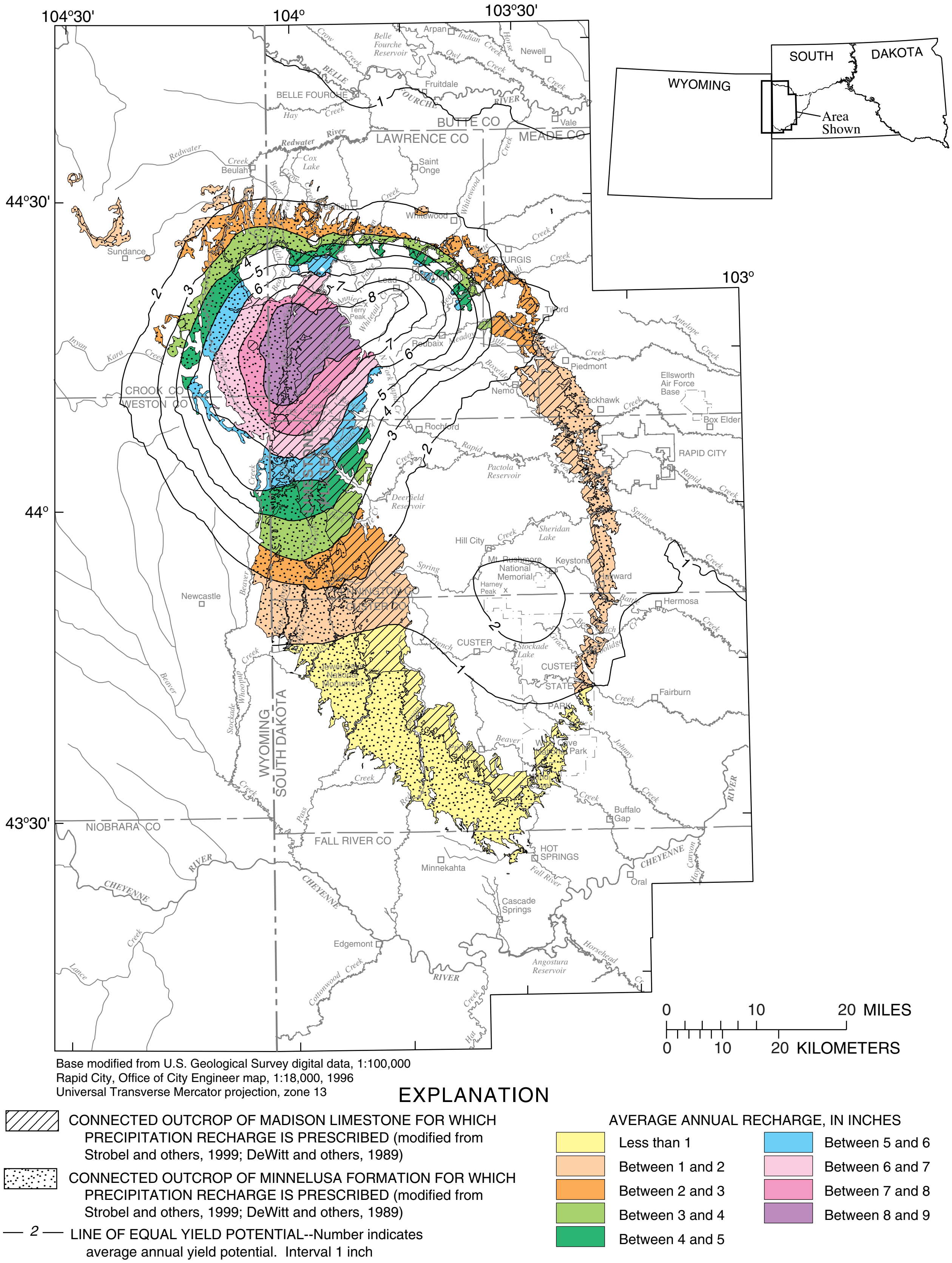

Figure 31. Estimated annual yield potential for the Black Hills area, water years 1950-98 (from Carter, Driscoll, and Hamade, 2001). Average annual recharge from precipitation on outcrops of the Madison Limestone and Minnelusa Formation is shown as an example.

Vertical leakage to and from adjacent aquifers is difficult to quantify and cannot be distinguished from ground-water inflows or outflows. Thus, for budget purposes, leakage is assumed to be small relative to other budget components and is included with ground-water inflows and outflows. Assuming that $\Delta Storage$ is equal to zero, the sum of the inflows is equal to the sum of the outflows, and the hydrologic budget equation can be written as:

$$\text{Ground-water}_{\text{outflow}} - \text{Ground-water}_{\text{inflow}} = \text{Recharge} - \text{Headwater springflow} - \text{Artesian springflow} - \text{Well withdrawals} \quad (3)$$

The terms on the right side of equation 3 generally can be quantified more accurately than the terms on the left. Therefore, net ground-water flow (outflow minus inflow) from the study area can be calculated as the residual, given estimates for the other budget components.

Because outcrops of the bedrock units are not entirely continuous throughout the study area, estimating precipitation recharge requires delineation of outcrop areas where effective recharge occurs. Within the crystalline core area, numerous erosional remnants of sedimentary outcrops occur that are “isolated” from regional ground-water flow systems (fig. 3). Precipitation recharge is prescribed only for “connected” outcrops and is not prescribed for isolated outcrops. Connected outcrops of the Madison Limestone and Minnelusa Formation, including outcrop areas in Wyoming, are shown as an example in figure 31. Infiltration of precipitation on isolated outcrops is assumed to contribute to streamflow, which eventually has potential to provide streamflow recharge to the Madison and Minnelusa aquifers.

Additional methods beyond identification of isolated and connected outcrop areas are used in quantifying precipitation recharge for the Deadwood aquifer. Spearfish, Little Elk, and Meadow Creeks are deeply incised within the Deadwood Formation, and some portion of infiltrated precipitation is presumably discharged as base flow to these streams. Therefore, for outcrops of the Deadwood Formation within the Spearfish Creek, Little Elk Creek, and Meadow Creek Basins, it is arbitrarily assumed that 50 percent of infiltrated precipitation contributes to headwater springs and 50 percent contributes to recharge of the Deadwood aquifer.

Budget for Madison and Minnelusa Aquifers

Recent investigations have provided extensive information regarding various budget components for the Madison and Minnelusa aquifers in the Black Hills area. Recharge estimates for 1931-98 were presented by Carter, Driscoll, and Hamade (2001) and hydrologic budgets for 1987-96, when change in storage was assumed negligible, were presented by Carter, Driscoll, Hamade, and Jarrell (2001). For both of these efforts, however, outcrop areas within Wyoming were considered. Thus, for the purposes of this report, various modifications of previous budgets are used to estimate long-term (1950-98) budget components for the study area of the Black Hills Hydrology Study (fig. 1), which is entirely in South Dakota.

As an initial step, the comprehensive 1987-96 budget (table 7) developed by Carter, Driscoll, Hamade, and Jarrell (2001), which includes an area in Wyoming, is modified to apply to 1950-98. Carter, Driscoll, and Hamade (2001) provided recharge estimates for 1950-98, with average streamflow and precipitation recharge estimated as 98 and 271 ft^3/s, respectively. Headwater springflow is estimated as 72 ft^3/s on the basis of a ground-water divide in the Limestone Plateau area (fig. 28) identified by Jarrell (2000). Headwater springflow is derived by applying the yield-efficiency algorithm (which utilizes equation 1) to determine recharge estimates, with recharge east of the divide assumed to result in discharge to headwater springs along the eastern fringe of the Limestone Plateau. West of the divide, a generally westerly ground-water flow direction is assumed, with no contribution to headwater springs. Thus, net recharge of 297 ft^3/s can be calculated by subtracting headwater springflow from the sum of streamflow and precipitation recharge.

The previous estimates by Carter, Driscoll, Hamade, and Jarrell (2001) for well withdrawals (28 ft^3/s) and net ground-water outflow (100 ft^3/s) also are applicable for 1950-98 (table 7). Well withdrawals for domestic and municipal use, especially in the Rapid City area, have increased somewhat in recent years; however, various flowing wells in the study area have been plugged during recent years, which

Table 7. Hydrologic budgets for Madison and Minnelusa aquifers for three budget scenarios

Units	Streamflow recharge	Precipitation recharge	Headwater springflow	Net recharge	Well withdrawals	Net ground-water outflow	Artesian springflow
Black Hills of South Dakota and Wyoming, Water Years 1987-96[1]							
Acre-feet per year	75,300	210,800	56,500	229,600	20,300	72,400	136,900
Cubic feet per second	104	291	78	317	28	100	189
Black Hills of South Dakota and Wyoming, Water Years 1950-98							
Acre-feet per year	71,000	196,300	52,200	215,100	20,300	72,400	122,400
Cubic feet per second	98	271	72	297	28	100	169
Black Hills of South Dakota, Water Years 1950-98							
Acre-feet per year	66,600	144,900	56,500	155,000	20,300	41,900	92,800
Cubic feet per second	92	200	[2]78	214	28	58	128

[1]From Carter, Driscoll, Hamade, and Jarrell, 2001.

[2]Includes 6 cubic feet per second of discharge for Beaver Creek and Cold Springs Creek in South Dakota, which subsequently recharges Minnelusa aquifer a short distance downstream in Wyoming. Thus, this flow is treated as a discharge for South Dakota; however, discharge and recharge are offsetting when both South Dakota and Wyoming are considered.

approximately offsets this increase (Jim Goodman, South Dakota Department of Environment and Natural Resources, oral commun., 2001). The net ground-water outflow term is assumed constant because changes in hydraulic gradient near the study area boundary can reasonably be assumed to be negligible. With these terms and recharge quantified, artesian springflow for 1950-98 can be calculated as 169 ft^3/s using equation 3. This value is slightly less than the estimate of 189 ft^3/s for 1987-96, during which wetter climatic conditions prevailed.

A 1950-98 budget for the study area (excluding Wyoming) can now be developed by modification of various components (table 7). Streamflow recharge is estimated as 92 ft^3/s by subtracting 6 ft^3/s of streamflow recharge that occurs in Wyoming (Carter, Driscoll, and Hamade, 2001). Precipitation recharge is estimated as 200 ft^3/s by applying the yield-efficiency algorithm to outcrops of the Madison Limestone and Minnelusa Formation in South Dakota; relatively large precipitation recharge (about 71 ft^3/s) also occurs in outcrops in Wyoming (fig. 31). Headwater springflow is increased to 78 ft^3/s to include an estimated average of 6 ft^3/s that is discharged by Beaver and Cold Springs Creeks within South Dakota (fig. 12, table 19). Discharge of these springs was not included in previous budgets because of subsequent recharge to the Minnelusa aquifer that occurs in streamflow loss zones just downstream from the gaging stations in Wyoming. Net recharge for the study area can then be calculated as 214 ft^3/s.

