Surface-Water Characteristics

Within this section, surface-water characteristics, including both streamflow and water-quality characteristics, are described. Surface-water characteristics can be affected by numerous physical variables such as topography, land cover, soil conditions, mineralogy, and ground-water conditions, all of which may be affected by geologic conditions. In addition, streamflow is affected by numerous climatic variables including timing, intensity, and amount of precipitation, as well as other variables affecting evaporative processes.

Streamflow Characteristics

Streamflow characteristics in the Black Hills area are highly affected by the hydrogeologic settings previously described (fig. 23). Streamflow characteristics described in this section include variability of streamflow, the response of streamflow to precipitation, and annual yield characteristics. More detailed discussions of these topics were presented by Driscoll and Carter (2001).

Streamflow Variability

A distinctive effect of hydrogeologic setting is on the timing and variability of streamflow, which results primarily from interactions between surface water and ground water. Locations of streamflow-gaging stations for basins representative of the five hydrogeologic settings were presented in figure 23. Site information and selected flow characteristics are summarized (by hydrogeologic setting) in table 5. One of the flow characteristics summarized is the "base flow index" (BFI), which represents the estimated percentage of average streamflow contributed by base flow, for any given gage. BFI's were determined with a computer program described by Wahl and Wahl (1995).

Table 5 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).

The last flow characteristic summarized in table 5 is the coefficient of variation (standard deviation divided by mean) for annual basin yield, which provides a useful 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 artesian spring basins—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 5; 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.

Duration curves showing variability in daily flow are presented in figure 40 for selected basins. Streamflow variability is small for limestone headwater and artesian spring basins because streamflow consists almost entirely of base flow from spring discharge. For the individual limestone headwater basins, measured daily flows generally vary by less than an order of magnitude, indicating that direct runoff is very uncommon from outcrops of the Madison Limestone and Minnelusa Formation, which are the predominant outcrops for this setting. Streams in the crystalline core setting have large variability in daily flow. Loss zone and exterior settings have large flow variability and low-flow and zero-flow periods are common.

Relative variability of monthly and annual flow also is much smaller for basins representative of limestone headwater and artesian spring settings than for the other settings (figs. 41 and 42). Annual flow values are expressed as annual yield (fig. 42) for all hydrogeologic settings except the artesian spring setting, for which annual yield values can be unrealistically large (table 5), as previously discussed. Coefficients of variation for these settings are consistently smaller than for the other settings (table 5). BFI's are consistently larger, indicating large proportions of base flow for these settings. All measures considered indicate much higher flow variability for the other three settings.

Table 5. Summary of selected site information and flow characteristics for streamflow-gaging stations representative of hydrogeologic settings

[Modified from Driscoll and Carter (2001). --, not determined]

Station number	Station name	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)	Standard deviation	Coefficient of variation (standard deviation/mean)
	Limestone Headwater Basins							
06392900	Beaver Creek at Mallo Camp, near Four Corners, WY[1]	10.3	1975-82, 1992-98	88.6	1.88	2.48	0.63	0.25
06408700	Rhoads Fork near Rochford	7.95	1983-98	98.7	5.47	9.34	2.48	.27
06409000	Castle Creek above Deerfield Reservoir, near Hill City	79.2	1949-98	87.1	11.73	2.01	.75	.37
06429500	Cold Springs Creek at Buckhorn, WY[1]	19.0	1975-82, 1992-98	91.4	4.33	3.10	.68	.22
06430770	Spearfish Creek near Lead	63.5	1989-98	[2]91.0	[2]25.43	[2]5.44	[2]2.59	[2].48
06430850	Little Spearfish Creek near Lead	25.8	1989-98	97.0	16.59	8.74	2.31	.26
	Crystalline Core Basins							
06402430	Beaver Creek near Pringle	45.8	1991-98	73.1	2.86	.85	.76	.89
06402995	French Creek above Stockade Lake, near Custer[3]	68.7	--	--	--	--	--	--
06403300	French Creek above Fairburn	105	1983-98	55.5	10.94	1.42	1.19	.84
06404000	Battle Creek near Keystone	58.0	1962-98	45.4	9.39	2.20	1.59	.72
06404800	Grace Coolidge Creek near Hayward[3]	7.48	--	--	--	--	--	--
06404998	Grace Coolidge Creek near Game Lodge, near Custer	25.2	1977-98	58.9	5.07	2.73	2.36	.86
06405800	Bear Gulch near Hayward	4.23	1990-98	41.1	1.48	4.75	2.76	.58
06406920	Spring Creek above Sheridan Lake, near Keystone[3]	127	--	--	--	--	--	--
06407500	Spring Creek near Keystone	163	1987-98	54.1	25.06	2.09	1.73	.83
06422500	Boxelder Creek near Nemo	96.0	1967-98	64.9	19.53	2.76	2.19	.79
06424000	Elk Creek near Roubaix	21.5	1992-98	61.1	13.42	8.48	4.08	.48
06430800	Annie Creek near Lead	3.55	1989-98	51.1	1.72	6.55	4.42	.67
06430898	Squaw Creek near Spearfish	6.95	1989-98	52.5	3.76	7.34	4.44	.60
06436156	Whitetail Creek at Lead	6.15	1989-98	63.0	4.79	10.57	6.01	.57
06437020	Bear Butte Creek near Deadwood[1]	16.6	1989-98	58.3	8.35	6.84	4.07	.60

Table 5. Summary of selected site information and flow characteristics for streamflow-gaging stations representative of hydrogeologic settings–Continued

[Modified from Driscoll and Carter (2001). --, not determined]

Station number	Station name	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)	Standard deviation	Coefficient of variation (standard deviation/mean)
			Loss Zones Basins					
06408500	Spring Creek near Hermosa	199	1950-98	44.1	7.15	.49	.73	1.49
06423010	Boxelder Creek near Rapid City	128	1979-98	14.4	5.88	.62	1.23	1.98
			Artesian Spring Basins					
06392950	Stockade Beaver Creek near Newcastle, WY[1]	107	1975-82, 1992-98	93.5	12.15	1.54	0.23	0.15
06400497	Cascade Springs near Hot Springs	.47	1977-95	99.2	19.53	564	40.34	.07
06402000	Fall River at Hot Springs	137	1939-46, 1948-98	96.0	23.61	2.34	.25	.11
06402470	Beaver Creek above Buffalo Gap	111	1991-97	97.4	10.21	1.25	.25	.20
06412810	Cleghorn Springs at Rapid City[3]	--	--	--	--	--	--	--
06429905	Sand Creek near Ranch A, near Beulah, WY[1]	267	1977-83, 1992-98	95.1	22.58	1.15	.22	.19
06430532	Crow Creek near Beulah, WY	40.8	1993-98	92.6	40.68	13.5	1.13	.08
06430540	Cox Lake outlet near Beulah, WY	.07	1991-95	99.3	4.22	819	9.16	.01
			Exterior Basins					
06395000	Cheyenne River at Edgemont[3]	7,143	--	--	--	--	--	--
06400000	Hat Creek near Edgemont	1,044	1951-98	15.5	16.61	.22	.26	1.18
06400875	Horsehead Creek at Oelrichs[1]	187	1984-98	12.6	6.75	.49	.70	1.43
06433500	Hay Creek at Belle Fourche	121	1954-96	17.5	1.74	.20	.23	1.15
06436700	Indian Creek near Arpan[1]	315	1962-81	6.6	19.98	.86	.92	1.07
06436760	Horse Creek above Vale[3]	464	--	--	--	--	--	--
06437500	Bear Butte Creek near Sturgis[1]	192	1946-72	32.3	13.93	.99	1.04	1.05

1Site used only for analysis of streamflow characteristics.

[2] Flow characteristics affected by relatively consistent diversions of about 10 cubic feet per second.

[3] Site used only for analysis of water-quality characteristics.

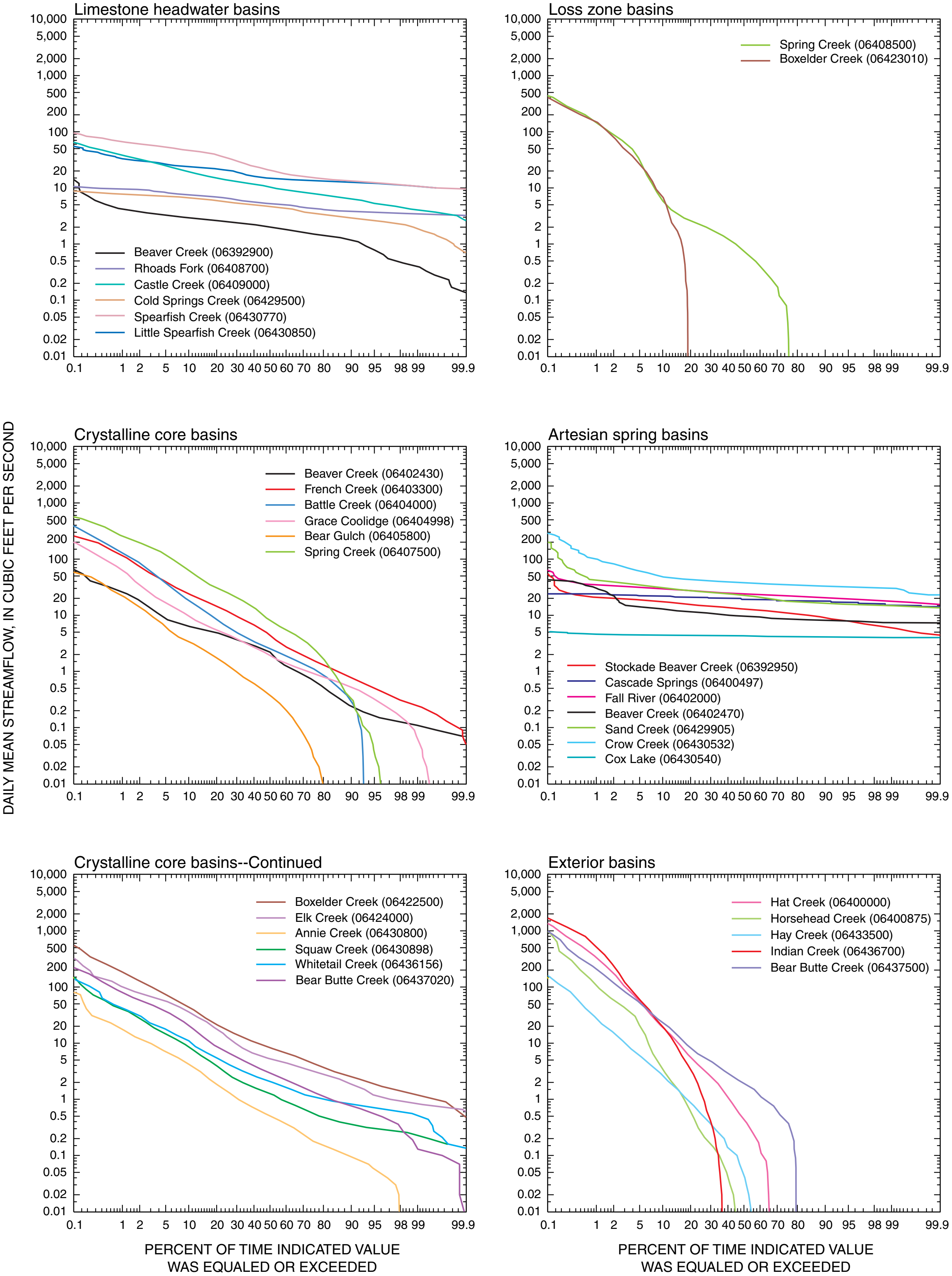


Figure 40. Duration curves of daily mean streamflow for basins representative of hydrogeologic settings (from Driscoll and Carter, 2001).

