## Contents

**Summary of Major Findings** .................................................................................................................. 1  
- Precipitation ......................................................................................................................................... 1  
- Ground Water ...................................................................................................................................... 1  
- Surface Water ..................................................................................................................................... 2  
- Water Quality ..................................................................................................................................... 2  
- Hydrologic Budgets ............................................................................................................................ 3  

**Introduction** ........................................................................................................................................... 4  
- Purpose and Scope ................................................................................................................................ 4  
- Description of Study and Study Area ....................................................................................................... 4  
- Overview of Study .................................................................................................................................. 4  
- Description of Study Area ....................................................................................................................... 8  

**Hydrologic Processes and Framework** ................................................................................................. 10  
- Hydrologic Processes ............................................................................................................................ 10  
- Local Hydrologic Framework .................................................................................................................. 12  
- Climate .................................................................................................................................................. 12  
- Geology .................................................................................................................................................. 15  
- Ground Water ....................................................................................................................................... 24  
- Surface Water ....................................................................................................................................... 26  
- Regional Ground-Water Framework ......................................................................................................... 35  

**Water Resources** ................................................................................................................................... 36  
- Ground-Water Resources ....................................................................................................................... 36  
- Characteristics of Major Aquifers ........................................................................................................... 38  
- Overview of Other Aquifers ..................................................................................................................... 55  
- Ground-Water Levels .............................................................................................................................. 55  
- Temporal Trends ..................................................................................................................................... 56  
- Comparisons between Madison and Minnelusa Aquifers ...................................................................... 57  
- Comparisons for Other Aquifers ............................................................................................................. 58  
- Responses to Climatic Conditions .......................................................................................................... 59  
- Ground-Water Quality .............................................................................................................................. 59  
- Background .......................................................................................................................................... 59  
- General Characteristics for Major Aquifers ............................................................................................. 63  
- General Characteristics for Minor Aquifers ............................................................................................. 70  
- Susceptibility to Contamination ............................................................................................................. 71  
- Ground-Water Quality Relative to Water Use ....................................................................................... 72  
- Surface-Water Resources ....................................................................................................................... 72  
- Streamflow Characteristics ...................................................................................................................... 72  
- Streamflow Variability ............................................................................................................................ 73  
- Annual Yield Characteristics .................................................................................................................... 75  
- Surface-Water Quality ............................................................................................................................ 80  
- Standards and Criteria ............................................................................................................................ 80  
- General Characteristics ........................................................................................................................... 82  
- Human Influences on Water Quality ....................................................................................................... 86  
- Surface-Water Quality Relative to Water Use ....................................................................................... 92  

**Hydrologic Budgets** ................................................................................................................................. 94  
- Methods for Estimating Basin Yield and Recharge ................................................................................. 94  
- Ground-Water Budgets ........................................................................................................................... 95  
- Surface-Water Budgets ........................................................................................................................... 100  
- Combined Ground-Water and Surface-Water Budget .......................................................................... 100  

**Madison and Minnelusa Flow System** .................................................................................................... 102  
- Flowpaths ........................................................................................................................................... 102  
- Springs ................................................................................................................................................... 108  

**Future Information Needs** ..................................................................................................................... 113  

**References** .............................................................................................................................................. 114  

**Definition of Terms** ................................................................................................................................. 118
Figures