The previous estimates of well withdrawals by Carter, Driscoll, Hamade, and Jarrell (2001) can be used because these estimates excluded withdrawals in Wyoming, which are relatively minor within the area that was considered. Artesian springflow in Wyoming (Stockade Beaver Creek and Redwater Creek) is estimated as 41 ft^3/s for the period 1950-98. Springflow along Stockade Beaver Creek is estimated as 11 ft^3/s using an average flow of 12.15 ft^3/s with the base flow index of 93.5 percent for the period of record at site 06392950 (table 2). Springflow along Redwater Creek is estimated as 30 ft^3/s, which is 95 percent of the average of median flows for November through February for site 06430500 for the period 1955-98. Thus, artesian springflow for South Dakota is estimated as 128 ft^3/s (table 7) by subtracting artesian springflow in Wyoming. Net ground-water outflow from the study area can then be calculated as 58 ft^3/s using equation 3.

Budgets for Other Bedrock Aquifers

Budgets for the other bedrock aquifers consist primarily of estimates for recharge and well withdrawals, from which estimates of net ground-water outflow from the study area can be derived. The only exception is the Deadwood aquifer, for which headwater springflow also is estimated.

Recharge estimates for the other bedrock aquifers consist only of precipitation recharge, which is derived using the yield-efficiency algorithm. Total yield, which is the sum of runoff plus recharge, is first computed by applying the yield-efficiency algorithm to the estimates of precipitation on outcrops of the various bedrock formations that were derived from precipitation grids developed by Driscoll, Hamade, and Kenner (2000). For the entire study area (table 8), 1950-98 precipitation averaged 18.98 inches per year or just over 5.2 million acre-ft per year. Of this amount, total yield is estimated as about 441,000 acre-ft per year (about 608 ft^3/s), which is equivalent to about 1.59 inches per year over the study area.

Table 8. Estimates of average precipitation, total yield, and evapotranspiration for the study area, water years 1950-98

Units	Precipitation	Total yield	Evapotranspiration
Acre-feet per year	5,245,400	440,600	4,804,800
Cubic feet per second	7,240	608	6,632
Inches per year	18.98	1.59	17.39

With the exception of localized aquifers in the crystalline core, as discussed later, recharge is then prescribed by multiplying the total yield by a recharge factor, which is the fraction of total yield estimated to result in recharge for the particular unit (table 9). The remainder of total yield (if any) is assumed to contribute to runoff from the outcrop area. Estimates of average precipitation, evapotranspiration, total yield, runoff, and precipitation recharge for outcrops of all bedrock aquifers are provided in table 10.

Carter, Driscoll, and Hamade (2001) assumed that direct runoff from outcrops of the Madison Limestone and Minnelusa Formation is negligible; hence, recharge factors for these aquifers are assumed to be 1.00. The recharge factor for the Minnekahta aquifer also is assumed to be 1.00, based on similar formation properties between the Minnekahta Limestone and Madison Limestone. Recharge factors for the Inyan Kara and Deadwood aquifers are assumed to be 0.80 because the formations contain more shale layers than the Madison, Minnelusa, and Minnekahta Formations. The Sundance aquifer within the Jurassic-sequence semiconfining unit is a productive aquifer, but only constitutes about one-half of the outcrop area of the total unit. Thus, a recharge factor of 0.40 (one-half of 0.80) is assumed for the entire Jurassic-sequence semiconfining unit. Likewise, the Newcastle Sandstone contains a productive aquifer within the Cretaceous-sequence confining unit; however, the Newcastle Sandstone constitutes only a small portion of the total unit in outcrop area. Thus, a recharge factor of 0.05 is assumed for the entire Cretaceous-sequence confining unit.

Table 9. Recharge factors and outcrop areas for bedrock aquifers

[--, not applicable]

Aquifer unit	Recharge factor[1]	Outcrop area (acres)
Localized aquifers in crystalline core area (Precambrian/Tertiary/Other[2])	--	616,800
Deadwood	0.80	66,200
Madison	1.00	292,600
Minnelusa	1.00	300,000
Minnekahta	1.00	72,100
Inyan Kara	.80	219,700
Jurassic-sequence semiconfining unit	.40	75,800
Cretaceous-sequence confining unit	.05	716,100

[1]Fraction of total yield estimated to result in recharge, with remainder (if any) assumed to contribute to runoff.

[2]"Other" consists of other units within the crystalline core area, including: (1) isolated outcrops of the Deadwood Formation, Madison Limestone, Minnelusa Formation, and Minnekahta Limestone above the loss zones; and (2) unconsolidated sedimentary deposits.

Recharge does occur to numerous localized aquifers within the crystalline core area, especially where extensive fractures or weathered zones are present in outcrop areas. These aquifers are not considered regional, however, as indicated by the fact that wells penetrating Precambrian rocks in western South Dakota outside of the Black Hills have not encountered measurable amounts of ground water (Rahn, 1985). Thus, regional ground-water flow in the Precambrian rocks is assumed to be negligible although some flow may occur in an upper weathered zone. Using equation 3 and assuming ground-water outflow to be equal to zero, recharge to localized aquifers in the crystalline core area is computed as equal to well withdrawals (5 ft^3/s) from this unit. Actual recharge to the crystalline core aquifers must be much larger than this estimate to accommodate ground-water discharge that contributes to base flow of many streams. Recharge conditions are highly transient and have large spatial variability; thus, quantification is not attempted.

Other than the Madison and Minnelusa aquifers, headwater springflow is considered only for the Deadwood aquifer. The average headwater springflow for the Deadwood aquifer (3 ft^3/s in the Spearfish Creek and Little Elk/Meadow Creek drainages and 9.6 ft^3/s in all other headwater areas) is computed using estimates of annual recharge on contributing ground-water areas in the Limestone Plateau and in the Spearfish Creek and Little Elk/Meadow Creek drainages. The estimate shown in table 10 (14 ft^3/s) also includes well withdrawals.

Well withdrawals from bedrock aquifers serve many categories of water use, including municipal, self supply (domestic), irrigation, livestock, industrial, mining, thermoelectric power, and unaccounted withdrawals. Detailed water-use estimates for the Madison and Minnelusa aquifers were presented by Carter, Driscoll, Hamade, and Jarrell (2001). Estimates of overall well withdrawals for the other bedrock aquifers are presented in table 10.

Municipal-use estimates for the Inyan Kara aquifer are available for Rapid Valley (an unincorporated area east of Rapid City) (Ed Royalty, Rapid Valley Water Department, written commun., 2000), Buffalo Gap, Fruitdale, and Hermosa (Joe Lyons, Bureau of Reclamation, written commun., 1999). Municipal-use estimates for the crystalline core aquifers are available for Custer, Hill City, and Keystone (Joe Lyons, Bureau of Reclamation, written commun., 1999).

Withdrawal estimates for the other use categories are estimated using 1995 water-use data (Amundson, 1998) available for the entire counties included in the study area. Thus, well withdrawals are slightly overestimated because the actual use within the study area would be slightly less than that attributed to the entire counties. Total self-supply (domestic) and total livestock ground-water withdrawals are not available by aquifer. Data for domestic wells and stock wells in the six-county area were compiled from the USGS Ground-Water Site Inventory database. The percentages of wells completed in the various bedrock aquifers for domestic and stock purposes were applied to the total domestic and livestock withdrawals to estimate these withdrawals. Data for other water-use categories (irrigation, industrial, mining, and thermoelectric) were compiled from the USGS Site-Specific Water-Use Data System for 1995.

Additional (unaccountable) withdrawals are estimated as 25 percent of the subtotal of all water-use categories, which is consistent with estimates of unaccountable withdrawals for the Madison and Minnelusa aquifers (Carter, Driscoll, Hamade, and Jarrell, 2001). Total well withdrawals for the other bedrock aquifers range from 1 ft^3/s for the Minnekahta aquifer and aquifers in the Jurassic-sequence semiconfining unit to 5 ft^3/s for the crystalline core aquifers.

Net ground-water outflow (table 10) is calculated using equation 2 for the other bedrock aquifers (excluding the crystalline core aquifers). Net ground-water outflow ranges from zero (assumed) for the crystalline core aquifers to 14 ft^3/s for the Inyan Kara aquifer.

An overall ground-water budget for all bedrock aquifers in the study area also is presented in table 10. For all bedrock aquifers, total recharge is estimated as 348 ft^3/s, discharge by well withdrawals and springflow is estimated as 259 ft^3/s, and net ground-water outflow is estimated as 89 ft^3/s. Most overall budget components are dominated by the budget for the Madison and Minnelusa aquifers, for which total recharge is estimated as 292 ft^3/s (84 percent of overall component), and well withdrawals and springflow are estimated as 234 ft^3/s (90 percent of overall component). Net ground-water outflow for the Madison and Minnelusa aquifers (58 ft^3/s), however, constitutes a somewhat smaller proportion (65 percent) of the overall budget component.

Table 10. Average ground-water budgets for bedrock aquifers in study area, water years 1950-98

[--, no data]

Units	Precipitation	Evapotranspiration	Total yield	Runoff	Precipitation recharge	Streamflow recharge	Total recharge	Well withdrawals and springflow[1]	Net ground-water outflow
Crystalline Core (Precambrian/Tertiary/Other[2])									
Acre-feet per year	1,084,500	964,200	120,300	116,700	3,600	0	3,600	3,600	0.0
Cubic feet per second	1,497	1,331	166	161	5	0	5	5	0
Inches per year	21.10	18.76	2.34	2.27	0.07	0	0.07	--	--
Deadwood									
Acre-feet per year	128,200	110,100	18,100	3,600	14,500	0	14,500	10,100	4,400
Cubic feet per second	177	152	25	5	20	0	20	[1]14	6
Inches per year	23.24	19.96	3.28	0.65	2.63	0	2.63	--	--
Madison and Minnelusa									
Acre-feet per year	1,021,500	876,600	144,900	0	144,900	66,600	211,500	169,500	41,900
Cubic feet per second	1,410	1,210	200	0	200	92	292	[1]234	58
Inches per year	20.69	17.76	2.93	0	2.93	1.35	4.28	--	--
Minnekahta									
Acre-feet per year	120,300	113,800	6,500	0	6,500	0	6,500	700	5,800
Cubic feet per second	166	157	9	0	9	0	9	1	8
Inches per year	20.02	18.94	1.08	0	1.08	0	1.08	--	--
Inyan Kara									
Acre-feet per year	326,700	312,200	14,500	2,900	11,600	0	11,600	1,400	10,200
Cubic feet per second	451	431	20	4	16	0	16	2	14
Inches per year	17.84	17.05	0.79	0.16	0.63	0	0.63	--	--
Jurassic-Sequence Semiconfining Unit									
Acre-feet per year	115,900	110,000	5,800	3,600	2,200	0	2,200	700	1,500
Cubic feet per second	160	152	8	5	3	0	3	1	2
Inches per year	18.35	17.43	0.92	0.57	0.35	0	0.35	--	--

Table 10. Average ground-water budgets for bedrock aquifers in study area, water years 1950-98–Continued

[--, no data]

Units	Precipitation	Evapotran-spiration	Total yield	Runoff	Precipitation recharge	Streamflow recharge	Total recharge	Well withdrawals and springflow[1]	Net ground-water outflow
Cretaceous-Sequence Confining Unit									
Acre-feet per year	1,028,700	980,900	47,800	45,600	2,200	0	2,200	1,400	800
Cubic feet per second	1,420	1,354	66	63	3	0	3	2	1
Inches per year	17.24	16.44	0.80	0.76	0.04	0	0.04	--	--
Overall Budget for Bedrock Aquifers									
Acre-feet per year	3,825,900	3,468,000	357,900	172,400	185,500	66,600	252,100	187,600	64,600
Cubic feet per second	5,281	4,787	494	238	256	92	348	259	89
Inches per year	19.46	17.64	1.82	0.88	0.94	1.35	1.28	--	--

[1]Springflow considered only for the Deadwood, Madison, and Minnelusa aquifers. Headwater springflow for the Deadwood aquifer is estimated as 3.0 cubic feet per second for the Spearfish and Little Elk/Meadow Creek drainages and 9.6 cubic feet per second for all other headwater areas. For the Madison and Minnelusa aquifers, headwater and artesian springflow are estimated as 78 and 128 cubic feet per second, respectively.