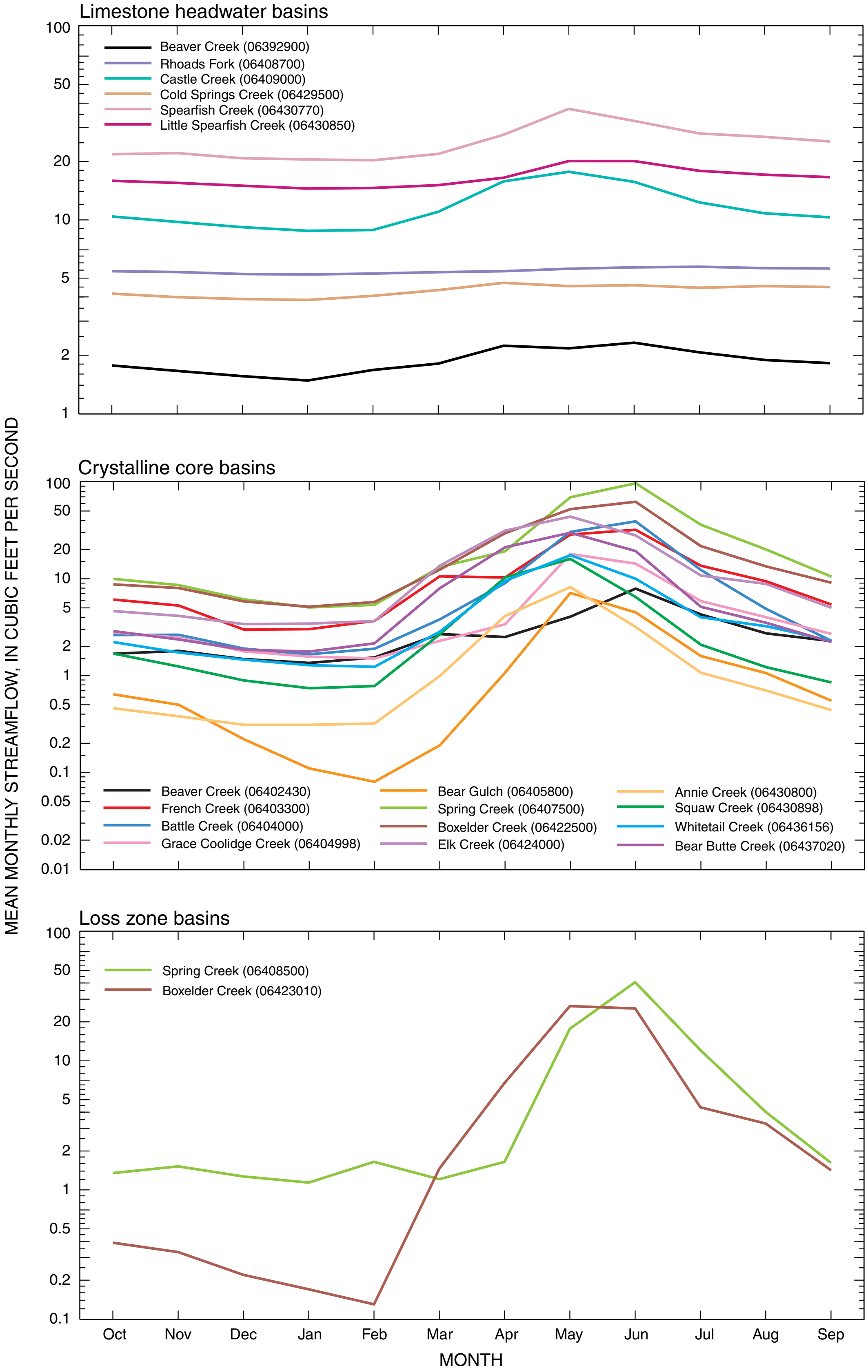


Figure 41. Mean monthly streamflow for basins representative of hydrogeologic settings (from Driscoll and Carter, 2001).

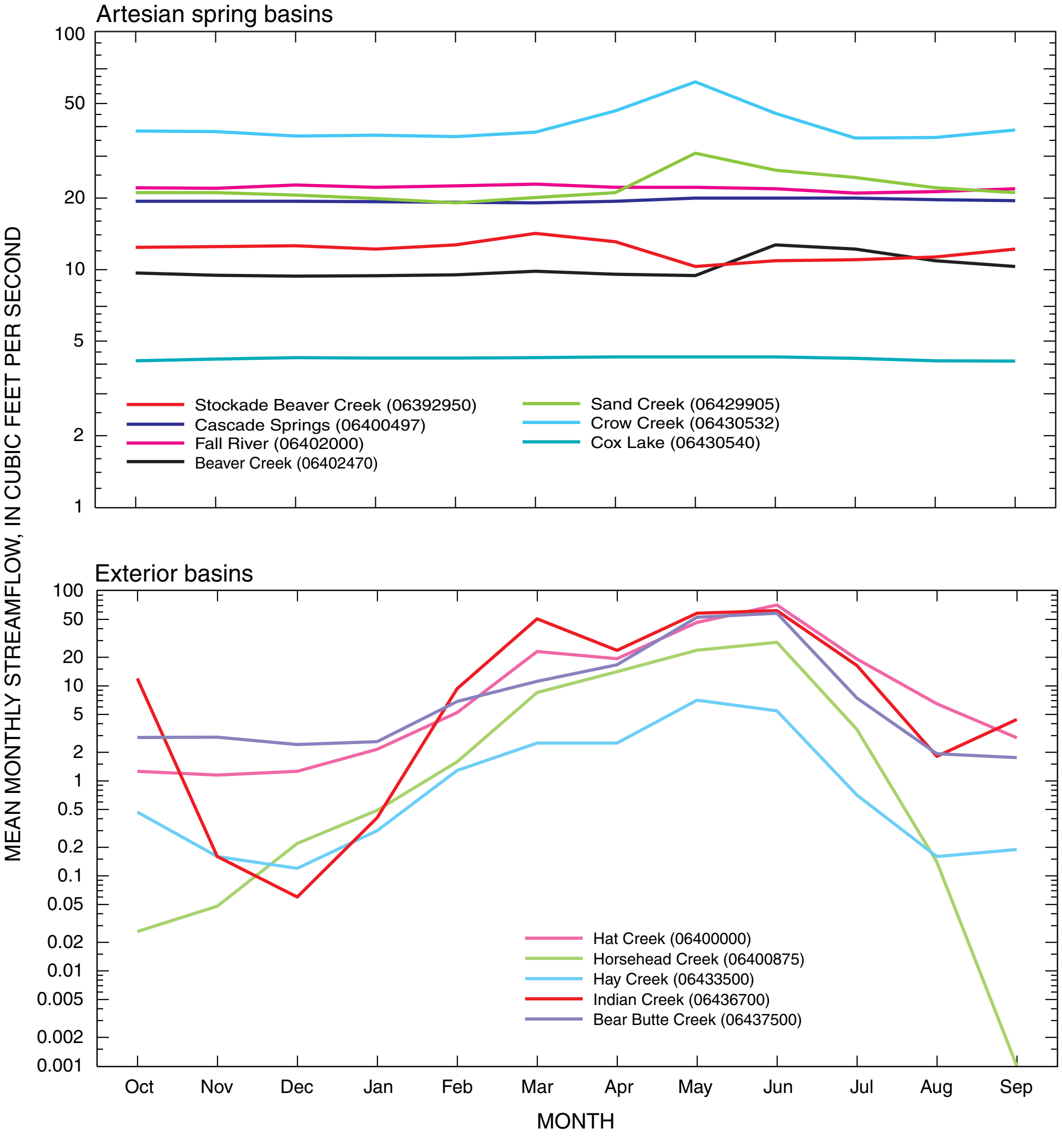


Figure 41. Mean monthly streamflow for basins representative of hydrogeologic settings (from Driscoll and Carter, 2001).—Continued

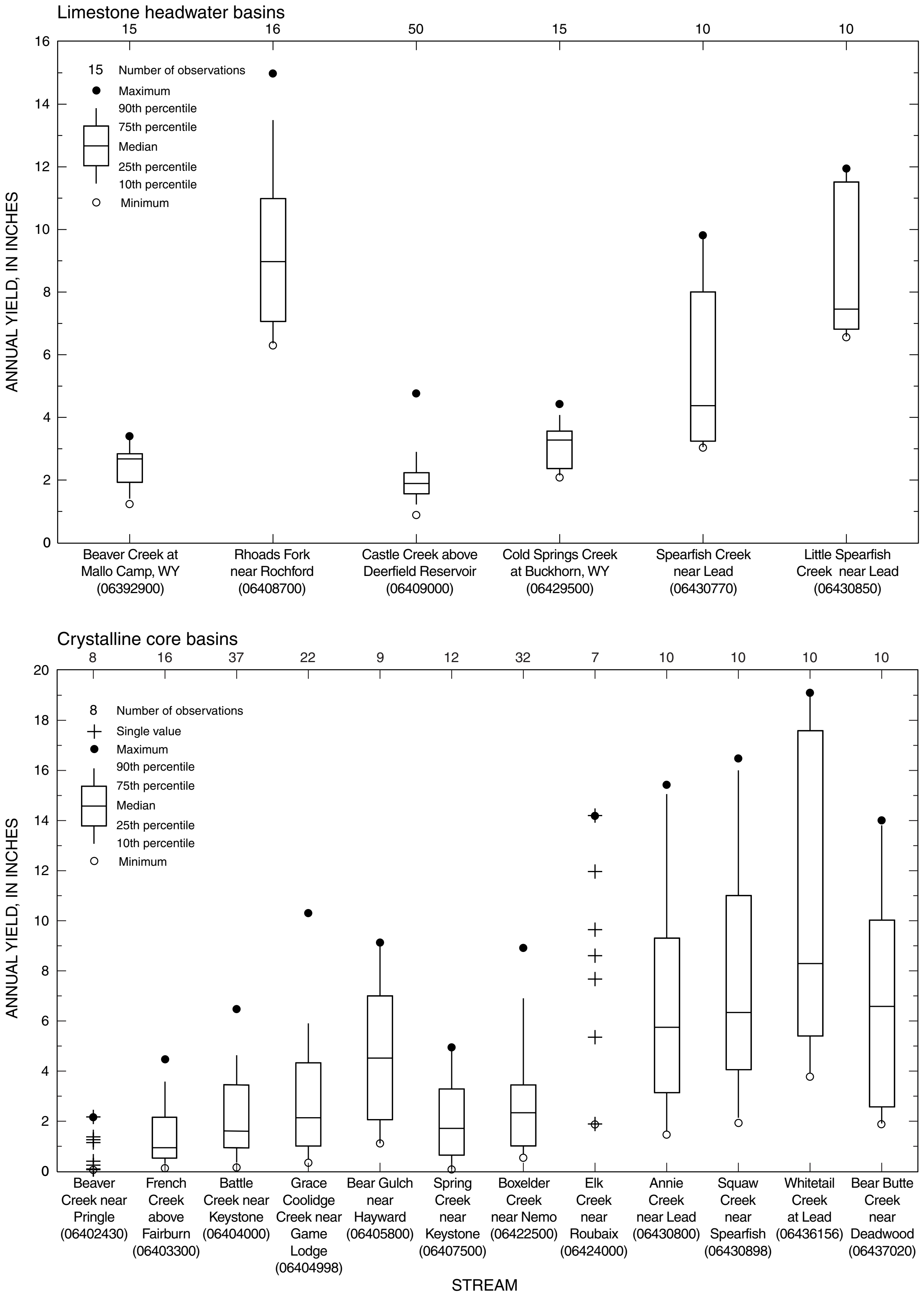


Figure 42. Distribution of annual yield for basins representative of hydrogeologic settings (from Driscoll and Carter, 2001).