1. Map showing area of investigation for the Black Hills Hydrology Study .......................................................... 4
2. Map showing data-collection network for the Black Hills Hydrology Study ..................................................... 6
3. Graph showing population growth, by county, for incorporated and unincorporated areas ................................... 8
4. Photographs of Calamity Peak near Custer and large-scale mines ................................................................. 8
5. Map showing distribution of 1890 land use in the Black Hills area ................................................................. 9
6. Schematic diagram illustrating hydrologic processes ......................................................................................... 10
7. Schematic diagram showing (A) porosity and permeability, and (B) aquifers and confining beds .......................... 11
8. Photograph of development of the Lime Creek observation well ..................................................................... 11
9. Map showing monthly precipitation distribution for October 1995 ................................................................. 12
10. Map showing distribution of average annual precipitation for the Black Hills area, water years 1950-98 .................. 13
11. Boxplots showing distribution of annual precipitation for the study area and counties within the study area, water years 1931-98 .................................................................................. 13
12. Boxplots and pie chart showing distribution of monthly precipitation and average annual precipitation ............. 14
13. Graph showing mean monthly precipitation for the study area and selected counties, water years 1931-98 .......... 14
14. Graphs showing long-term trends in precipitation for the Black Hills area, water years 1931-98 ......................... 14
15. Stratigraphic column for the Black Hills ......................................................................................................... 16
16. Photograph of folds and fractures in Precambrian rock near Rechford ............................................................. 16
17. Schematic diagrams and photographs showing (A) anticline and syncline, (B) monocline, (C) fault, and (D) dome ...................................................................................................................... 17
18. Photograph of Bear Butte ........................................................................................................................................ 17
19. Map showing distribution of hydrogeologic units ............................................................................................. 18
20. Geologic cross section A-A’ ........................................................................................................................... 19
22. The Madison Limestone .................................................................................................................................... 20
23. Large cave openings in the Madison Limestone at Jewel Cave ................................................................. 20
24. The Minnelusa Formation .............................................................................................................................. 21
25. Collapse breccia and a breccia pipe in the Minnelusa Formation ................................................................. 21
26. The Minnekahta Limestone ............................................................................................................................ 22
27. Red cliffs of the Spearfish Formation ............................................................................................................... 22
28. Massive gypsum and a sinkhole in the Spearfish Formation ............................................................................. 22
29. The Inyan Kara Group .................................................................................................................................... 23
30. Schematic diagram showing simplified hydrologic setting of the Black Hills area ........................................... 24
31. Photographs of cave lakes ................................................................................................................................... 25
32. Photograph of Cox Lake ....................................................................................................................................... 26
33. Photograph of the Pierre Shale ......................................................................................................................... 26
34. Map showing hydrogeologic settings for the Black Hills area ........................................................................... 27
35. Photographs of headwater springflow along Beaver Creek and Cold Springs Creek .................................... 28
36. Photograph of headwater springflow along Rhoads Fork ................................................................................ 29
37. Schematic diagram showing various spring types found in the limestone headwater area ................................. 29
38. Schematic diagram illustrating interactions between ground water and surface water in the combined loss zone and artesian spring settings ...................................................................................... 30
39. Photographs of: 39. Downstream progression of channel conditions along Grace Coolidge Creek .................. 31
40. Ash bars and large deltas of fine-grained sediment following the Galena Fire ............................................. 32
41. Cascade Springs ................................................................................................................................................. 33
42. Artesian springflow along Sand Creek and the Redwater River .................................................................... 33
43. Pactola Reservoir ................................................................................................................................................. 34
44. Maps showing approximate extent of rocks containing regional aquifers in the Northern Great Plains area .......................................................................................................................... 34
45. Map showing general direction of ground-water flow in regional aquifers within Paleozoic rock units ......... 35
46. Photograph of fractured and weathered Precambrian rocks ........................................................................ 36
47. Boxplots showing distribution of well yields from selected aquifers ........................................................... 37
48. Maps showing depth to top of: 48. Deadwood Formation ...................................................................................... 38
49. Madison Limestone ........................................................................................................................................... 39
50. Minnelusa Formation ....................................................................................................................................... 40
51. Minnekahta Limestone ................................................................................................................................... 41
52. Inyan Kara Group ............................................................................................................................................ 42
53. Maps showing generalized thickness of: 53. Deadwood Formation ............................................................... 43
54. Madison Limestone and Englewood Formation ................................................................................................. 44
55. Minnelusa Formation ........................................................................................................................................ 45
56. Minnekahta Limestone ..................................................................................................................................... 46
57. Inyan Kara Group ............................................................................................................................................... 47
58. Maps showing potentiometric surface of: 58. Deadwood aquifer ............................................................................... 48
59. Madison aquifer and locations of major artesian springs .............................................................................. 49
60. Minnelusa aquifer and locations of major artesian springs ........................................................................... 50
61. Minnekahta aquifer .......................................................................................................................................... 51
62. Inyan Kara aquifer ............................................................................................................................................ 52
63. Maps showing saturated thickness of the Madison aquifer ............................................................................ 53
64. Map showing saturated thickness of the Minnekahta aquifer ........................................................................ 54
65. Map showing location of observation wells for which hydrographs are presented .................................... 55
Figures—Continued