[2]"Other" included only for estimates of precipitation, evapotranspiration, and total yield. "Other" consists of other units within the crystalline core area, including (1) isolated outcrops of the Deadwood Formation, Madison Limestone, Minnelusa Formation, and Minnekahta Limestone above the loss zones; and (2) unconsolidated sedimentary deposits.

Surface-Water Budgets

Various surface-water budgets are presented within this section, for the primary purpose of quantifying average surface-water inflows and outflows for the study area, as well as quantifying tributary flows generated within the study area. The surface-water budgets are developed by consideration of stream channels within various specified areas, for which the basic continuity equation (eq. 2) is applied. Inflows considered include stream channels crossing boundaries for specified areas and net tributary flows generated within specified areas. Because net tributary flows (flows less depletions) are considered, flow depletions such as streamflow losses or diversions are not included as outflows. Storage changes for the four large Bureau of Reclamation reservoirs (Angostura, Deerfield, Pactola, and Belle Fourche) located within the study area are considered, with records of storage changes (positive change reflects increased storage) derived primarily from Miller and Driscoll (1998). Large storage increases occurred during 1950-98 for Angostura Reservoir (completed during 1950), Pactola Reservoir (not completed until 1956), and Belle Fourche Reservoir, which had very low storage during 1950.

Because of the locations of available streamflow-gaging stations, it is first necessary to develop surface-water budgets for an expanded area, which is defined by drainage areas for the gages considered and which encompasses most of the study area (fig. 32). Site information for all gages is included in table 2, which was presented previously. Some of the gages are representative of hydrogeologic settings and are included with the representative groupings. For example, stations 06392900 (Beaver Creek) and 06429500 (Cold Springs Creek) are included with the limestone headwater basins. Other gages that are used only for various water-budget purposes are grouped at the end of table 2.

Mean flows (calculated or estimated, as necessary) for 1950-98 for gaged locations are shown in figure 32 and summations of inflow and outflow components for the expanded area are provided in table 11. Individual budgets are included for areas within the Belle Fourche River Basin, which drains approximately the northern one-quarter of the study area, and the Cheyenne River Basin, which drains the southern part of the study area. Net tributary flows generated within the expanded area are calculated as 385 ft^3/s by subtracting inflows (252 ft^3/s) from outflows (630 ft^3/s) and adjusting for increased storage in reservoirs (7 ft^3/s). Tributary flows generated outside of the area are estimated as 77 ft^3/s, which is used in calculating tributary flows of 308 ft^3/s from within the study area. This information is then used to calculate surface-water budgets specific to the study area (table 12), which include estimated outflows for the study area boundary. Additional details regarding the surface-water budgets are provided in the following discussions.

Table 11. Average surface-water budgets for expanded area extending beyond study area, water years 1950-98

[Approximate drainage boundary for area considered is shown in figure 32. All values in cubic feet per second]

Basin	Outflows	+ Change in storage	- Inflows	= Net tributary flow	- Estimated outside tributaries	= Study area tributaries
Cheyenne River	348.1	4.5	105.8	246.8	45.7	201.1
Belle Fourche River	282.1	2.7	146.4	138.4	31.2	107.2
Combined	630.2	7.2	252.2	385.2	76.9	308.3

Table 12. Average surface-water budgets for study area, water years 1950-98

[All values in cubic feet per second]

Basin	Study area inflows	+ Study area tributaries	- Change in storage	= Study area outflows
Cheyenne River	105.8	201.1	4.5	302.4
Belle Fourche River	146.4	107.2	2.7	250.9
Combined	252.2	308.3	7.2	553.3

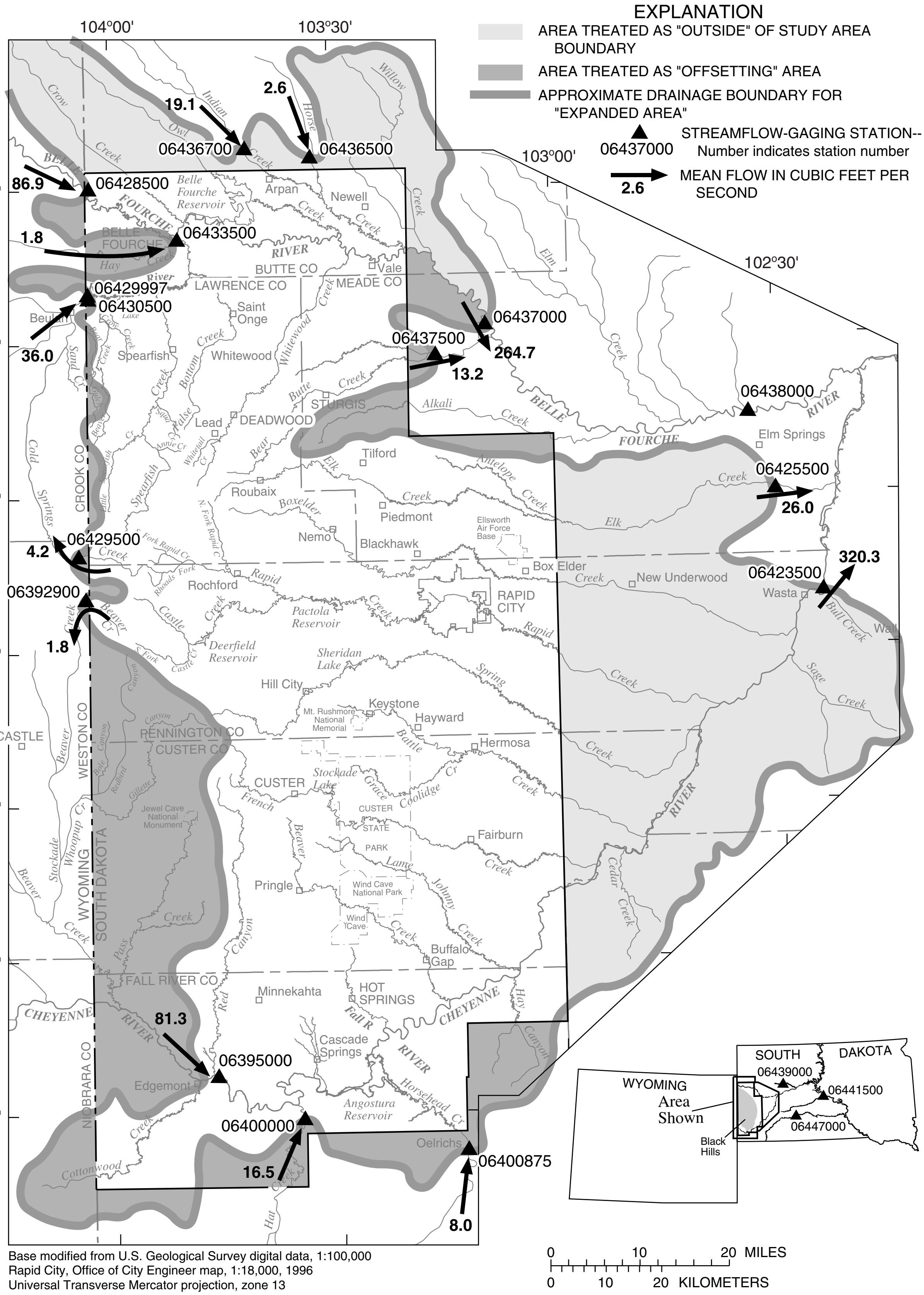

Figure 32. Streamflow-gaging stations used in surface-water budgets and mean flow rates, water years 1950-98.

Detailed budgets for the Cheyenne and Belle Fourche River Basins, which include annual budget components for 1950-98, are provided in tables 26 and 27 in the Supplemental Information section. Readers are cautioned that because many of the budget components are estimated (as noted in these tables), values for individual years are subject to much larger potential errors than the long-term averages, development of which was the purpose of this exercise. Some of the annual streamflow values for various gages were estimated using simple linear regressions with other gages, with regression information provided in table 13. Methods for estimating tributary flows generated outside of the study area are described in the following discussions.

For the Cheyenne River Basin (fig. 32), stream inflows are measured at stations 06395000 (Cheyenne River at Edgemont), 06400000 (Hat Creek), and 06400875 (Horsehead Creek), with downstream outflows measured at stations 06423500 (Cheyenne River at Wasta) and 06425500 (Elk Creek). Additional outflows are measured at station 06392900 (Beaver Creek), which loses flow to the Minnelusa Formation (fig. 12) a short distance downstream from the gage in Wyoming.

Minor unmeasured outflow in Whoopup Creek (fig. 32) leaves the study area, but re-enters a short distance downstream via Beaver Creek; however, surface flows in Whoopup Creek are uncommon because of extensive outcrops of the Minnelusa Formation within the basin (fig. 12). Measured inflow at station 06395000 (Cheyenne River at Edgemont) includes flow from Pass Creek, which does not leave the study area and also is influenced by outcrops of the Minnelusa Formation. Contributing areas for several additional tributaries along the southern edge of the study area do not coincide exactly with the study area boundary; however, outflows and inflows for all of these unmeasured areas are considered offsetting (as shown in fig. 32) and are neglected.