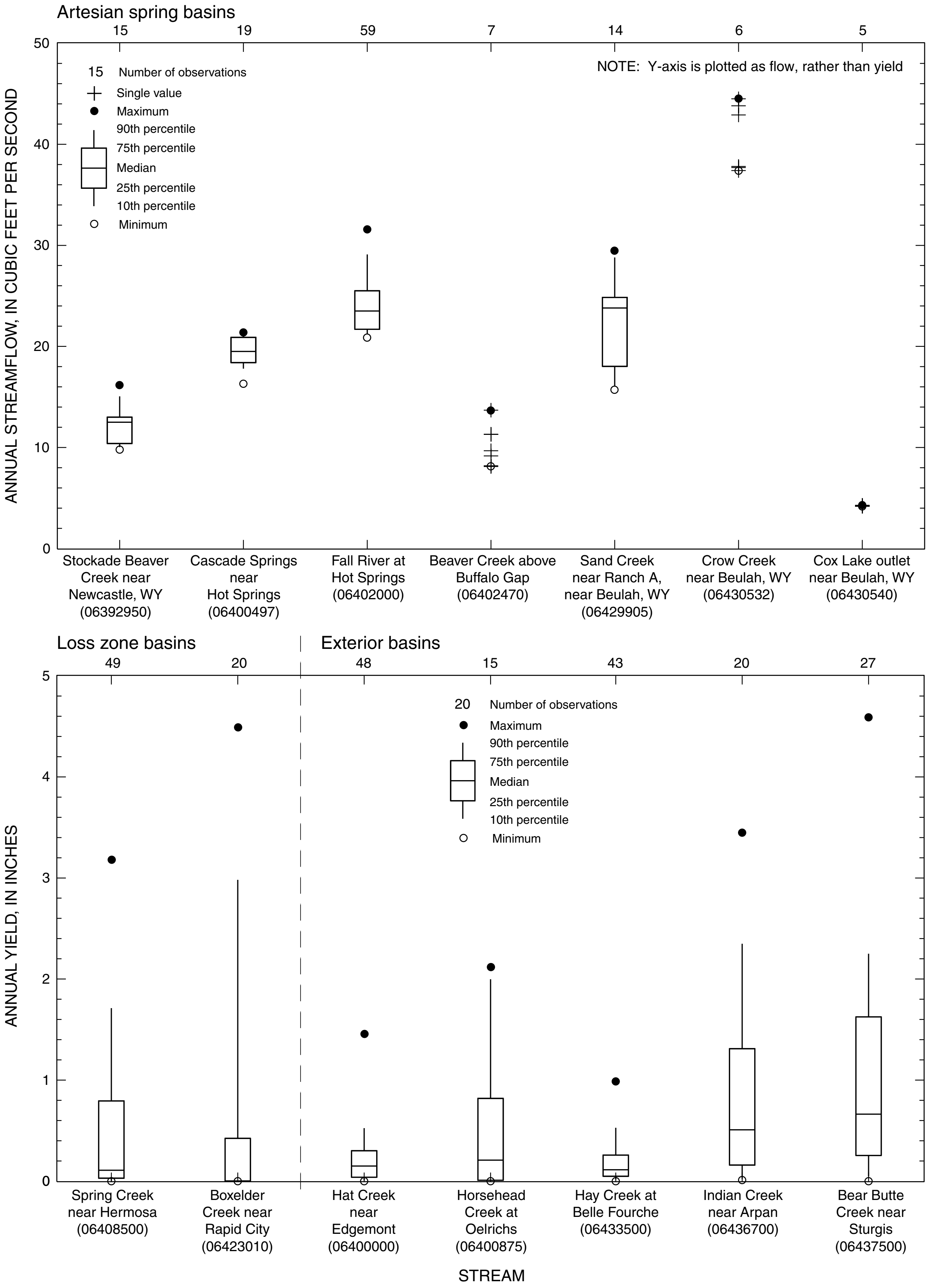


Figure 42. Distribution of annual yield for basins representative of hydrogeologic settings (from Driscoll and Carter, 2001).—Continued

BFI's for the crystalline core basins generally approach or slightly exceed 50 percent (table 5). Monthly flow characteristics (fig. 41), 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 conditions amenable to non-vertical flow components in the unsaturated zone. Ground-water discharge also contributes to streamflow; 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. 42). Daily flow values span two or more orders of magnitude for all crystalline core basins (fig. 40).

Few gages representative of the loss zone setting exist 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. 23) are located on Spring Creek (06408500) and Boxelder Creek (06423010). Annual basin yields for these gages 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 (table 5, figs. 40-42). Spring Creek does have relatively consistent base flow (table 5, BFI = 44 percent) from alluvial springs that occur a short distance upstream from the gage.

Seven representative gages for the artesian spring setting are considered (fig. 23), of which two (Cascade Springs and Cox Lake) 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 basin (Fall River, 06402000) heads predominantly within the loss zone setting (fig. 23). Monthly means (fig. 41) for Fall River show no apparent influence of flows through loss zones, in spite of storm flows that occasionally increase daily flows (fig. 40). Minor influence of flows through loss zones is apparent in both monthly and daily flow characteristics for the other four gages (figs. 40 and 41). The influence of minor irrigation diversions along Stockade Beaver Creek (06392950) during late spring and summer months also is apparent.

For the exterior setting, daily flows for representative gages vary by more than four orders of magnitude (fig. 40) and zero-flow conditions are common, which is consistent with BFI's that typically are small (table 5). Large variability in monthly and annual flows also is characteristic for the exterior setting (figs. 41 and 42). Annual basin yields also are smaller than for most other settings, which is consistent with smaller precipitation and larger evaporation rates at lower altitudes. Many of these sites also are affected by minor irrigation withdrawals.

Response to Precipitation

Streams representative of the various hydrogeologic settings generally have distinctive characteristics relative to responsiveness to precipitation, as described within this section. Methods used for determination of precipitation over drainage areas were described by Driscoll and Carter (2001), who provided detailed discussions regarding relations between streamflow and precipitation.

The limestone headwater basins generally have weak correlations between annual streamflow and precipitation, as summarized in table 6. The r^2 values are low and p-values indicate that the correlations are not statistically significant (>0.05) for most of the representative basins, which is consistent with minimal variability in daily (fig. 40) and monthly (fig. 41) flow. Correlations with annual streamflow improve when "moving-average" precipitation (annual precipitation averaged over multiple years) is considered as the explanatory variable. Regression information is summarized in table 6 for the number of years of moving-average precipitation for which r^2 values are maximized for each basin.

The regression equation (table 6) for Castle Creek (station 06409000) probably is the most reliable, in spite of an associated r^2 value that is relatively low, primarily because the length of record is the longest (table 5). High r^2 values for several basins probably result primarily from relatively short periods of record; thus, associated regression equations for these stations may not be representative of long-term conditions. The p-values generally indicate strong statistical significance, however, which provides confidence that 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.

Table 6. Summary of regression information for limestone headwater basins

[Regression information (from Driscoll and Carter, 2001) is provided for streamflow as a function of annual precipitation and as a function of moving average precipitation over a specified number of years. Int, intercept; <, less than]

Station number	Station name	Annual precipitation		Moving average precipitation				
		r^2	p-value	Number of years	r^2	p-value	Slope	Int
06392900	Beaver Creek at Mallo Camp	0.01	0.668	11	0.24	0.063	0.211	-2.78
06408700	Rhoads Fork	.16	.123	9	.93	<.010	.658	-9.12
06409000	Castle Creek	.31	<.010	3	.58	<.010	1.043	-10.70
06429500	Cold Springs Creek	.01	.800	11	.70	<.010	.722	11.65
06430770	Spearfish Creek near Lead	.72	<.010	7	.99	<.010	3.858	-68.63
06430850	Little Spearfish Creek	.53	.017	7	.93	<.010	1.450	-19.32

Graphs showing relations between annual streamflow and precipitation for crystalline core basins are presented in figure 43. 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 r^2 values range from 0.52 for Beaver Creek (06402430) to 0.87 for Bear Gulch (06405800), and are much higher as a group than for the limestone headwater basins (table 6), which is consistent with larger variability in flow characteristics (figs. 40-42).

An exponential regression curve, along with the corresponding equation and r^2 value, also is shown on each graph in figure 43. 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, which is indicated for many of the linear regression equations.

Each graph in figure 43 also includes a curve labeled "runoff efficiency prediction," which is derived from linear regression equations of runoff efficiency as a function of precipitation. Runoff efficiency (the ratio of annual basin yield to precipitation) represents the percentage of annual precipitation returned as streamflow. Runoff efficiency regression lines for the 12 representative crystalline core basins are shown in figure 44; regression equations were presented by Driscoll and Carter (2001). Figure 44 indicates that within each basin, runoff efficiency increases with increasing annual precipitation, and that basins with higher precipitation generally have higher efficiencies.

The runoff efficiency predictions (fig. 43) are derived by substituting values for annual precipitation into the runoff efficiency regression equations. Runoff efficiency predictions are unrealistic (slightly negative) for very low precipitation values, but are consistently positive for the measured ranges of precipitation and also closely resemble the linear regression equations (streamflow versus precipitation) through this range.

Relations between streamflow and precipitation for the two loss-zone basins are presented in figure 45. 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 are shown for each basin, which provide reasonable fits for the nonlinear data.

Regression statistics (annual streamflow versus precipitation) for artesian spring basins are summarized in table 7. Regression equations, which are not meaningful because of low r^2 values and p-values greater than 0.05, are not provided. Weak correlations are consistent with small variability in flow characteristics (figs. 40-42) associated with ground-water discharge and with long ground-water residence times. Naus and others (2001) concluded that large proportions of springflow for several of the representative artesian springs have residence times exceeding 50 years.