66-70. Hydrographs illustrating:
66. Temporal trends in ground-water levels .......................................................... 56
67. General similarities in water levels for some colocated Madison/Minnelusa wells with
confined conditions ............................................................................................... 57
68. Large hydraulic separation for colocated Madison/Minnelusa wells with unconfined conditions .......................... 57
69. Generally separated water levels for some colocated Madison/Minnelusa wells ............... 58
70. Colocated Minnelusa/Minnekahta and Deadwood/Madison wells .................. 58

71-77. Maps showing:
71. Water temperature in the Madison aquifer ..................................................... 63
72. Specific conductance in the Madison aquifer .................................................. 64
73. Specific conductance in the Minnelusa aquifer ............................................... 65
74. Specific conductance in the Inyan Kara aquifer ............................................ 66
75. Hardness in the Inyan Kara aquifer ................................................................. 67
76. Sulfate concentrations in the Minnelusa aquifer ............................................. 68
77. Radon concentrations in the Deadwood aquifer ............................................. 69

78. Boxplots of concentrations of nitrite plus nitrate for selected aquifers ............... 70
79. Photographs of potential sources of nitrogen in ground water ....................... 71
80. Graphs showing duration curves of daily mean streamflow ......................... 73
81. Graphs showing variations in mean monthly streamflow for basins representative of
hydrogeologic settings ........................................................................................ 74
82. Map showing basin yields for selected streamflow-gaging stations ................ 75
83. Map showing comparison between surface-drainage areas and contributing ground-water
areas for streamflow-gaging stations in Limestone Plateau area ....................... 76
84. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types . . . . . . . . . 77
85. Map showing generalized average annual yield efficiency, water years 1950-98 .......... 78
86. Map showing estimated annual yield potential for the Black Hills area, water years 1950-98 ... 79
87. Graph showing relations between dissolved solids and specific conductance by hydrogeologic setting ....... 82
88. Graph showing relations between specific conductance and streamflow for a selected
site within each hydrogeologic setting ............................................................... 83
89. Diagrams of median concentrations of common ions by hydrogeologic setting ...... 83
90. Map showing median sulfate concentrations in surface water ....................... 84
91. Map showing median uranium concentrations in surface water .................... 85
92. Photographs of activities that can impact surface-water quality ..................... 86
93. Map showing maximum selenium concentrations in surface water ................ 87
94. Graph showing downstream progression of pH for selected streams influenced by acid-mine drainage .... 88
95. Photographs of an abandoned mine, acid-mine drainage, and a bog-iron area .... 89
96. Graph showing changes in sulfate and sodium concentrations at Bear Butte Creek near Deadwood ............. 89
97. Graph showing comparison of dissolved copper concentrations to hardness-adjusted
chronic and acute aquatic criteria for Bear Butte Creek near Deadwood ............ 89
98. Maps showing maximum arsenic concentrations in surface water ................. 90
99. Graph showing nitrite plus nitrate concentrations in Annie Creek near Lead, 1988-97 .... 91
100. Boxplots of concentrations of dissolved nitrite plus nitrate by hydrogeologic setting,
with Annie Creek separated from other crystalline core sites .......................... 91
101. Boxplots of concentrations of dissolved nitrite plus nitrate within the Rapid Creek Basin . 92
102. Pie chart showing evapotranspiration, runoff, and precipitation recharge as percentages
of annual precipitation ....................................................................................... 94
103. Schematic showing components considered for ground-water budgets .......... 95
104. Photograph of headwater springflow in the Limestone Plateau area ............... 96
105. Photograph of artesian springflow at Evans Plunge ....................................... 96
106. Pie charts showing percentages of average annual budget components for bedrock