Table 13. Summary of linear regression information used for extending streamflow records

Station number	Station name	Slope	Intercept	r^2	Station used in regression
06392900	Beaver Creek at Mallo Camp	0.0243	1.53	0.09	Castle Creek (06409000)
06400000	Hat Creek	.0919	9.06	.13	Cheyenne River at Edgemont (06395000)
06400875	Horsehead Creek	.5858	-1.80	.87	Hat Creek (06400000)
06429500	Cold Springs Creek	.0334	3.85	.04	Castle Creek (06409000)
[1]06429997	Murray Ditch	.1571	14.93	.72	Redwater River above Belle Fourche (06433000)
[1]06430500	Redwater Creek at State line				
06433500	Hay Creek	.0110	-1.11	.83	Belle Fourche River near Sturgis (06437000)
06436500	Horse Creek	.0868	.34	.34	Elk Creek near Elm Springs (06425500)
06436700	Indian Creek	.4640	7.00	.30	Elk Creek near Elm Springs (06425500)
06437500	Bear Butte Creek near Sturgis	.0613	-3.44	.85	Belle Fourche River near Sturgis (06437000)

[1]Flows from sites were combined prior to linear regression.

For purposes of estimating tributary flows to the Cheyenne River, only the area immediately east of the study area is treated as being outside of the study area (fig 32). Tributary flows from this 1,220-mi^2 area are estimated as 45.7 ft^3/s (table 11) from yields for a number of gaged basins located around the periphery of the study area, with annual yields provided in table 28 in the Supplemental Information section. Stations used include 06395000 (Cheyenne River at Edgemont) and 06400000 (Hat Creek), which measure flows into the study area (fig. 32). Station 06400875 (Horsehead Creek) is not used because substantial irrigation diversions occur within the basin. Three stations with relatively large drainage areas located generally east of the study area (see index map on fig. 32) also are used; these are 06439000 (Cherry Creek), 06441500 (Bad River), and 06447000 (White River). Mean annual yields for these stations range from 0.15 to 0.84 inch and average 0.51 inch (table 28).

For the Belle Fourche River Basin (fig. 32), stream inflows are measured at stations 06428500 (Belle Fourche River at State line), 06429997 (Murray Ditch), 06430500 (Redwater Creek), 06433500 (Hay Creek), 06436700 (Indian Creek), and 06436500 (Horse Creek). Downstream outflows are measured at stations 06437000 (Belle Fourche River near Sturgis) and 06437500 (Bear Butte Creek). Additional outflows are measured at station 06429500 (Cold Springs Creek), which loses flow to the Minnelusa Formation (fig. 12) a short distance downstream from the gage in Wyoming.

Tributary flows are estimated as 31.2 ft^3/s (table 11) for an area of about 530 mi^2 located generally north of the study area, which is treated as being outside of the study area (fig 32). Two small areas that are just outside, and west, of the study area are considered offset by a small part of the Hay Creek Basin that is within the study area. Part of the Alkali Creek Basin (southeast of Sturgis) that is within the study area is considered offset by a small part of the Bear Butte Creek Basin that is outside the study area, and by a small area south of the Belle Fourche River just east of the study area. Tributary flows for the outside area are estimated using the annual yield for the area between two gages along the Belle Fourche River, just east of the study area (stations 06437000, Belle Fourche River near Sturgis and 06438000, Belle Fourche River near Elm Springs). The average yield for this area is 0.82 inch (table 28), which is computed from the difference in annual flow for these stations, converted to inches of yield over the intervening drainage area.

The estimates of tributary flows generated within the study area boundary can be evaluated, to some extent, for the Cheyenne River Basin by consideration of flow records for 1983-98 for 10 gages near the study area boundary. Gages used for this analysis are shown with open (unfilled) triangles in figure 33. Annual flows for these gages are presented in table 29 in the Supplemental Information section. Flows for several years are estimated for two stations (06392900, Beaver Creek at Mallo Camp and 06400497, Cascade Springs), which have only minor variability in annual flow. Measured flows for station 06403300 (French Creek) are adjusted by subtracting 5 ft^3/s to account for streamflow losses downstream from the gage. Annual flows for all 10 of the gages are summed to provide an estimate of a portion of the tributary flows generated within that part of the study area contributing to the Cheyenne River (upstream from the confluence with the Belle Fourche River).

A graphical comparison of values for tributary flows (1983-98) derived using different methods is presented in figure 34, with calculations provided in table 29. In the figure, the uppermost line shows calculated values for all tributary flows from the expanded area contributing to the Cheyenne River. The lowermost line shows estimated tributary flows from the area outside of the study area. Of the two intermediate lines, the upper line shows estimated tributary flows from the study area that are computed as the difference between the two values previously described, and the lower line shows the sum of values for the 10 measured tributaries contributing to the Cheyenne River (described in previous paragraph). These measured values generally are somewhat smaller than the estimated values, which is consistent with a smaller contributing drainage area. A negative difference (table 29) occurs between these values for 3 years, all of which are years with small tributary flows. This is not necessarily unrealistic because substantial flow depletions (natural and anthropogenic) can occur downstream from gages on the measured tributaries, especially during low-flow years. Results generally agree very favorably, which provides confidence that methods for estimating tributary flows perform reasonably.

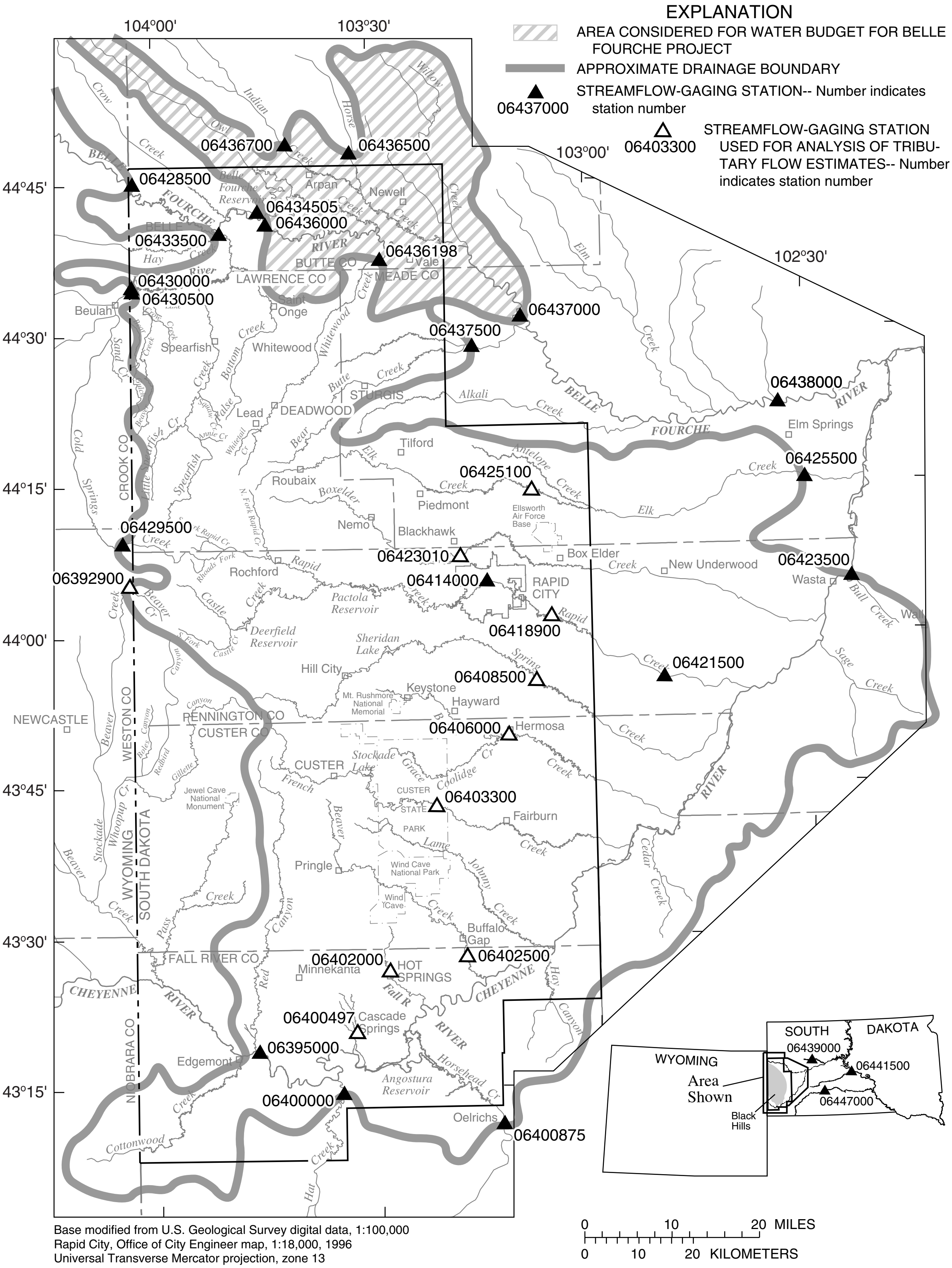

Figure 33. Streamflow-gaging stations used for various water-budget purposes, relative to stations and area considered for surface-water budgets.

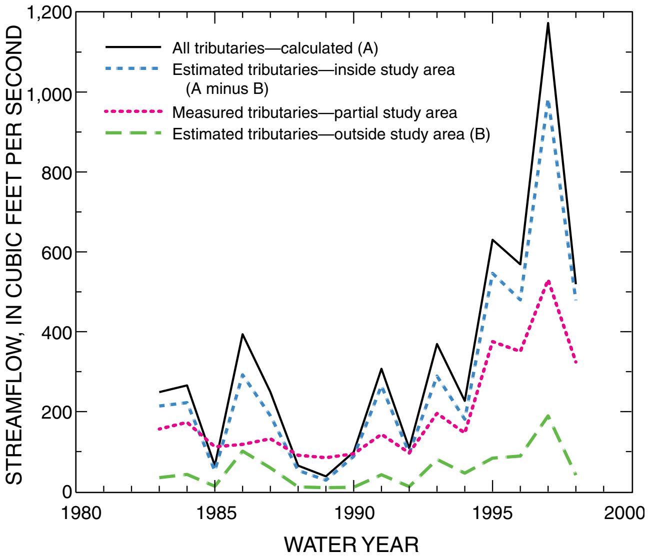

Figure 34. Comparison of tributary flows to Cheyenne River (measured and estimated), for areas within and near Black Hills study area.

Combined Ground- and Surface-Water Budgets

Because of the numerous hydrogeologic complexities in the Black Hills area, it has been necessary to develop ground- and surface-water budgets independently. Additional insights can be obtained, however, from quantification of combined budgets, as discussed in the following section. The combined budgets are used extensively for estimating streamflow depletions resulting from streamflow losses and consumptive withdrawals.

Many of the discussions in the following sections draw heavily on information presented in previous sections within this report. Thus, it is assumed that readers are familiar with subject matter previously presented, and detailed discussions of previous information are not provided.

Quantification of Combined Budgets

Combined ground- and surface-water budgets (1950-98) for the study area are schematically illustrated in figure 35. A detailed budget that illustrates complex ground- and surface-water interactions that occur primarily within the outcrop band of the Madison Limestone and Minnelusa Formation is provided in figure 35A. A simplified version that summarizes major budget components from figure 35A is provided in figure 35B.