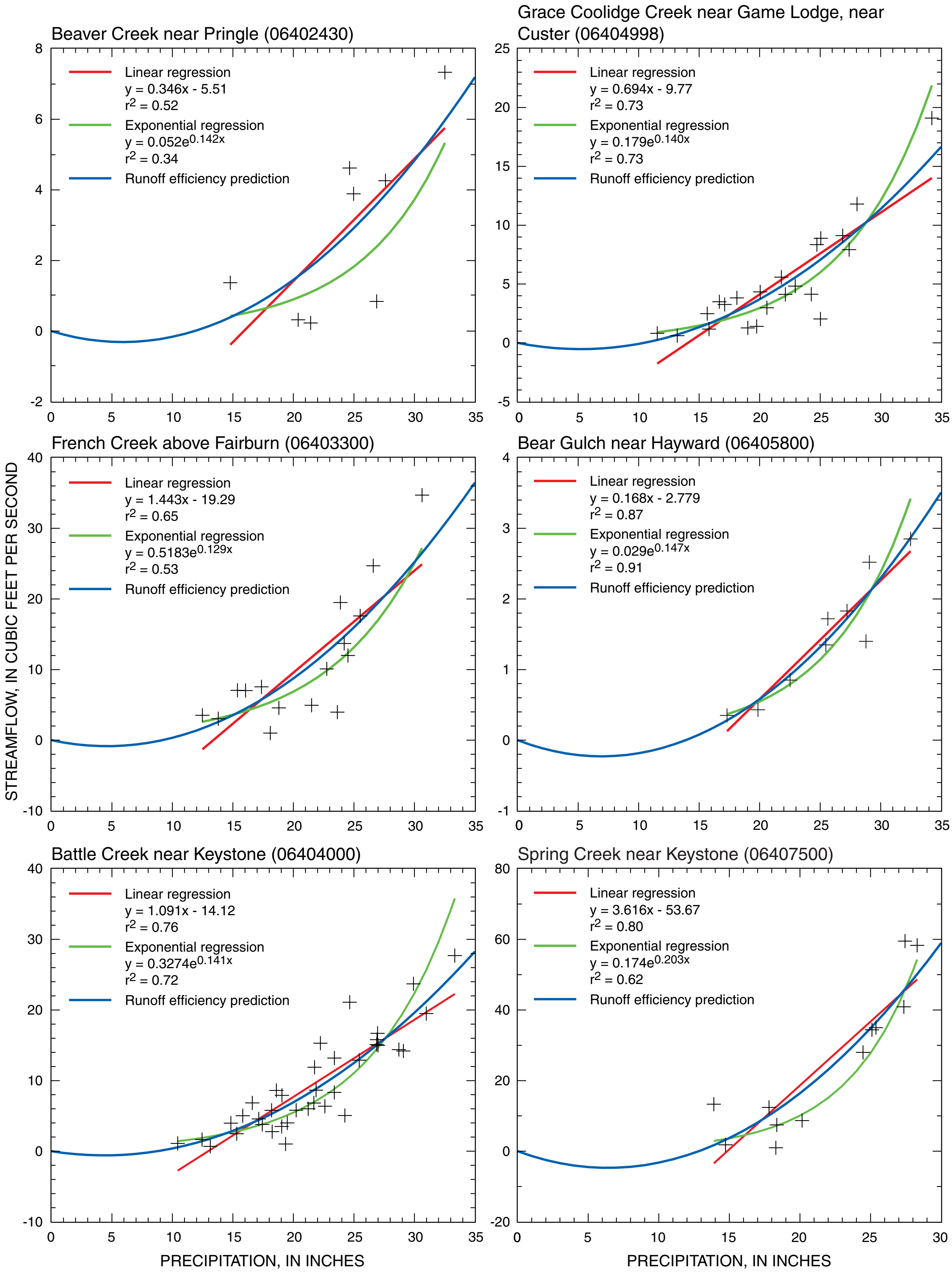
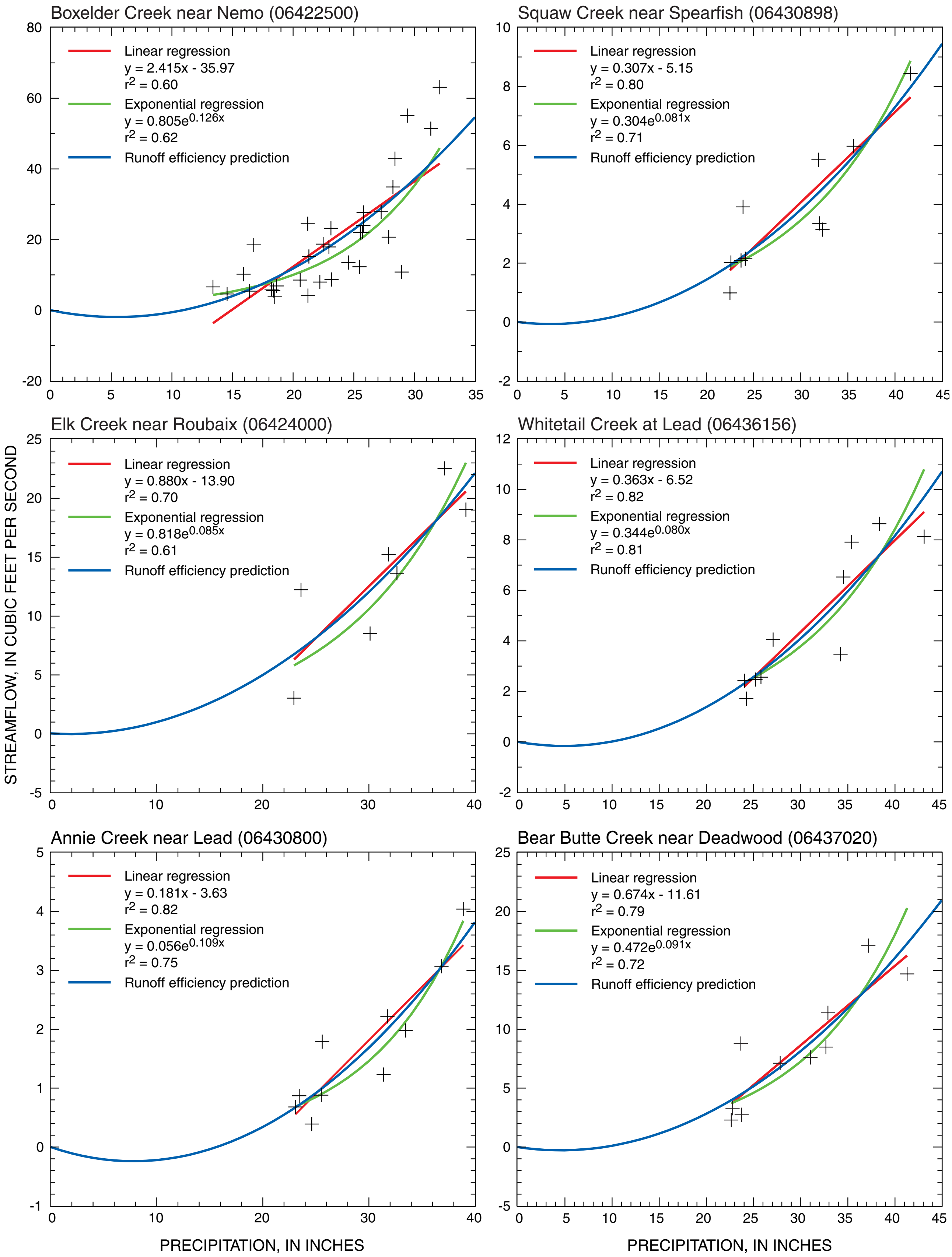


Figure 43. Relations between annual streamflow and precipitation for crystalline core basins (from Driscoll and Carter, 2001).


Boxelder Creek near Nemo (06422500)

Squaw Creek near Spearfish (06430898)

Elk Creek near Roubaix (06424000)

Whitetail Creek at Lead (06436156)

Annie Creek near Lead (06430800)

Bear Butte Creek near Deadwood (06437020)

Figure 43. Relations between annual streamflow and precipitation for crystalline core basins (from Driscoll and Carter, 2001).—Continued

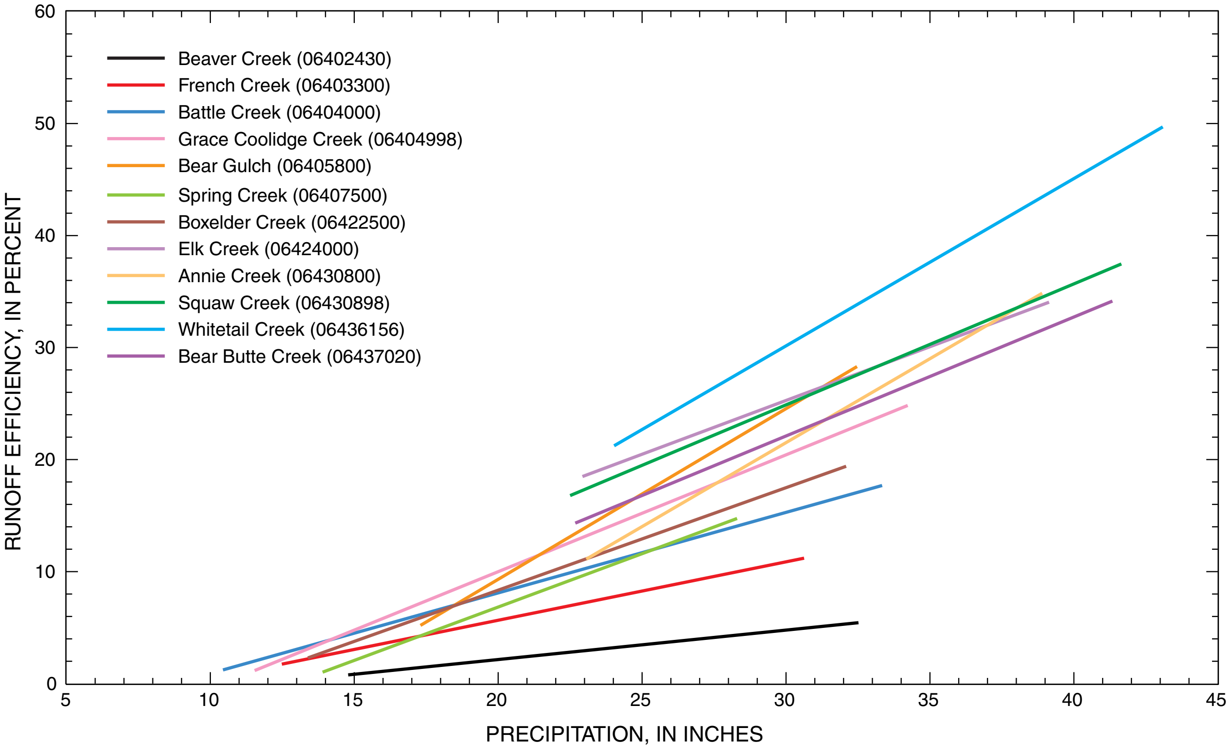


Figure 44. Relations between annual runoff efficiency and precipitation for crystalline core basins (from Driscoll and Carter, 2001).