aquifers for water years 1950-98 ................................................................. 97
107. Pie charts showing percentages of average annual budget components for the Madison
and Minnelusa aquifers in South Dakota and Wyoming for water years 1950-98 ...... 98
108. Pie chart showing percentages of water use from the Madison and Minnelusa aquifers,
by category, for South Dakota counties in the Black Hills area for water years 1987-96 . . 99
109. Graph showing annual recharge to the Madison and Minnelusa aquifers, in the Black Hills
of South Dakota and Wyoming, water years 1931-98 ................................... 99
110. Photographs of the Cheyenne and Belle Fourche Rivers ............................ 100
111. Schematic diagram showing average hydrologic budget components for the study area,
water years 1950-98 ..................................................................................... 101
112. Schematic diagram showing generalized average streamflow relative to surface geology
and depletion, water years 1950-98 ............................................................... 101
113. Schematic diagram showing fractionation of stable oxygen isotopes ............... 102
114. Map showing generalized flowpaths in the Madison aquifer in the Black Hills area of
South Dakota and Wyoming ........................................................................... 103
115. Graph showing estimated tritium concentrations in precipitation for the Black Hills area
and decay curves for selected years ................................................................. 104
116. Boxplots of tritium concentrations for selected ground-water and surface-water
samples collected during 1990-98 in the Black Hills area .............................. 104
117. Map showing tritium occurrence for selected sample sites in the Black Hills area .. 105
118. Map showing concentrations of δ¹⁸O in Madison and Minnelusa aquifers in the Rapid City area ......................................................... 106
119. Photographs of dye testing along Boeckler Creek ........................................ 107
120. Graph showing long-term streamflow and precipitation trends for gaging station
06409000, Castle Creek above Deerfield Reservoir ..................................... 108
121. Graph showing long-term streamflow trends for gaging station 8402000, Fall River at Hot Springs .......... 109
122. Photograph of red sediment at Cascade Springs .......................................... 110
123. Schematic diagrams illustrating the development and abandonment of an artesian spring
at the Mammoth Site of Hot Springs .......................................................... 111
Tables

1. List of individuals involved with the Black Hills Hydrology Study steering committee ........................................ 5
2. List of U.S. Geological Survey reports published as part of the Black Hills Hydrology Study ........................................ 7
3. Geologic history of the Black Hills area ......................................................................................................................... 15
4. Summary of loss thresholds from Black Hills streams to bedrock aquifers ........................................................................ 31
5. Summary of the characteristics of major aquifers in the study area .................................................................................. 36
6. Water-quality criteria, standards, or recommended limits for selected properties and constituents ................................. 60
7. Surface-water-quality standards for selected physical properties and constituents .......................................................... 81
8. Estimates of average precipitation, precipitation recharge, runoff, total yield, and evapotranspiration for the study area, water years 1950-98 ........................................................................................................ 94
9. Recharge factors and outcrop areas for bedrock aquifers ............................................................................................... 95
10. Average ground-water budgets for bedrock aquifers, water years 1950-98 .................................................................... 96
11. Detailed average hydrologic budgets for the Madison and Minnelusa aquifers, water years 1950-98 ............................. 99
12. Average surface-water budgets for study area, water years 1950-98 .............................................................................. 100
13. Selected hydraulic and chemical information for large artesian springs ................................................................. 109