Average precipitation (1950-98) over the study area was previously estimated as 7,240 ft^3/s (table 8), of which 6,632 ft^3/s is returned to the atmosphere via evapotranspiration (fig. 35B). The remaining 608 ft^3/s becomes either runoff (352 ft^3/s) or precipitation recharge to various bedrock aquifers (256 ft^3/s). By far, the largest proportion of precipitation recharge is to the Madison and Minnelusa aquifers (200 ft^3/s), with much smaller proportions contributing to precipitation recharge of other aquifers (fig. 35A). Conversely, the largest proportion of runoff is from outcrops located beyond the Madison/Minnelusa outcrop band (186 ft^3/s), followed closely by runoff from the various units in the crystalline core area (161 ft^3/s). Estimated runoff from the Deadwood Formation is minor (5 ft^3/s) and runoff from the Madison Limestone and Minnelusa Formation is assumed to be negligible. Runoff from the Ordovician-sequence semiconfining unit is estimated to be less than 1 ft^3/s and thus is neglected.

The various units in the crystalline core area are presumed to contain only localized aquifers, with negligible regional ground-water outflow in the Precambrian basement rocks that underlie the sedimentary bedrock sequence. Thus, for the crystalline core aquifers, precipitation recharge was assumed equal to estimated well withdrawals of 5 ft^3/s. For the various aquifers beyond the Madison/Minnelusa outcrop band, net ground-water outflow (outflow from the study area minus inflow) of 25 ft^3/s is considerably larger than well withdrawals (6 ft^3/s).

Extensive ground- and surface-water interactions for the Deadwood aquifer and the Madison and Minnelusa aquifers result in more complicated budgets for these aquifers. Springflow of 13 ft^3/s and 78 ft^3/s, respectively, is discharged from these aquifers in headwater areas where water-table conditions prevail. Some portion of this amount contributes to subsequent streamflow recharge to the Madison and Minnelusa aquifers, in downstream loss zones. Regional net outflow for the Deadwood aquifer is estimated as 6 ft^3/s, after accounting for well withdrawals of 1 ft^3/s. For the Madison and Minnelusa aquifers, total recharge is estimated as 214 ft^3/s, which includes streamflow recharge of 92 ft^3/s. The largest proportion of this is discharged as artesian springflow (128 ft^3/s), with well withdrawals of 28 ft^3/s and regional net outflow of 58 ft^3/s.

Net recharge for all aquifers is 257 ft^3/s, which includes both precipitation and streamflow recharge, from which headwater springflow has been subtracted. As discussed, the overall ground-water budget for the study area is dominated by the Madison and Minnelusa aquifers, which have the largest components of recharge, spring discharge, well withdrawals, and regional net outflow.

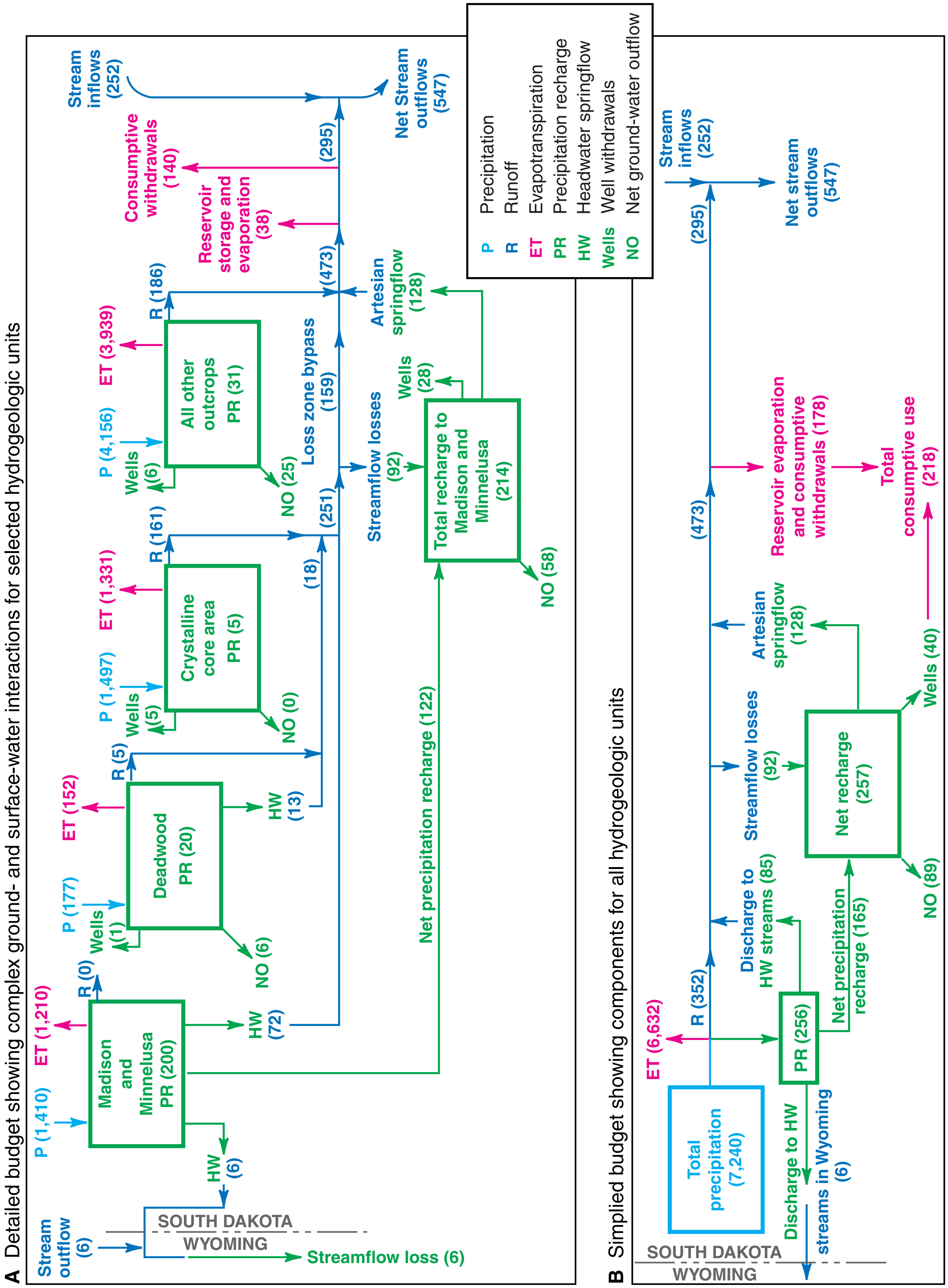

Figure 35. Schematic diagram showing average hydrologic budget components for study area, water years 1950-98. All values in cubic feet per second.

The combined budgets are used extensively in quantifying streamflow depletions and consumptive withdrawals, as described in detail in the following section. Total consumptive use is estimated as 218 ft^3/s, including 40 ft^3/s from wells and 178 ft^3/s from surface-water sources, which includes both reservoir evaporation and storage changes (38 ft^3/s) and consumptive withdrawals from streams (140 ft^3/s). An evaluation of these estimates also is provided in a subsequent section.

Streamflow Depletions and Consumptive Withdrawals

The primary streamflow depletions in the Black Hills area are streamflow losses to outcrops of the Madison and Minnelusa aquifers and consumptive withdrawals and reservoir evaporation associated with irrigation operations. Average streamflow losses of 92 ft^3/s for 1950-98 (table 7) are quantified quite accurately, relative to other budget components, from estimates of annual streamflow recharge in Carter, Driscoll, and Hamade (2001). Detailed information regarding annual reservoir operations and releases are available for the four large reservoirs operated by the Bureau of Reclamation (1999); however, accurate information regarding consumptive withdrawals is not readily available. Thus, a general water-budget approach is used to estimate cumulative streamflow depletions and consumptive withdrawals for the entire study area.

Quantification of Depletions and Consumptive Withdrawals

Various components from the combined ground- and surface-water budgets are used in generalizing the downstream progression of average streamflow conditions, relative to surface geology and mechanisms for streamflow depletions (fig. 36). Prior to accounting for depletions from streamflow losses, an estimate of average streamflow upstream from outcrops of the Madison Limestone and Minnelusa Formation is needed. An estimate of 251 ft^3/s is indicated by figure 35A, which consists of headwater springflow from the Madison and Minnelusa aquifers (72 ft^3/s) and from the Deadwood aquifer (13 ft^3/s), combined with runoff from the Deadwood Formation (5 ft^3/s) and from the crystalline core area (161 ft^3/s). Depletions of 92 ft^3/s result from streamflow losses, from which "loss zone bypass" of 159 ft^3/s is calculated.

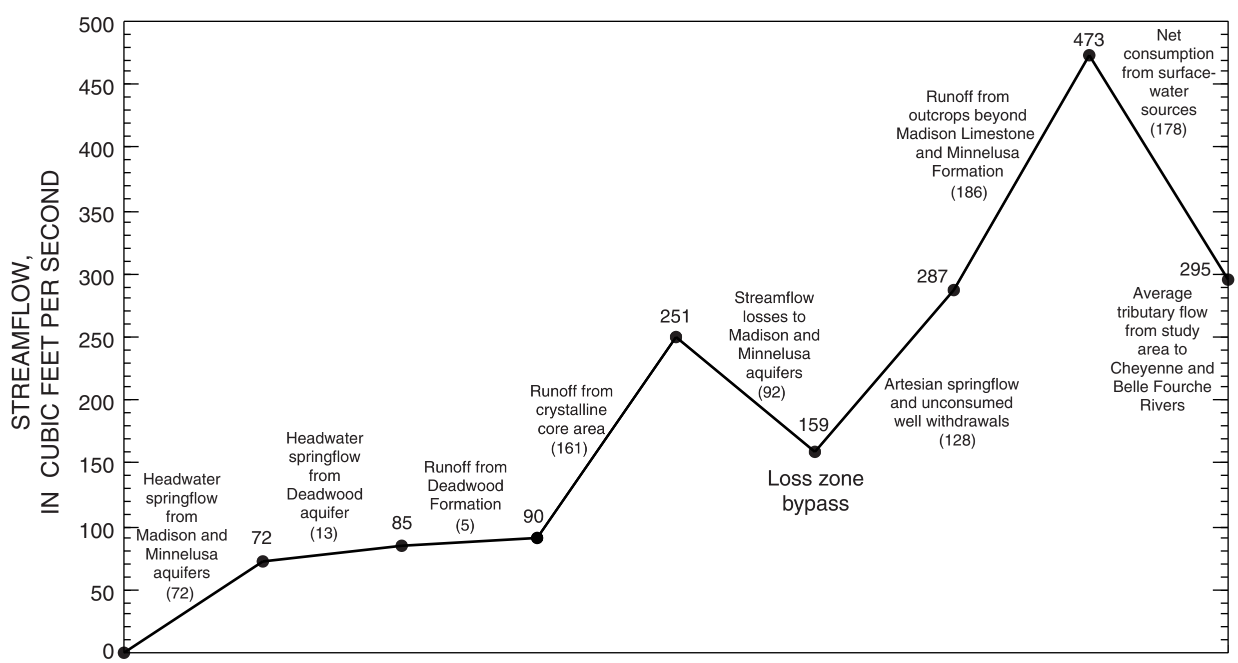

Figure 36. Schematic showing generalized average streamflow (water years 1950-98) relative to surface geology and depletions.