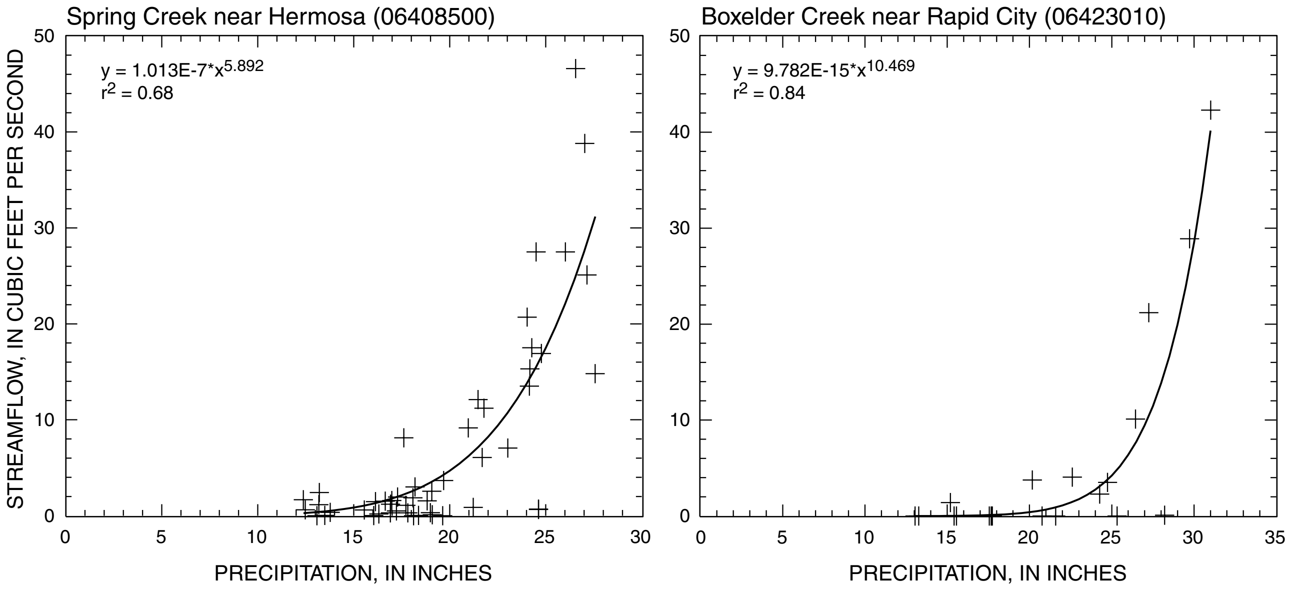


Figure 45. Relations between annual streamflow and precipitation for loss zone basins (from Driscoll and Carter, 2001).

Table 7. Summary of regression information for artesian spring basins

[Regression information (from Driscoll and Carter, 2001) is provided for streamflow as a function of annual precipitation]

Station number	Station name	Annual precipitation	
		r^2	p-value
06392950	Stockade Beaver Creek	0.16	0.135
06400497	Cascade Springs	.07	.289
06402000	Fall River	.003	.660
06402470	Beaver Creek above Buffalo Gap	.49	.079
06429905	Sand Creek	.04	.481
06430532	Crow Creek	.39	.185
06430540	Cox Lake	.55	.152

Driscoll and Carter (2001) identified a distinctive temporal trend in streamflow for the Fall River, which is composed almost entirely of artesian springflow. Peterlin (1990) investigated possible causes for declining streamflow that occurred during about 1940-70 (fig. 46), but did not conclusively determine causes. Wet climatic conditions during the 1990's have resulted in increased streamflow.

Relations between annual flow and precipitation for representative exterior basins are presented in figure 47. The p-values indicate that all correlations are statistically significant; however, the r^2 values generally are weak, relative to r^2 values for linear regressions for the crystalline core basins (fig. 43). A probable explanation is that crystalline core basins generally have larger base-flow components than exterior basins (table 5), which apparently are strongly influenced by annual precipitation amounts. In contrast, exterior basins are dominated by direct runoff, which is more responsive to event-oriented factors such as precipitation intensity.

Relations between annual runoff efficiency and precipitation for exterior basins are shown in figure 48. Runoff efficiencies generally increase with increasing precipitation, but efficiencies generally are lower than for the crystalline core basins (fig. 44) because of generally lower precipitation, increased evaporation potential, and minor irrigation withdrawals.

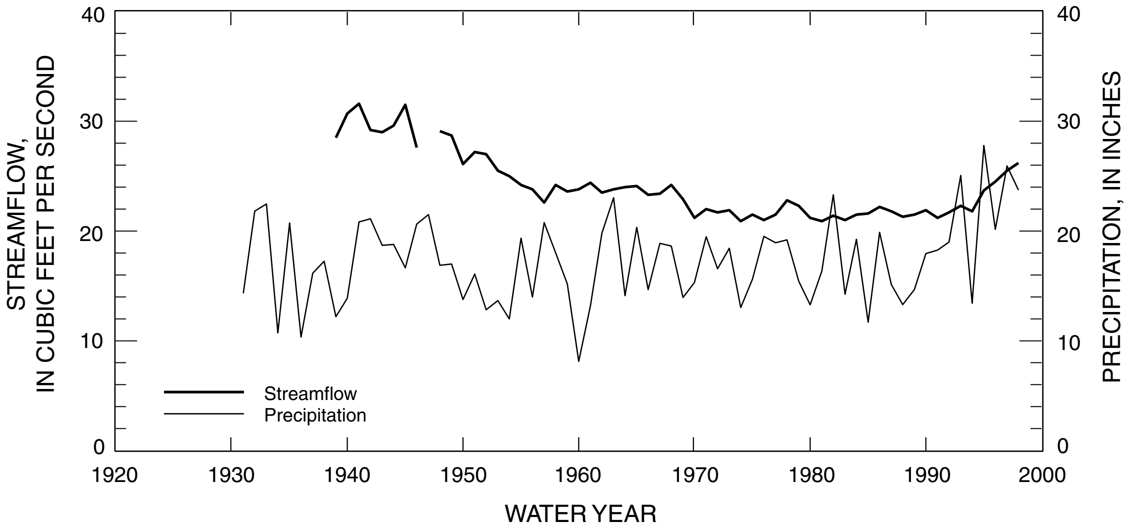


Figure 46. Long-term trends in annual streamflow for station 06402000 (Fall River near Hot Springs), relative to annual precipitation.

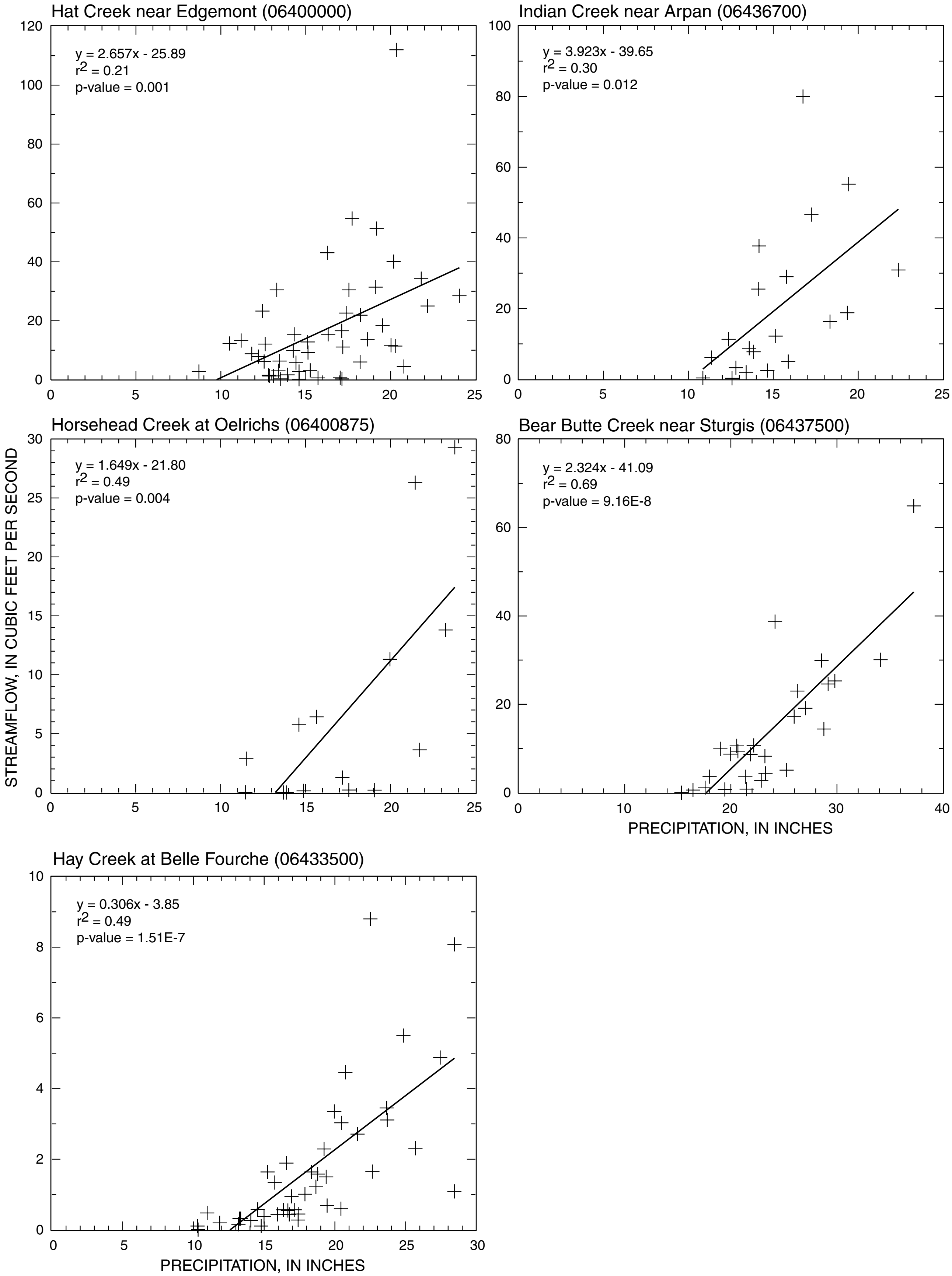


Figure 47. Relations between annual streamflow and precipitation for exterior basins (from Driscoll and Carter, 2001).

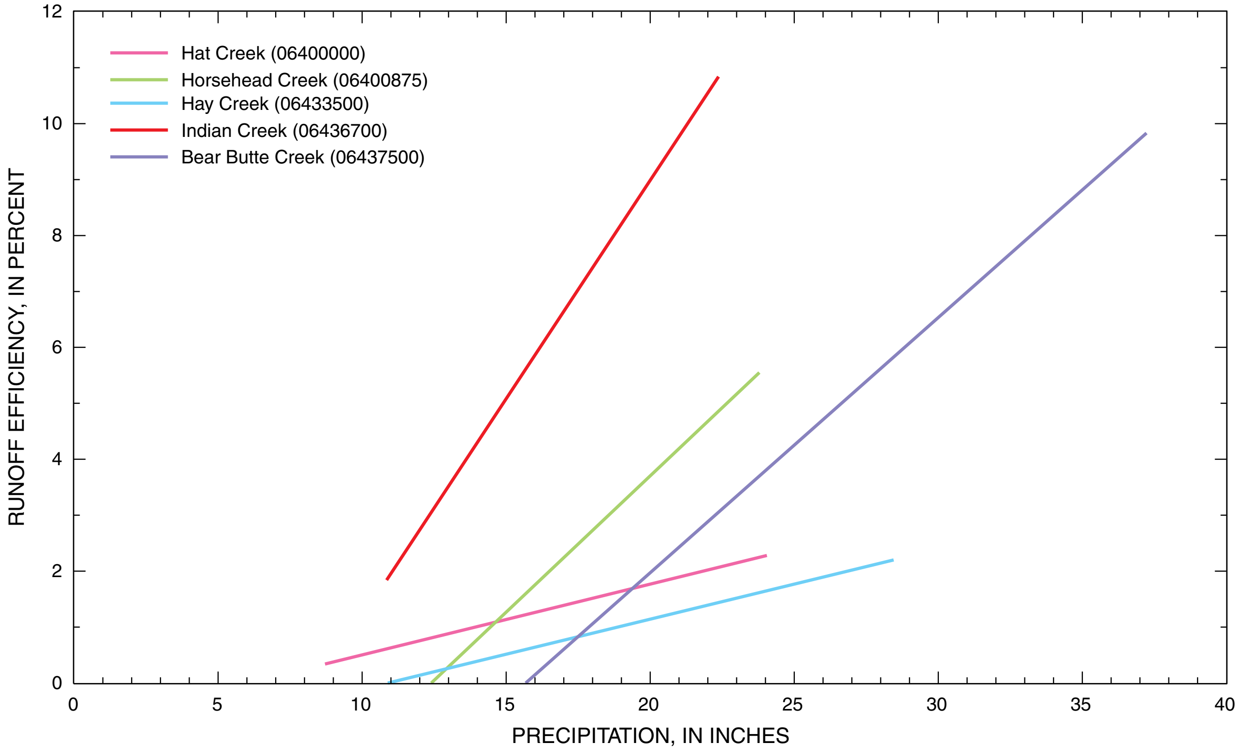


Figure 48. Relations between annual runoff efficiency and precipitation for exterior basins (from Driscoll and Carter, 2001).