Conversion Factors and Vertical Datum

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>acre</td>
<td>4,047</td>
<td>square meter</td>
</tr>
<tr>
<td>acre</td>
<td>0.4047</td>
<td>hectare</td>
</tr>
<tr>
<td>acre-foot</td>
<td>1.233</td>
<td>cubic meter</td>
</tr>
<tr>
<td>acre-foot</td>
<td>0.001233</td>
<td>cubic hectometer</td>
</tr>
<tr>
<td>cubic foot per second</td>
<td>0.02832</td>
<td>cubic meter per second</td>
</tr>
<tr>
<td>foot</td>
<td>0.3048</td>
<td>meter</td>
</tr>
<tr>
<td>gallon per minute</td>
<td>0.06309</td>
<td>liter per second</td>
</tr>
<tr>
<td>inch</td>
<td>2.54</td>
<td>centimeter</td>
</tr>
<tr>
<td>inch per year</td>
<td>25.4</td>
<td>millimeter per year</td>
</tr>
<tr>
<td>mile</td>
<td>1.609</td>
<td>kilometer</td>
</tr>
<tr>
<td>square mile</td>
<td>259.0</td>
<td>hectare</td>
</tr>
<tr>
<td>square mile</td>
<td>2.590</td>
<td>square kilometer</td>
</tr>
<tr>
<td>ton per day</td>
<td>0.9072</td>
<td>metric ton per day</td>
</tr>
<tr>
<td>ton per day</td>
<td>0.9072</td>
<td>megagram per day</td>
</tr>
</tbody>
</table>

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

°C = (°F - 32) / 1.8

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Water year: Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends. Thus, the water year ending September 30, 1998, is called the “1998 water year.”

In the text, the first occurrence of terms included in the “Definition of terms” section are in boldface type.
Other Abbreviations, Acronyms, and Symbols Used

- mg/L: milligrams per liter
- µg/L: micrograms per liter
- mL: milliliters
- µS/cm: microsiemens per centimeter at 25 degrees Celsius
- pCi/L: picocuries per liter
- %: per cent
- TU: tritium units
- <: less than
- >: greater than
- ≥: greater than or equal to
- ≈: approximately equal to
- δ18O: isotopic ratio of oxygen-18 (18O) to oxygen-16 (16O)

DENR: South Dakota Department of Environment and Natural Resources
GIS: Geographic information system
GWSI: Ground Water Site Inventory database
USEPA: U.S. Environmental Protection Agency
MCL: Maximum Contaminant Level
MSL: Mean sea level
SMCL: Secondary Maximum Contaminant Level
USGS: U.S. Geological Survey

Boxplots are a useful and concise graphical display for summarizing the distribution of a data set. Two different types of boxplots are used in this report. In both types, the center of the data (known as the median) is shown as the center line of the box. The variation or spread of the data (known as the interquartile range) is shown by the box height.

- Maximum
- 90th percentile
- 75th percentile
- Median
- 25th percentile
- 10th percentile
- Minimum
- Outlier data value more than 3 times the interquartile range outside the quartile
- Outlier data value less than or equal to 3 and more than 1.5 times the interquartile range outside the quartile
- Data value less than or equal to 1.5 times the interquartile range outside the quartile
- 75th percentile
- Median
- 25th percentile
- Data value less than or equal to 1.5 times the interquartile range outside the quartile

The first type is a truncated boxplot, and is used for all boxplots that do not show water-quality data. In the truncated boxplot, the whiskers are drawn only to the 90th and 10th percentiles of the data set. Thus, values included in largest 10 percent and the smallest 10 percent of the data are not shown. The maximum and minimum values for the data set are shown.

The second type is a standard boxplot, and is used for all boxplots that show water-quality data. In the standard boxplot, the whiskers are drawn only to the last data value that is within 1.5 times the interquartile range (height of the box). Values outside 1.5 times the interquartile range are called "outliers." For water-quality data, these outliers are of interest when comparing to water-quality standards and general distribution of extreme values.

- Spring
- Water table