A cursory evaluation of available streamflow information provides confidence that this estimate is reasonable. Estimates of mean flows (1950-98) bypassing loss zones are provided in table 14 for selected gages that are located downstream from loss zones. Mean flows are first shown for available periods of record, along with a "bypass fraction" that is assumed to be 1.0 for most gages. Flows for stations 06406000 (Battle Creek) and 06425100 (Elk Creek) are influenced by artesian springs. Thus, bypass fractions for these gages are calculated as 1.0 - BFI, where BFI is the base flow index (expressed as a decimal) from table 2, which is used to estimate the fraction of flow bypassing the loss zone. The estimate for Elk Creek is extrapolated to 1950-98 by multiplying by 0.94, which is based on the ratio of flow in Spearfish Creek for 1950-98 relative to 1980-98. A similar adjustment for the period of record is made for Whitewood Creek. The majority of flow for Boxelder Creek is comprised of bypass; however, mean flow for the period of record is heavily influenced by high flows during the 1990's. Thus, the mean 1950-98 bypass for Boxelder Creek is arbitrarily assumed to be one-half of the 1979-98 value. Flows of Battle, Spring, Rapid, and Spearfish Creeks need no adjustments.

The combined estimate of average loss zone bypass for selected streams included in table 14 is 150 ft^3/s for 1950-98, compared with the estimate of 159 ft^3/s for all streams in the study area, which was derived using the water-budget approach. The streams included in table 14 constitute most of the area streams for which substantial bypasses occur, with the exception of French Creek, which has insufficient data available for a viable estimate. A bypass rate of 6.5 ft^3/s for 1983-98 was estimated for French Creek in table 29, which was derived by arbitrarily applying a loss rate of 5 ft^3/s to annual flows. This estimate is skewed, however, by extremely high flows that occurred during the 1990's. Comparing estimates by Carter, Driscoll, and Hamade (2001) of annual yield and recharge for French Creek indicates that the average bypass rate for 1950-98 probably is about one-half of this rate.

Loss zone bypass occurs in numerous other streams during high-flow years, especially in the northern Black Hills, where basin yields are relatively high. During years with average conditions, however, additional loss zone bypasses generally are relatively minor. Thus, the estimate for loss zone bypass of 159 ft^3/s, which is based primarily on the yield-efficiency algorithm, may represent a slight underestimation, but shows no apparent tendency for overestimation. This provides confidence that the yield-efficiency algorithm, which also has been used extensively for estimation of precipitation recharge, provides credible estimates that may be slightly conservative.

Table 14. Estimated average flows bypassing Madison/Minnelusa loss zones for selected streams, water years 1950-98

[ft^3/s, cubic feet per second]

Station number	Station name	Period of record considered	Mean flow (ft^3/s)	Assumed bypass fraction[1]	Period-of-record ratio[2]	Estimated 1950-98 bypass[3] (ft^3/s)
06406000	Battle Creek at Hermosa	1950-98	11.90	0.411	1.0	4.89
06408500	Spring Creek near Hermosa	1950-98	7.15	1.0	1.0	7.15
06412500	Rapid Creek above Canyon Lake	1950-98	44.07	1.0	1.0	44.07
06423010	Boxelder Creek near Rapid City	1979-98	5.88	1.0	[4].5	2.94
06425100	Elk Creek near Rapid City	1980-98	13.88	.760	.94	9.92
06431500	Spearfish Creek at Spearfish	1950-98 1980-98 1983-98	54.01 57.46 57.36	1.0	1.0	54.01
06436180	Whitewood Creek above Whitewood	1983-98	29.10	1.0	.94	27.35
Estimated combined bypass for 1950-98						150

[1]Bypass fraction computed as 1.0 minus Base Flow Index for Battle and Elk Creeks.

[2]Adjusted relative to long-term (1950-98)/short-term average for Spearfish Creek for applicable period of record.

[3]Computed as product of mean flow times bypass fraction times period-of-record ratio.

[4]Value of 0.5 arbitrarily assumed.

Immediately downstream from loss zones, artesian springflow provides substantial contributions (accretions) to streamflow in many locations, typically within, or just upgradient from the outcrop of the Spearfish Formation (figs. 2 and 3), which is the upper confining unit for the aquifers in the Paleozoic rock interval. The average contribution from artesian springflow is estimated as 128 ft^3/s (fig. 35), which is represented in figure 36 as including "unconsumed well withdrawals." This representation recognizes large municipal withdrawals from Jackson Springs in Rapid City (Anderson and others, 1999), which result in some consumptive use, especially during summer months when substantial lawn watering occurs. This consumptive use is assumed to be offset by other unconsumed municipal production that is returned to Rapid Creek, some of which is obtained from Madison and Minnelusa wells.

Additional accretions of 186 ft^3/s are estimated to occur from runoff from other outcrops beyond the Madison/Minnelusa outcrop band (fig. 35). Thus, average streamflow prior to major withdrawals, which result primarily from irrigation operations, is estimated as 473 ft^3/s (fig. 36). This value, in combination with average tributary flows of 295 ft^3/s from the study area, is used to estimate average consumptive use of 178 ft^3/s from surface-water sources. The average tributary flows are only those that contribute to the flow of the Cheyenne and Belle Fourche Rivers, which is derived by adjusting values from the surface-water budget for the study area (table 12). The value of 295 ft^3/s is derived by adjusting tributary flows generated within the study area (308 ft^3/s) by the storage change (7 ft^3/s) and by combined flows of 6 ft^3/s for Beaver and Cold Springs Creeks (tables 26 and 27). This adjustment is made because these headwater springs generally provide no sustained contribution to surface flow because of streamflow losses that occur a short distance downstream from the Wyoming border, as previously discussed.

Consumptive withdrawals of 140 ft^3/s are estimated by adjusting average consumptive use of 178 ft^3/s for estimated reservoir evaporation and storage changes of 38 ft^3/s (fig. 35). This estimate is obtained from estimates of reservoir evaporation by Bureau of Reclamation (1998) for 1964-96, which are summarized in table 15. These estimates were based on published averages for annual reservoir evaporation rates (adjusted by annual precipitation estimates), applied to large reservoirs (surface areas of 10 acres or more; or storage of 100 acre-ft or more) within an area slightly larger than the study area considered in this report. The majority of this estimate is for evaporation from the four large Bureau of Reclamation reservoirs in the study area that supply water primarily for irrigation operations (Angostura, Deerfield, Pactola, and Belle Fourche). Two of the reservoirs (Deerfield and Pactola) and various smaller reservoirs are along streams within the crystalline core area, for which runoff estimates are inclusive of evaporative effects. Minor evaporation from reservoirs slightly beyond the study area boundary also is included in the estimated evaporation of 38 ft^3/s; thus, this estimate is taken to include the average storage increase of 7 ft^3/s for 1950-98 (table 12).

Table 15. Bureau of Reclamation (1998) estimates of reservoir evaporation and net consumptive irrigation demand, 1964-96

County	Net reservoir evaporation[1]		Net consumptive irrigation demand[2]	
	(Acre-feet)	(Cubic feet per second)	(Acre-feet)	(Cubic feet per second)
Butte	12,300	17.0	75,700	104
Lawrence	70	.1	5,700	7.9
Meade	30	.1	10,600	14.6
Pennington	3,400	4.7	15,700	21.7
Custer	820	1.1	7,100	9.8
Fall River	11,100	15.3	20,200	27.9
Totals	27,700	38.3	135,000	186

[1]Estimates derived using average reservoir evaporation rate, adjusted for annual precipitation, applied to mean annual surface area.
[2]Theoretical estimates derived using Modified Blaney-Criddle procedures (U.S. Department of Agriculture, 1970).

Evaluation of Consumptive Withdrawal Estimates

As discussed, consumptive withdrawals within the study area cannot be directly quantified because of numerous complicating factors. Thus, a general water-budget approach was used to estimate cumulative consumptive withdrawals from the entire study area. Because of this approach, the resulting estimate is subject to cumulative errors in all of the other terms of the water-budget equation. Estimates of consumptive withdrawals are evaluated within this section.

Estimates of theoretical consumptive irrigation demand in and near the study area have been made by the Bureau of Reclamation (1998) and are summarized in table 15. These estimates were derived using Modified Blaney-Criddle procedures (U.S. Department of Agriculture, 1970), which consider climatic factors and cropping patterns in calculating theoretical net irrigation demand. These estimates are not directly applied because: (1) irrigated areas beyond the study area (for this report) were considered; (2) estimates include water withdrawn from ground-water sources; and (3) estimates are only theoretical and do not necessarily consider factors such as cost or availability of water. The Bureau of Reclamation estimates, which total 186 ft^3/s, do agree reasonably well, however, with estimated surface-water consumptive withdrawals of 140 ft^3/s derived using the water-budget approach. They also provide a useful breakdown of the distribution of consumptive withdrawals within the study area.

Examination of available streamflow data for selected stream reaches provides another useful basis for comparison and also provides estimates of consumptive withdrawals for specific stream reaches with substantial irrigation withdrawals. Estimated withdrawals for five stream reaches are presented in table 16, with details provided in subsequent discussions. These streams include most of the major irrigation areas within the study area and account for the majority of demand, including some demand beyond the study area boundary. For the streams considered, the sum of estimated withdrawals (155 ft^3/s) is intermediate between estimates from the water-budget analysis (140 ft^3/s) and Bureau of Reclamation (1998) estimates (186 ft^3/s).

The estimates presented in table 16 are constrained by locations of applicable gaging stations and available periods of streamflow record. In many cases, flow estimates are made for ungaged tributaries or for gages without complete flow records for periods considered, which increases uncertainty. As usual, uncertainties for individual years tend to be much larger than for multi-year averages.

Estimates of consumptive irrigation demand for the Angostura Irrigation Unit are taken from a Draft Environmental Impact Statement (Bureau of Reclamation, 2001), which included a detailed water-budget analysis for 1955-97. The average release to the irrigation district was estimated as 56 ft^3/s, with return flows of about 30 ft^3/s and consumptive use of about 26 ft^3/s. Methods used in developing these estimates were very similar to methods used within this report.