Annual Yield

Annual yield characteristics are highly variable throughout the study area, primarily because of orographic effects, which influence both precipitation and evapotranspiration. Selected information for gages used for analysis of basin yield is presented in table 8. With the exception of site 2 (station 06395000, Cheyenne River), all of the sites considered are representative gages for either the limestone headwater, crystalline core, or exterior hydrogeologic settings (table 5). Two of the representative gages from these settings (stations 06405800, Bear Gulch and 06436700, Indian Creek) are excluded because annual yields may not be representative of areal conditions (Driscoll and Carter, 2001). All of the loss zone and artesian spring gages also are excluded.

Mean annual basin yields that are based on surface drainage areas for periods of measured record for selected gages are shown in figure 49. The largest yields occur in high-altitude areas of the northern Black Hills that receive large annual precipitation (fig. 4).

Large differences in annual yields are apparent for several of the limestone headwater basins, which results from incongruences between contributing ground- and surface-water areas. Mean annual yields for the four limestone headwater basins in South Dakota (sites 10, 11, 15, and 17; fig. 49) were estimated by Carter, Driscoll, Hamade, and Jarrell (2001) based on contributing ground-water areas. The contributing ground-water areas (fig. 50) were delineated by Jarrell (2000), based primarily on the structural orientation of the underlying Ordovician and Cambrian rocks. For the two limestone headwater basins in Wyoming (sites 1 and 14), relatively low yields indicate that contributing ground-water areas probably are smaller than the associated surface-water areas; however, estimates of contributing areas are not available.

Table 8. Summary of information used in analysis of yield characteristics

[From Driscoll and Carter (2001). --, not applicable]

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

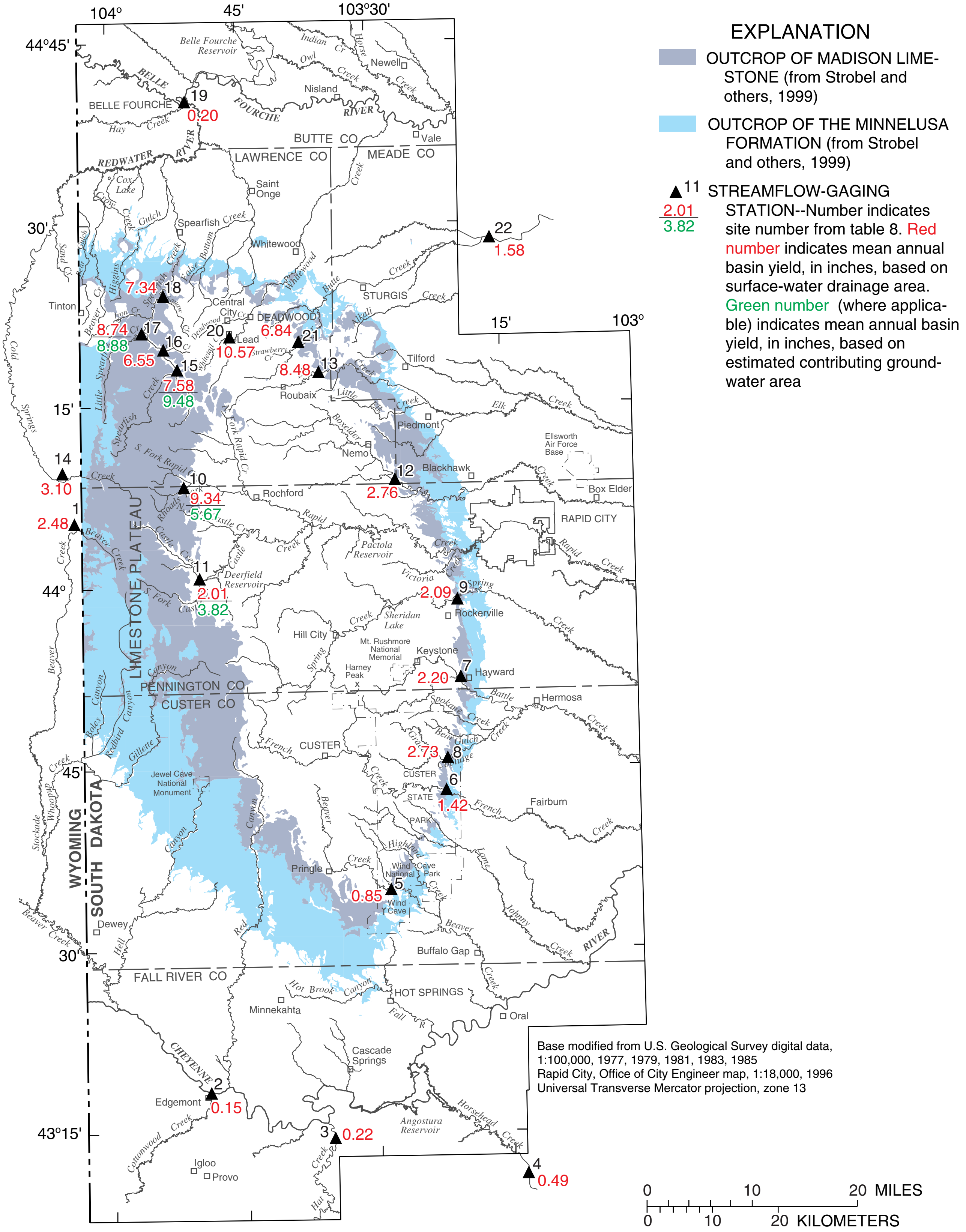
[4] Contributing areas for surface water and ground water probably not congruent; however, no estimates available.

[5] Estimated using average runoff efficiency for the available period of record.

[6] Period of record sufficient for computation of yield efficiency.

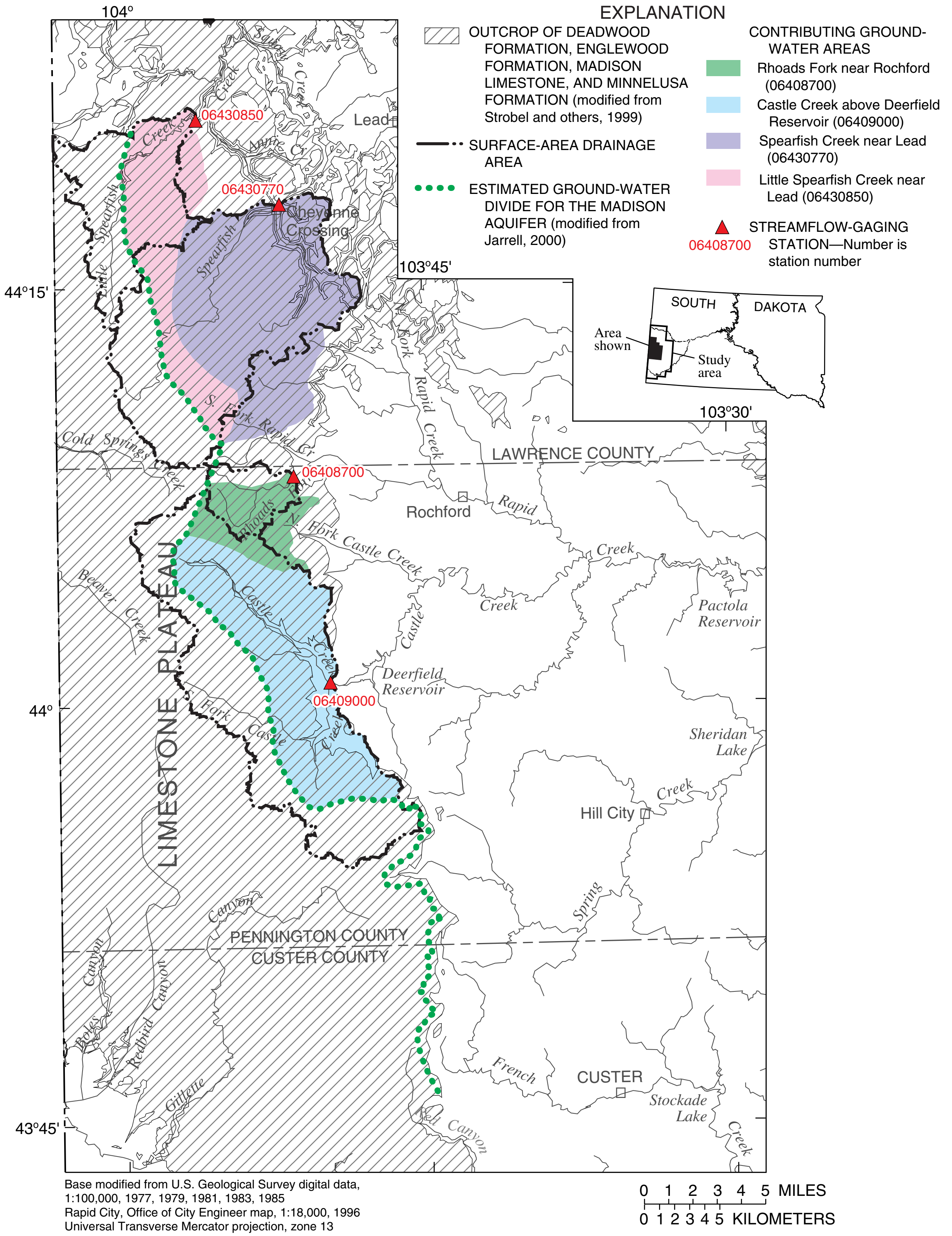
[7] A flow of 10 cubic feet per second has been added to the measured streamflow to account for diverted flow.

[8] Approximate drainage area below loss zone. Actual drainage area is 192 square miles.



Base modified from U.S. Geological Survey digital data,
1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996
Universal Transverse Mercator projection, zone 13

Figure 49. Basin yields for selected streamflow-gaging stations. For some stations, basin yields that are based on contributing ground-water areas estimated by Jarrell (2000) also are shown. Basin yields are for periods of record, which are not the same for all stations.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996
Universal Transverse Mercator projection, zone 13

Figure 50. Comparison between surface-drainage areas and contributing ground-water areas for streamflow-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.

The approximate location of a ground-water divide that was identified by Jarrell (2000) also is shown in figure 50. This divide coincides with the western extent of the contributing ground-water areas for the four gaging stations that are shown. West of the ground-water divide, infiltration of precipitation results in ground-water recharge that is assumed to flow to the west, contributing to regional flowpaths in the Madison and Minnelusa aquifers that wrap around the northern or southern flanks of the uplift (fig. 17). East of the divide, recharge is assumed to contribute to headwater springflow along the eastern flank of the Limestone Plateau.

The ground-water divide extends about 10 mi south of the Castle Creek Basin and approximately coincides with the western extent of the Spring and French Creek drainage areas in this vicinity. The ground-water divide is not defined south of this point because the surface drainages contribute to Red Canyon, which flows to the south and provides streamflow recharge to the Madison and Minnelusa aquifers along the western flank of the uplift. Westerly ground-water flow directions are not possible immediately north of the ground-water divide because the Madison and Minnelusa aquifers are absent in the vicinity of Tertiary intrusive units (fig. 14).

After adjusting for contributing ground-water areas, annual yields for the limestone headwater basins (table 8; fig. 49) generally are consistent with a pattern of increasing yields corresponding with increasing annual precipitation (fig. 4). Adjusted yields for limestone headwater basins, which are dominated by ground-water discharge, also are generally similar to yields for nearby streams that are dominated by surface influences. These similarities were used by Carter, Driscoll, and Hamade (2001) in developing a method for estimating precipitation recharge to the Madison and Minnelusa aquifers. An important initial assumption was that in areas of comparable precipitation, evapotranspiration in outcrops of the Madison and Minnelusa Formations is similar to evapotranspiration for crystalline core settings, where recharge to regional flow systems is considered negligible. A further assumption was made that direct runoff is negligible for Madison and Minnelusa outcrops, which is supported by the daily flow characteristics for the limestone headwater setting. These assumptions resulted in a concept that streamflow yield in the crystalline core setting 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 51.

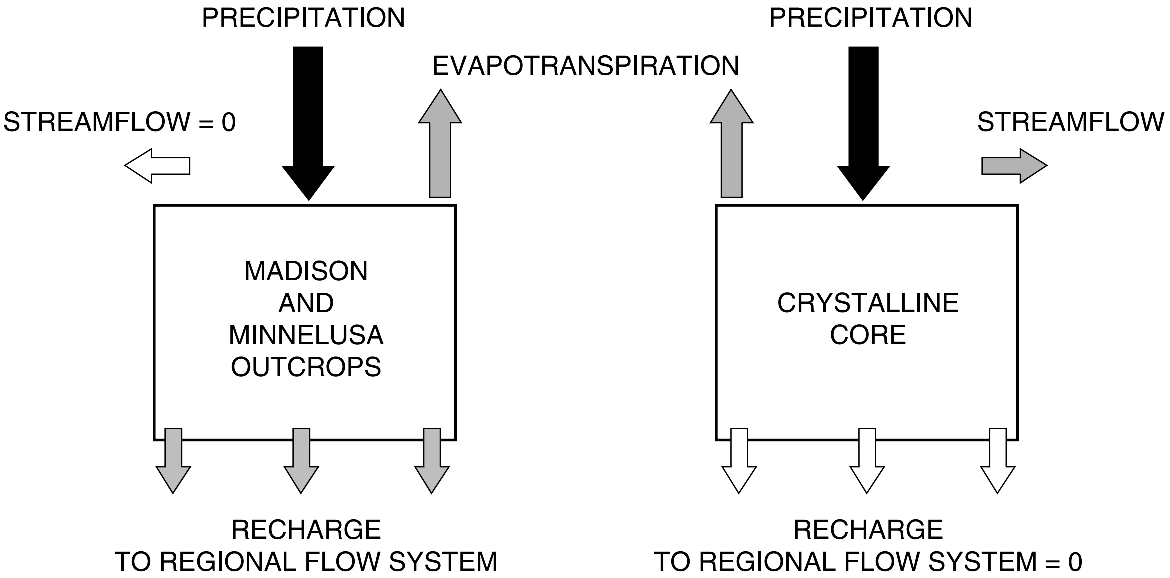


Figure 51. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types (from Carter, Driscoll, and Hamade, 2001).

Carter, Driscoll, and Hamade (2001) used estimates of average runoff efficiencies for 1950-98 to develop a map of generalized yield efficiency for the study area (fig. 52). Where applicable, estimated yield efficiencies shown in figure 52 are representative of estimated yield efficiencies for the contributing ground-water areas. For basins where contributing surface- and ground-water areas are assumed to be congruent, yield efficiency is considered equivalent to runoff efficiency. For areas where direct runoff is negligible, yield efficiency is considered equivalent to the efficiency of precipitation recharge. For many gages, estimation of average yield efficiencies for this period required extrapolation of incomplete streamflow records (table 5) using precipitation records. Records were extrapolated to compensate for bias resulting from short-term records for many gages that are skewed towards wet climatic conditions during the 1990's. Yield efficiencies for most of the limestone headwater gages are simply averages for the available periods of record, because relations between streamflow and precipitation for this setting generally are very weak or unrealistic.

Carter, Driscoll, and Hamade (2001) also considered precipitation patterns and topography in contouring yield efficiencies, which provide a reasonable fit with calculated efficiencies (fig. 52). Estimates of contributing areas are not available for the two limestone headwater gages in Wyoming (sites 1 and 14); thus, yield efficiencies could not be adjusted. 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. 14).

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 5) 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

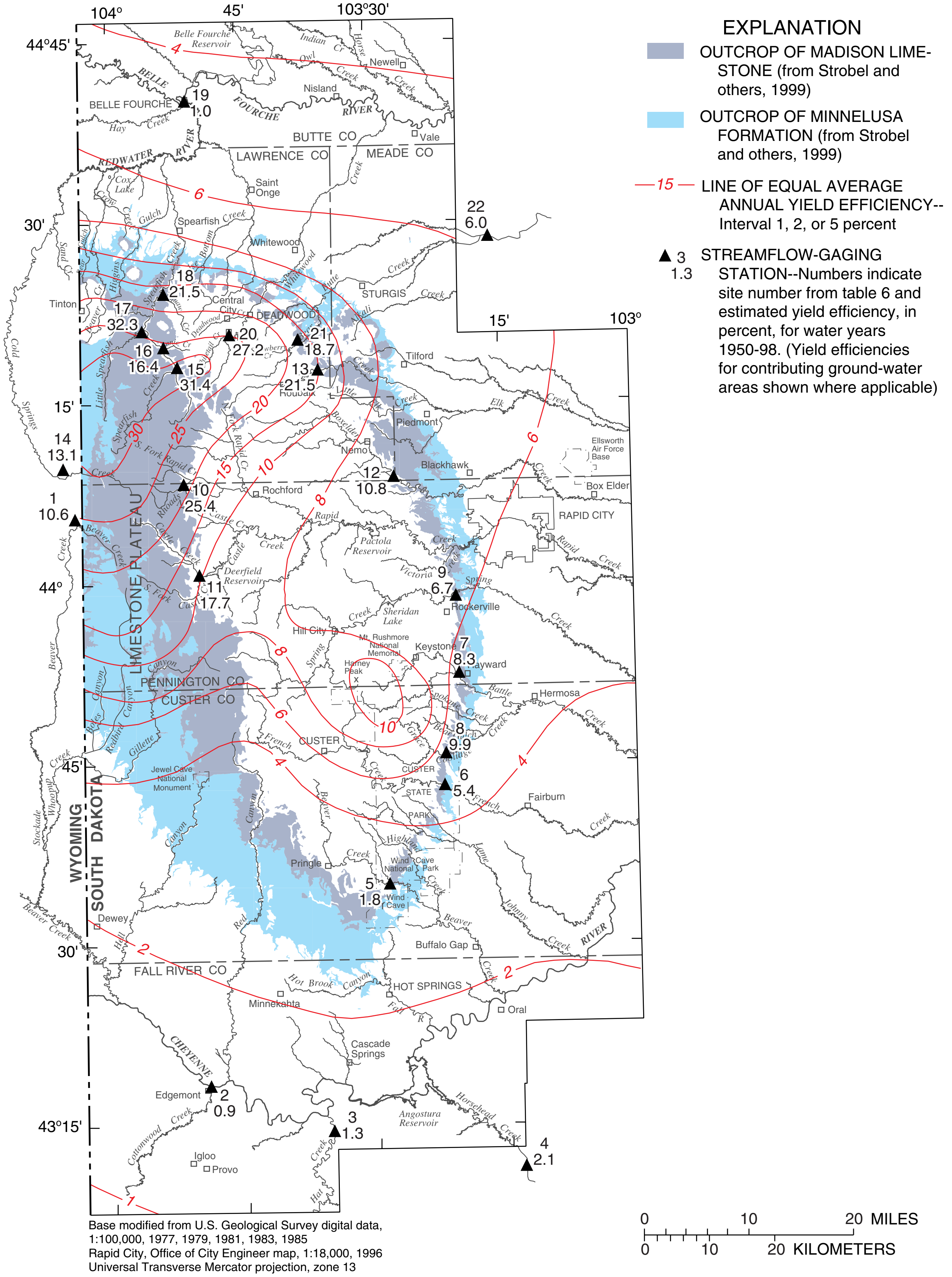
n = exponent.

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 53. 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.

The spatial distribution of average annual yield potential for the Black Hills area is shown in figure 54. 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. 4), and average annual yield efficiency (fig. 53). 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 used later in this report.

Water Quality

This section summarizes water-quality characteristics for surface water within the study area. More detailed discussions are presented by Williamson and Carter (2001). Standards and criteria that apply to surface waters are presented in the following section, after which common-ion characteristics, anthropogenic effects on water quality, and additional factors relative to in-stream standards are discussed.



EXPLANATION

▨ OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)

▨ OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)

—15— LINE OF EQUAL AVERAGE ANNUAL YIELD EFFICIENCY--Interval 1, 2, or 5 percent

▲ 3 1.3 STREAMFLOW-GAGING STATION--Numbers indicate site number from table 6 and estimated yield efficiency, in percent, for water years 1950-98. (Yield efficiencies for contributing ground-water areas shown where applicable)

Base modified from U.S. Geological Survey digital data,
1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996
Universal Transverse Mercator projection, zone 13

Figure 52. Generalized average annual yield efficiency (in percent of annual precipitation), water years 1950-98 (from Carter, Driscoll, and Hamade, 2001).