Estimates for Beaver Creek (table 16) are derived from monthly flow statistics for station 06402500 (table 17). Most of the flow of Beaver Creek results from relatively stable artesian springflow, as discussed in a previous section; thus, most of the variability in monthly flow for this station results from irrigation withdrawals. Median monthly values for November through February, which average 9.66 ft^3/s, probably reflect very little influence from irrigation withdrawals or direct runoff. Median values for the other eight months average 5.62 ft^3/s, which reflects an average depletion of 2.69 ft^3/s on an annual basis. Assuming annual basin yield averages about 1 inch (fig. 27), additional runoff of about 1.4 ft^3/s would be generated in the 19-mi^2 intervening area downstream from station 06402430 (fig. 12), which is located immediately downstream from the artesian spring. Much of this additional runoff typically would occur

Table 16. Estimates of consumptive withdrawals for major irrigation areas

[Estimates derived primarily from available streamflow records]

Irrigation area	Period of record considered (water years)	Estimated consumptive withdrawals: Cubic feet per second	Estimated consumptive withdrawals: Acre-feet per year
Angostura Irrigation Unit	1955-97	26	18,800
Beaver Creek	1950-98	4	2,900
Rapid Creek[1]	1950-98	19	13,700
Redwater River[1]	1950-98	35	25,400
Belle Fourche Irrigation Project[1]	1950-98	71	51,400
Total		155	112,200

[1]Estimates include some areas beyond study area boundary. Estimates for Redwater River include withdrawals from Spearfish Creek.

Table 17. Statistics on mean flow for selected streams with irrigation withdrawals, water years 1950-98

[All values in cubic feet per second]

Statistic	Month												Annual
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	
Beaver Creek near Buffalo Gap (06402500)													
Maximum	11.6	12.4	12.5	12.4	13.5	16.1	12.8	10.6	42.7	26.4	18.3	12.1	12.5
75th percentile	9.36	10.1	10.7	10.9	10.8	9.87	8.73	6.93	9.99	7.12	4.83	7.61	8.07
Median	7.36	9.13	9.54	9.98	9.99	9.05	6.63	4.29	4.61	4.05	3.21	5.75	6.76
25th percentile	4.78	7.71	8.49	9.13	9.43	8.26	2.87	1.76	1.41	1.02	1.35	2.93	5.94
Minimum	.67	3.40	5.96	7.10	7.12	4.34	.79	.61	.39	.24	.25	.37	3.78
Mean	6.84	8.76	9.54	9.92	10.03	9.19	6.06	4.42	6.75	4.99	4.03	5.37	7.14
Redwater River above Belle Fourche (06433000)													
Maximum	283	217	203	246	278	276	359	988	739	180	178	172	241
75th percentile	156	162	150	151	152	171	214	291	261	71.4	57.7	110	174
Median	123	138	137	129	138	147	167	180	130	36.0	32.7	78.7	127
25th percentile	102	110	121	112	119	126	132	111	58.6	19.3	15.9	58.6	95.8
Minimum	50.6	82.7	69.9	83.5	91.7	105	62.9	20.0	4.07	2.13	2.72	19.3	57.1
Mean	129.59	140.75	138.41	132.68	142.93	152.80	175.24	240.34	177.10	52.39	44.33	86.05	134.27

during irrigation months. Thus, average consumptive withdrawals for Beaver Creek are estimated as about 4 ft^3/s, or 2,900 acre-ft/yr. Effects of additional withdrawals or return flows downstream from station 06402500 cannot be evaluated.

Consumptive withdrawals for Rapid Creek (fig. 33) are estimated as about 19 ft^3/s (table 16), using streamflow records for gages located at Rapid City (06414000) and near Farmingdale (06421500). Data sets used in deriving estimates are presented in table 30 in the Supplemental Information section. Inflows in the reach include discharge from the Rapid City municipal sewage treatment plant and tributary inflows. Municipal records of treatment plant discharge were obtained for 1976-98; methods for estimating discharge for 1950-75 are noted in table 30. Tributary inflows from the intervening area of 192 mi^2 are estimated as 0.4 times the measured flow of Elk Creek near Elm Springs (station 06425500). Estimates of consumptive withdrawals are highly sensitive to estimated tributary inflow, as demonstrated by figure 37, which shows calculations using three different coefficients (0.3, 0.4, and 0.5) as multipliers for flow of Elk Creek. Use of different coefficients has

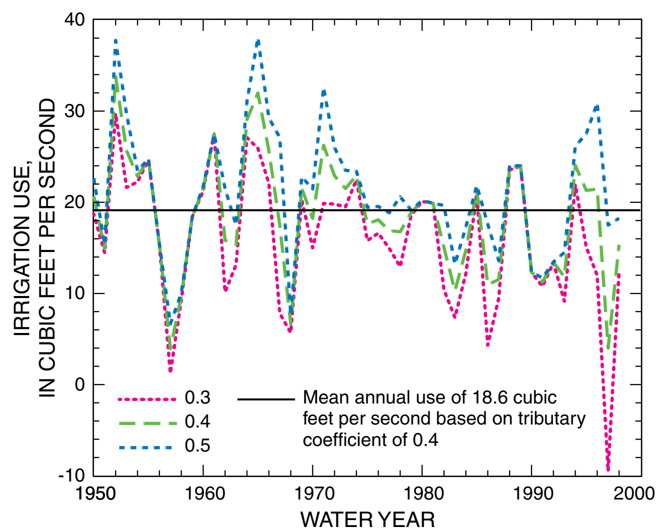

Figure 37. Estimated consumptive irrigation use for Rapid Creek, based on various estimates of tributary inflow. Tributary inflow is estimated as flow of Elk Creek at station 06425500 multiplied by a coefficient (0.3, 0.4, or 0.5).

negligible effect on estimates for low-flow years for Elk Creek; however, variability increases proportionally with increasing flow of Elk Creek. The use of 0.4 as a coefficient provides an intermediate estimate that smooths outlier values. Estimates of consumptive withdrawals might be refined by analysis of monthly streamflow records and improved methods for estimating tributary inflows; however, such efforts are beyond the scope of this evaluation.

Estimates for Redwater River (table 16) are derived using monthly flow statistics (table 17), again because of a large and stable component of springflow during base flow months. Estimated consumptive withdrawals for the Redwater River also include withdrawals along Spearfish Creek. Median monthly flows for November through February, which average 135.5 ft^3/s, are again used as an estimate of base flow during non-irrigation months. The median values for June through October indicate an average depletion of 23.1 ft^3/s on an annual basis. Actual depletions are considerably larger than this, but are masked by substantial direct runoff that can occur within the 920-mi^2 drainage basin. Effects of tributary inflows relative to irrigation withdrawals are apparent from examination of statistics for April through June. Reliable methods for estimating runoff during irrigation months are not available; thus, consumptive withdrawals for the Redwater River are arbitrarily estimated to average 35 ft^3/s (1.5 times 23.1 ft^3/s).

Consumptive withdrawals for irrigation areas in and near the Belle Fourche Irrigation Project (table 16) are estimated using a water-budget analysis for a reach of the Belle Fourche River. The reach considered is similar to that which was considered for the surface-water budget for the Belle Fourche River; however, several different measurement locations for inflows are used (fig. 33). The different measurement sites include Inlet Canal (06434505), Belle Fourche River near Fruitdale (06436000), and Whitewood Creek above Vale (06436198). Stations on Indian Creek (06436700) and Horse Creek (06436500) are retained as inflow sites. Belle Fourche River near Sturgis (06437000) is the only outflow site.

Data sets used in estimating consumptive withdrawals are presented in table 31 in the Supplemental Information section. Tributary inflows for ungaged areas outside of the study area are estimated based on annual yield for the Belle Fourche River between stations 06437000 and 06438000, which is similar to the method used for surface-water budgets. The outside tributary area is reduced to 430 mi^2, however, because Crow Creek is excluded (fig. 33).

Estimates of consumptive use for individual years (table 31) are not considered accurate or reliable because of relatively large error potential resulting from sensitivity to estimates of tributary inflow and estimated periods for measured tributaries (Indian, Horse, and Whitewood Creeks). Error potential also results from the large number of sites involved and generally tends to increase with increasing flows. Overall, the largest error potential is for the sum of inflows, which involves numerous measured values and one or more estimated values for all years considered. Errors are obvious for negative use estimates, which generally would indicate underestimation of cumulative inflows, because outflows are measured at only one site. Errors also are likely for some of the larger estimates. For example, maximum calculated use of 163.7 ft^3/s occurred during 1964, when reservoir storage decreased only slightly.

The distribution of annual use estimates for the Belle Fourche Project area is shown in figure 38. The median value (88 ft^3/s) is larger than the mean (72 ft^3/s) because the data set is skewed by a small number of years with negative values. Thus, the median is taken as a better estimate of central tendency for the data set. Calculated use includes evaporation from Belle Fourche Reservoir, which was estimated as 17 ft^3/s (table 15) for 1964-96 by the Bureau of Reclamation (1998). Thus, consumptive irrigation withdrawals (exclusive of reservoir evaporation) are estimated as 71 ft^3/s, to be consistent with other estimates in table 16.

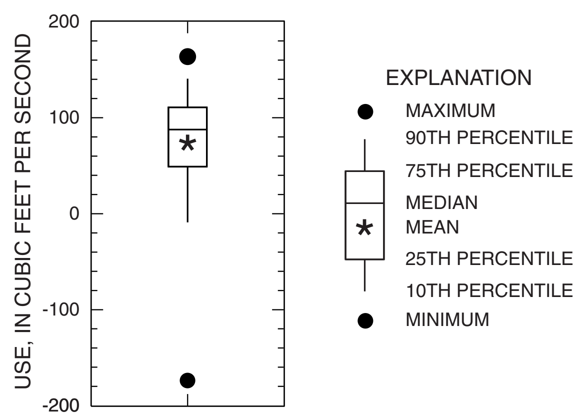

Figure 38. Distribution of estimated annual consumptive irrigation use for Belle Fourche Project area.

Cumulative consumptive withdrawals for major irrigation areas are estimated as 155 ft^3/s (table 16). This rate is about 10 percent higher than the estimate of 140 ft^3/s from the water-budget analysis (fig. 35), which applies only to withdrawals within the study area boundary. Estimates for Rapid Creek, Redwater River, and the Belle Fourche Project area (table 16) all include withdrawals from areas beyond the study area boundary, however.

Additional withdrawals also are made from a number of other streams within and near the study area. Water-right permits exist for surface-water irrigation from Hat, Cascade, Horsehead, French, Battle, Spring, Boxelder, Elk, Alkali, Whitewood, and Bear Butte Creeks (Mark Rath, South Dakota Department of Environment and Natural Resources, oral commun., 2001). Most withdrawals are small, relative to withdrawals for the major irrigation areas, and many of the withdrawal points are beyond the study area boundary.

Thus, it is concluded that 140 ft^3/s is a reasonable estimate of consumptive withdrawals of surface water. Consumptive use is considerably larger if reservoir evaporation and areas beyond the study area are considered. Average cumulative use upstream from the confluence of the Cheyenne and Belle Fourche Rivers probably approaches 250 ft^3/s, if demand within Wyoming is considered. Within Wyoming, the largest sources of consumptive surface-water use are irrigation withdrawals from Stockade Beaver Creek, Redwater River, and Belle Fourche River, along with evaporation from Keyhole Reservoir (located about 50 mi west of Spearfish).