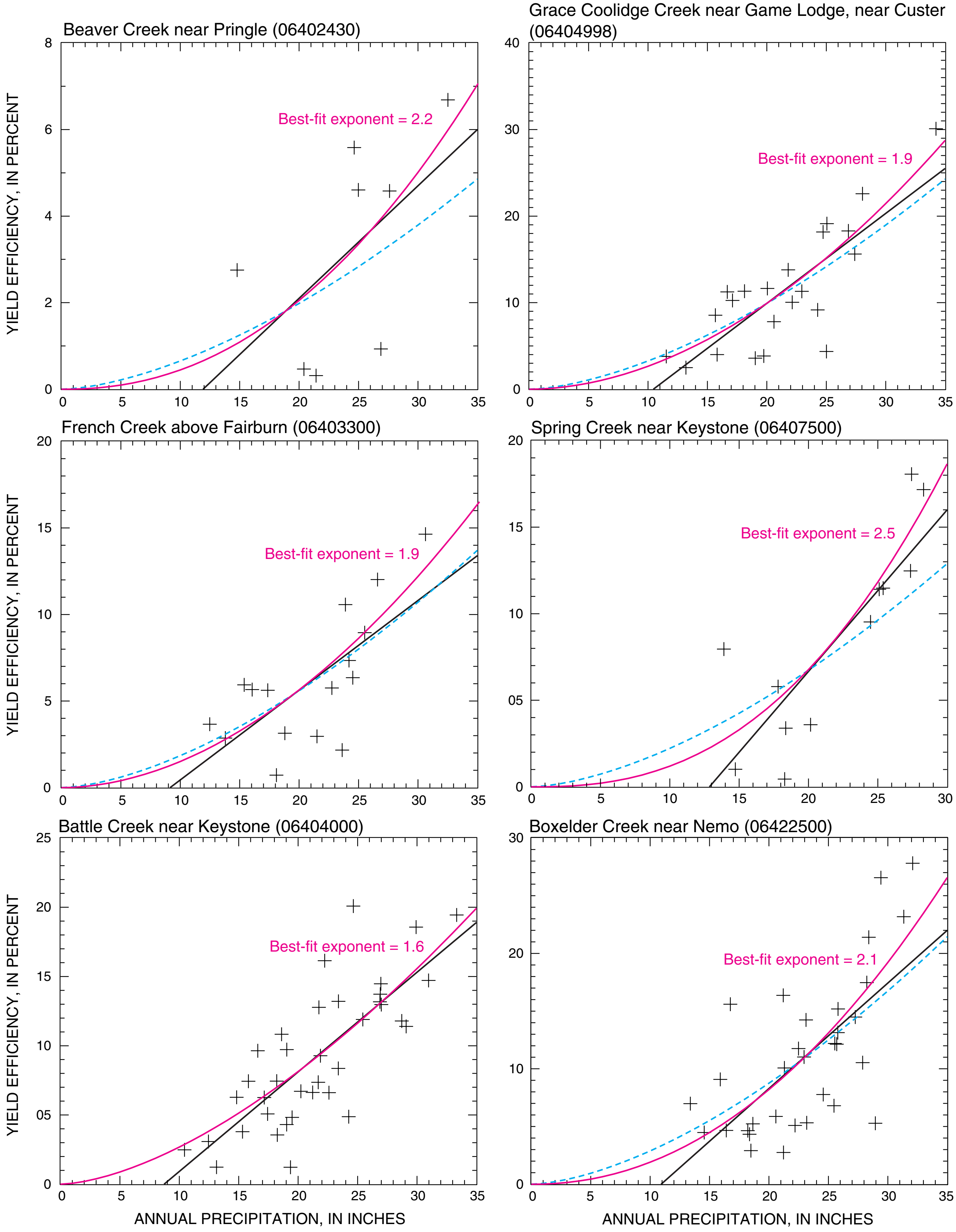


Figure 53. Relations between yield efficiency and precipitation for selected streamflow-gaging stations (modified from Carter, Driscoll, and Hamade, 2001).

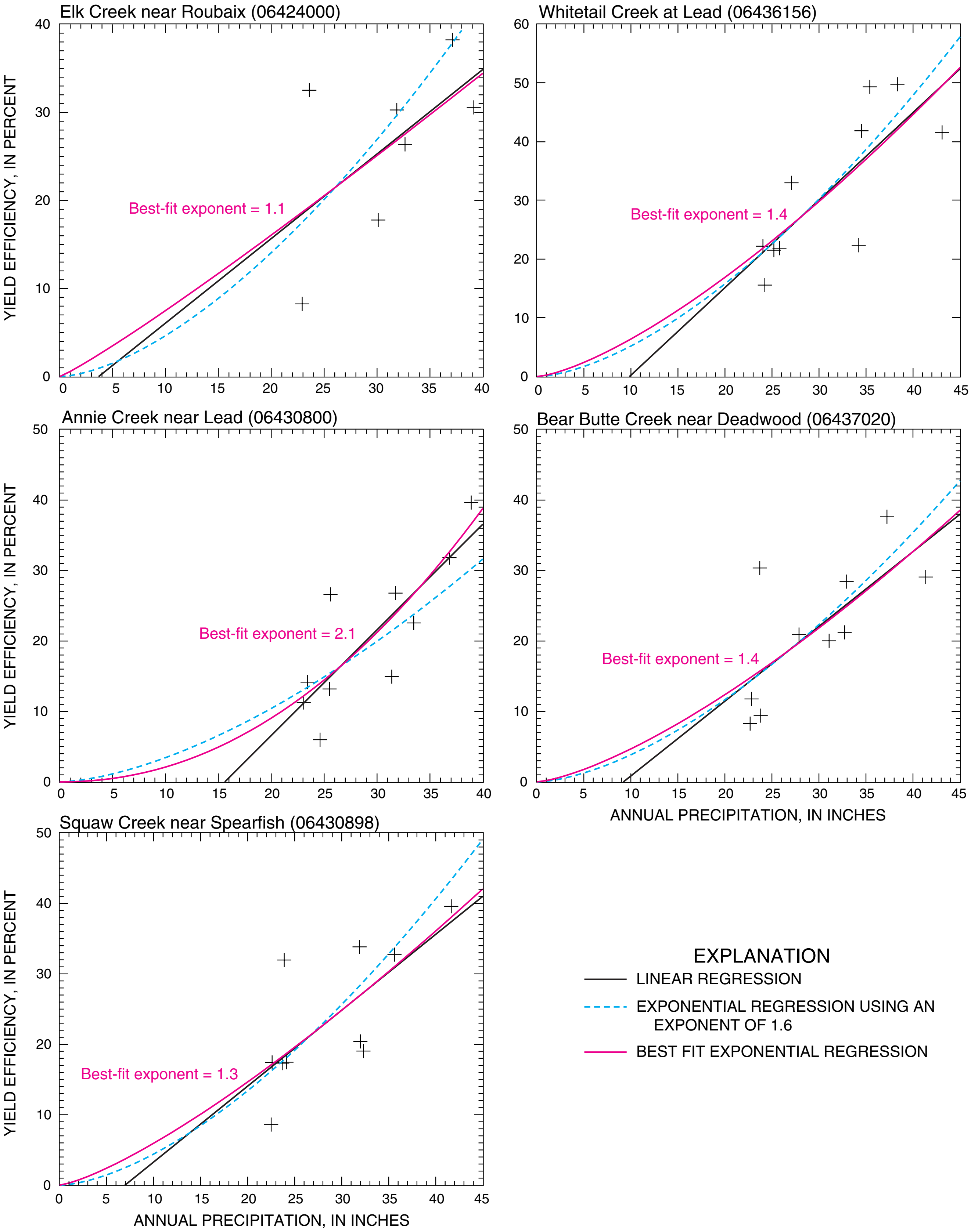
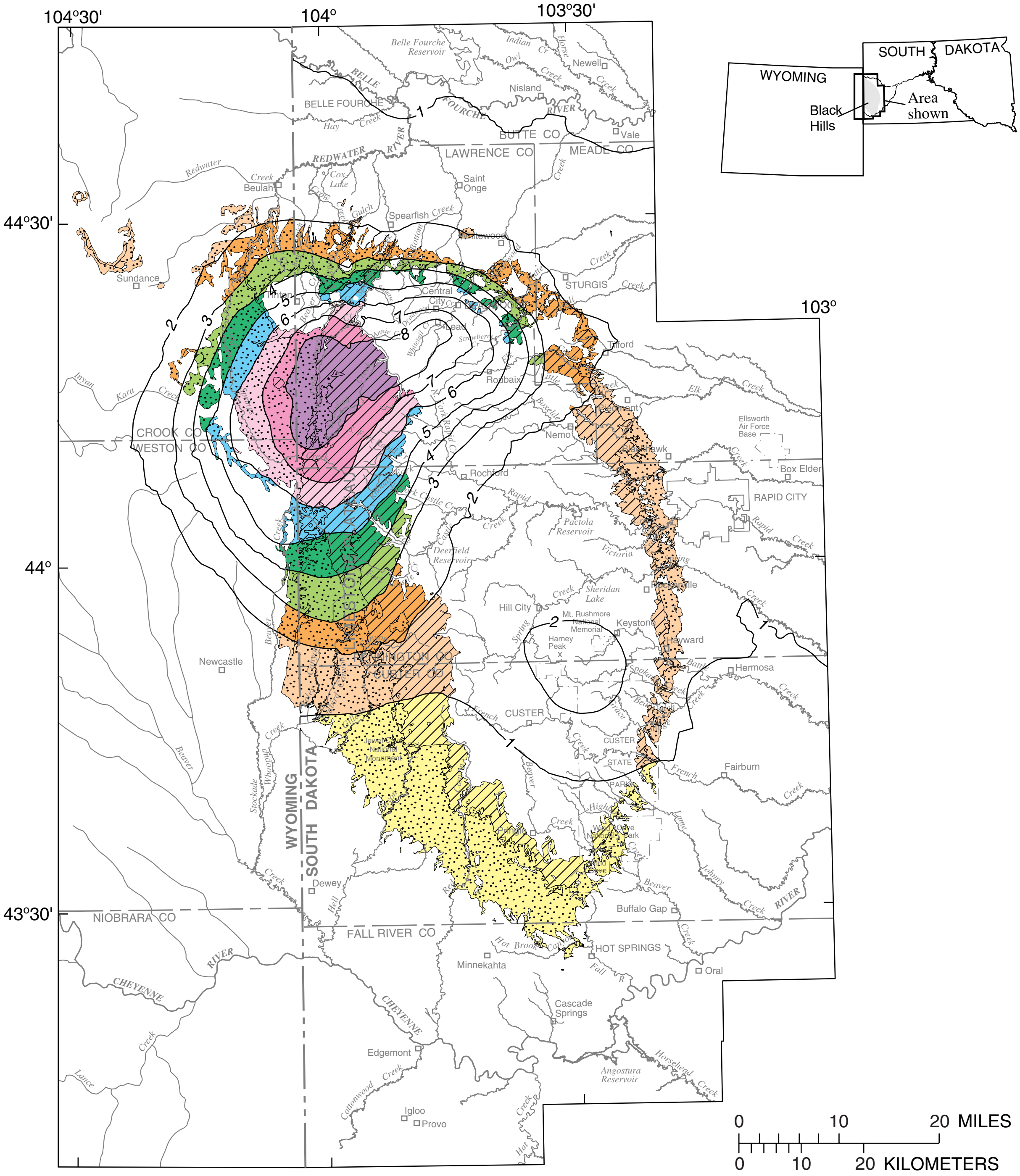


Figure 53. Relations between yield efficiency and precipitation for selected streamflow-gaging stations (modified from Carter, Driscoll, and Hamade, 2001).—Continued



Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

EXPLANATION

▨ CONNECTED OUTCROP OF MADISON LIMESTONE FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED (modified from Strobel and others, 1999; DeWitt and others, 1989)

⁙ CONNECTED OUTCROP OF MINNELUSA FORMATION FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED (modified from Strobel and others, 1999; DeWitt and others, 1989)

—2— LINE OF EQUAL YIELD POTENTIAL--Number indicates average annual yield potential. Interval 1 inch

AVERAGE ANNUAL RECHARGE, IN INCHES

🟨 Less than 1
🟧 1 to 2
🟧 2 to 3
🟩 3 to 4
🟩 4 to 5
🟦 5 to 6
🟪 6 to 7
🟪 7 to 8
🟪 8 to 9

Figure 54. 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.