It should be recognized that consumptive use varies considerably on an annual basis, as shown by figures 37 and 38. Variability in actual consumptive use is much smaller than indicated by figure 38, which includes several years for which negative use is computed (table 31). The 25th and 75th percentiles probably provide a reasonable depiction of typical variability, although consumptive use beyond this range probably occurs, especially for higher values.

Consumptive withdrawals during particularly dry years can be highly affected by availability of irrigation supplies. The largest withdrawals typically would occur during dry periods following closely after wet periods that have provided high flows and large available storage. Similarly, withdrawals can be severely limited by availability of irrigation supplies, especially during prolonged dry periods. Water quantities needed to supply irrigation demand are systematically larger than consumptive use because of inherent non-consumptive losses that eventually result in return flows.

General Evaluation of Budget Estimates

Various assumptions have been made in developing hydrologic budgets, and numerous budget components have been estimated. Thus, a general evaluation of budget estimates is provided within this section.

Recent investigations have provided extensive information regarding various budget components for the Madison and Minnelusa aquifers, which are shown to dominate the overall ground-water hydrology of the Black Hills area and heavily influence the surface-water hydrology. Recharge estimates were derived from information previously provided by Carter, Driscoll, and Hamade (2001). Estimates of streamflow recharge, which are based largely on measured values, are considered more accurate than estimates of precipitation recharge, which have two primary causes for uncertainties. Considerable uncertainty results from the assumption that recharge efficiency is reasonably approximated by yield efficiency for streams with little influence from ground-water discharge. Additional uncertainty is associated with the yield-efficiency algorithm that has been used to estimate annual precipitation recharge.

Other budget components for the Madison and Minnelusa aquifers were derived from information presented by Carter, Driscoll, Hamade, and Jarrell (2001). Estimates for artesian springflow, which are based primarily on measured values, have fairly small uncertainty, relative to the magnitude of the estimates. Uncertainties are larger for estimates of headwater springflow, which are based on yield potential for inferred areas contributing to ground-water discharge. Comparisons of estimated springflow to measured streamflow (Jarrell, 2000), however, provided confidence that estimates are reasonable. Uncertainties are small for well withdrawals; thus, most of the uncertainties for estimates of net ground-water outflow from the study area are related to uncertainties for estimates of precipitation recharge. Detailed water-budget analyses for specific subareas within the Black Hills area (Carter, Driscoll, Hamade, and Jarrell, 2001), however, provided confidence that estimates for all water-budget components for the Madison and Minnelusa aquifers are reasonable.

Budgets for other aquifers are based primarily on estimates of precipitation recharge, which again have been derived using the yield-efficiency algorithm. The assumed "recharge factors" used to apportion overall yield potential between runoff and recharge are another source of potential error. Considerable evidence exists that direct runoff is uncommon from outcrops of the Madison and Minnelusa aquifers; however, information regarding other outcrops is sparse.

The yield-efficiency algorithm also was used extensively in developing surface-water budgets and in estimating consumptive withdrawals for the study area. An analysis of streamflow depletion from streamflow losses, which was presented in a previous section, indicated that estimates of total basin yield from the crystalline core area provided reasonable results. An evaluation of consumptive withdrawal estimates (also presented in a previous section) indicated that the yield-efficiency algorithm also provided reasonable results for areas beyond the Madison/Minnelusa outcrop band. Thus, besides providing general confidence in the surface-water budgets, these evaluations also provide confidence that the yield-efficiency algorithm systematically produces reasonable and reproducible estimates of total yield from the spatial distribution of annual precipitation. Readers again are cautioned that because of the inherent, unexplained variability between annual yield and precipitation, estimates for individual years that are based on this algorithm have a relatively high level of uncertainty. Uncertainties associated with long-term estimates are much smaller, however.

SUMMARY

The Black Hills are an important recharge area for aquifers in the northern Great Plains. The surface-water hydrology of the area is highly influenced by interactions with the Madison and Minnelusa aquifers, including large springs and streamflow loss zones. Defining responses of ground water and streamflow to a variety of hydrogeologic influences is critical to development of hydrologic budgets for ground- and surface-water systems.

Precipitation patterns are highly influenced by orographic effects, with the largest precipitation amounts occurring in the high-altitude areas of the northern Black Hills. Annual precipitation for the study area (water years 1931-98) averages 18.61 inches and has ranged from 10.22 inches to 27.39 inches. Annual averages for counties within the study area range from 16.35 inches for Fall River County to 23.11 inches for Lawrence County. Average annual precipitation for most of the study area is less than average pan evaporation, which ranges from about 30 inches at Pactola Reservoir to 50 inches at Oral. Long-term precipitation trends are an important consideration for hydrologic analysis because of a bias towards wetter conditions during the 1990's, which coincides with a period of intensive hydrologic data collection in the Black Hills area.

The response of ground-water to precipitation patterns is shown by comparing water-level hydrographs for 52 observation wells and 1 cave site to cumulative precipitation departures for counties in which the sites are located. Aquifers considered include the Precambrian, Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers. Of these, water-level fluctuations for wells completed in the Inyan Kara aquifer generally show the least response to precipitation patterns. In comparison, many wells completed in the other aquifers have large short- and long-term fluctuations in water levels. Madison and Minnelusa wells in the southern Black Hills show a general tendency for smaller water-level fluctuations than in other areas.

The response of streamflow to precipitation influences is different for five different hydrogeologic settings that are identified. Streamflow characteristics and relations with precipitation are examined for 33 gaging stations that are representative of the five different settings.

The "limestone headwater" setting occurs primarily within outcrops of the Madison Limestone and Minnelusa Formation along the "Limestone Plateau" area on the western side of the study area. For this setting, direct runoff is uncommon and streamflow consists almost entirely of base flow originating as ground-water discharge from headwater springs, which results in small variability for daily, monthly, and annual flow. Annual streamflow generally correlates poorly with precipitation; however, relations improve substantially with consideration of "moving averages" for annual precipitation. Coefficient of determination (r^2) values exceeding 0.90 are obtained for several streams, with best-fit regression equations obtained for moving averages involving 3 to 11 years of precipitation data.

The "crystalline core" area is encircled by the outcrop band of the Madison and Minnelusa Formations and is dominated by igneous and metamorphic rocks. Base flow ranges from about 41 to 73 percent for representative streams in this setting; however, monthly flow records demonstrate short-term response to precipitation, which probably indicates a relatively large component of interflow contributing to base flow. Similarly, streamflow generally correlates well with annual precipitation, with r^2 values ranging from 0.52 to 0.87.

The "loss zone" setting is located downgradient from the crystalline core area, within outcrops of the Madison and Minnelusa Formations where large streamflow losses provide recharge to the associated aquifers. Because sustained flow is uncommon for this setting, only two representative gages exist, with relations between streamflow and annual precipitation best defined by a power equation. A common area extending to the outcrop of the Inyan Kara Group is identified for the loss zone and "artesian spring" settings because many artesian springs are located along stream channels that are influenced by streamflow losses and several artesian springs are within outcrops of the Minnelusa Formation. Similar to headwater springs, streamflow characteristics for artesian spring settings generally demonstrate small variability and poor correlations with annual precipitation because of large influence from relatively consistent ground-water discharge.

The "exterior" setting is located downgradient from the outcrop of the Inyan Kara Group, which coincides with the outer extent of the loss zone/artesian spring setting. Large flow variability is characteristic for this setting and base flow generally is smaller than for other settings.

Basin yield is highly variable within the study area, with the largest yields generally occurring in high-altitude areas that receive large annual precipitation. Basin yields for several limestone headwater gages are shown to be influenced by incongruences between contributing ground- and surface-water areas; however, measured yields compare well with estimates of precipitation recharge over contributing ground-water areas delineated by previous investigators. These investigators estimated recharge using a "yield-efficiency algorithm" that compares spatial distributions for annual precipitation, average annual precipitation, and efficiency of basin yield, which is used as a surrogate for efficiency of precipitation recharge. Relations between these variables are used to compensate for the climatic bias associated with short-term gaging records.

The aforementioned methods are used extensively in developing average hydrologic budgets for water years 1950-98 for ground- and surface-water systems and are applied in estimating precipitation recharge on aquifer outcrops and in estimating streamflow yield from various outcrop areas. For the entire study area, 1950-98 precipitation averaged 18.98 inches or just over 5.2 million acre-ft per year. Of this amount, total yield is estimated as 441,000 acre-ft per year (608 ft^3/s), which is equivalent to about 1.59 inches over the study area.

Average ground-water budgets are developed for the major bedrock aquifers within the study area (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers) and for additional minor bedrock aquifers. The overall ground-water budgets are dominated by the Madison and Minnelusa aquifers, which have the largest outcrop areas of the major aquifers in the study area. Annual recharge to all bedrock aquifers is estimated as 252,000 acre-ft per year (348 ft^3/s), of which 292 ft^3/s is recharge to the Madison and Minnelusa aquifers. Of this amount, 200 ft^3/s is from precipitation recharge and 92 ft^3/s is from streamflow losses.

Discharge of all wells and springs is about 259 ft^3/s, of which the Madison and Minnelusa aquifers account for 206 ft^3/s of springflow and 28 ft^3/s of well withdrawals. Estimated springflow and well withdrawals from the Deadwood aquifer are 12.6 ft^3/s and 1.4 ft^3/s, respectively. Estimated well withdrawals from other aquifers account for about 11 ft^3/s.

All of the aforementioned estimates are obtained by making direct estimates for various budget components, which are used in calculating net ground-water outflow from the study area. The resulting residual indicates that estimated outflow from the study area exceeds inflow by about 89 ft^3/s, which also is dominated by net ground-water outflow of 58 ft^3/s from the Madison and Minnelusa aquifers.

Surface-water budgets also are developed for 1950-98, with inflows and outflows estimated as 252 and 553 ft^3/s, respectively. Storage in major reservoirs increased by about 7 ft^3/s; thus, net tributary flows (flows less depletions) generated within the study area are calculated as 308 ft^3/s. Consideration of combined ground- and surface-water budgets is used to estimate consumptive streamflow withdrawals of 140 ft^3/s. Total consumptive use within the study area is estimated as 218 ft^3/s, by including estimates of reservoir evaporation and storage changes (38 ft^3/s) and well withdrawals (40 ft^3/s).

Estimates of budget components are evaluated, where possible. Estimates for consumptive streamflow withdrawals are derived using numerous other budget components; thus, annual estimates generally are considered unreliable. Various evaluation mechanisms provide confidence, however, that estimates for long-term averages are realistic. The largest error potential associated with development of hydrologic budgets is the use of the yield-efficiency algorithm, which was developed as part of previous investigations and is applied for estimating precipitation recharge and streamflow yield. The ability to balance overall hydrologic budgets within realistic ranges provides confidence that the method systematically produces reasonable estimates when applied over sufficiently large spatial extents and timeframes. This conclusion is especially important because estimation of precipitation recharge for the Madison and Minnelusa aquifers is critical to developing realistic hydrologic budgets for the Black Hills area.

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