SHALLOW GROUND WATER IN THE POWDER RIVER BASIN, NORTHEASTERN WYOMING--DESCRIPTION OF SELECTED PUBLICATIONS, 1950-91, AND INDICATIONS FOR FURTHER STUDY

By J.B. Lindner-Lunsford and James F. Wilson, Jr.

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CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per mile (acre-ft/mi)	766.2	cubic meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile [(ft^3/s)/mi]	0.01760	cubic meter per second per kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06308	liter per second
gallon per day per foot [(gal/d)/ft]	0.01242	cubic meter per day per meter
inch (in.)	25.4	millimeter
inch per hour (in/hr)	25.4	millimeter per hour
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 9/5\ (°C) + 32$$

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ABSTRACT

Seventy-six publications dealing with ground water in geologic units overlying the Upper Cretaceous Pierre Shale and equivalents in the Powder River Basin are described. The publications were prepared by the U.S. Geological Survey, other government agencies, and academic and private organizations, including mining companies and engineering consultants.

Deficiencies in the accumulated knowledge of the shallow ground water system are identified. The hydrogeologic setting in the basin is heterogeneous and complex. The local occurrence and quality of ground water in the basin are reasonably well documented; however, reliable information about hydrologic and geochemical processes in the basin is scarce. Further study is needed to resolve the differing interpretations expressed in the literature as to the nature of the flow system and the relative importance of regional, subregional, and local flow components, and the extent of interaction between shallow ground water and streams. Different interpretations regarding the importance of local heterogeneity in defining hydrologic properties and processes in the basin also need to be resolved. Information regarding hydrologic and geochemical effects of mining and other economic development is not sufficient for planning; follow-up investigations and long-term monitoring would provide more detailed information.

INTRODUCTION

Ground water is the primary source for rural-domestic, municipal, industrial, and agricultural uses in the Powder River structural basin of northeastern Wyoming, called the Powder River Basin in this report (fig. 1). The basin contains substantial deposits of coal, uranium, and other minerals, as well as oil and natural gas (Lowry, Wilson, and others, 1986, p. 34-37). Human activities most likely to affect ground water in the basin are oil-field waterflooding, surface mining, and pumpage for municipal use (Wallace and Crist, 1989, p. 13). Because of its importance, shallow ground water in the Powder River Basin has been the subject of many investigations on regional, subregional, and local scales.

Publications from investigations to date (1991) reflect a progression of the type of ground-water information needed and the corresponding approach to the study of ground-water resources in the basin. In order to help define the accumulated state of knowledge about shallow ground water in the Powder River

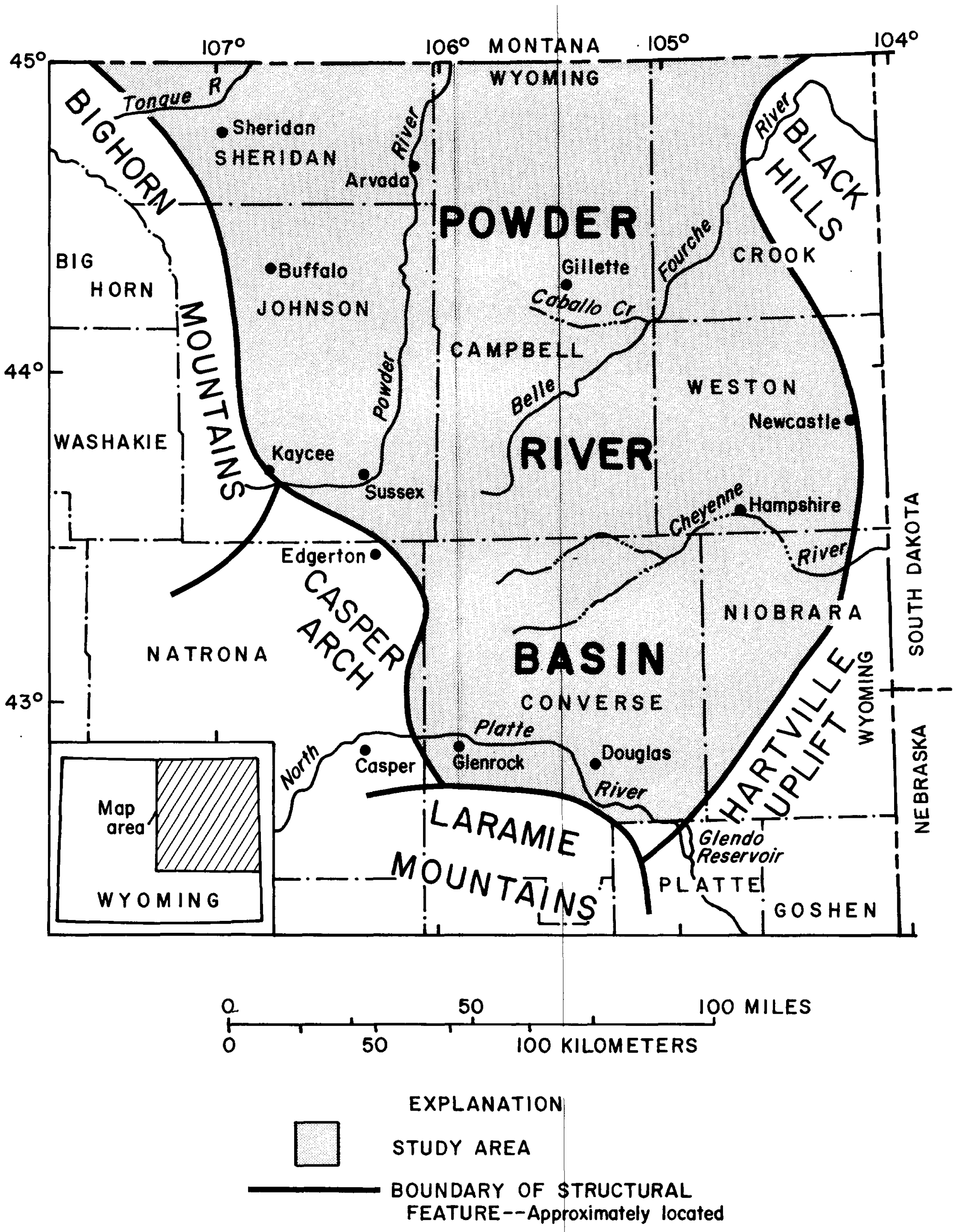


Figure 1.--Location of the Powder River Basin and other structural features, northeastern Wyoming.

Basin, a project was begun by the U.S. Geological Survey (USGS) in cooperation with the U.S. Bureau of Land Management. The project objectives were to compile and to describe pertinent publications, and to identify topics for further study.

Purpose and Scope

This report describes the conclusions and contributions to knowledge of shallow ground water in publications resulting from previous ground-water investigations in the Powder River Basin and describes indications for further study. For this report, shallow ground water is defined as water in geologic formations overlying the Upper Cretaceous Pierre Shale and equivalents.

The types of information in the publications are summarized in a table, and the descriptions are in a section at the back of this report that contains detailed bibliographic information and brief summaries of the conclusions about shallow ground water for each publication listed in the table. The 76 publications described were produced from 1950-91 by the U.S. Geological Survey, other government agencies, and academic and private organizations, including mining companies and engineering consultants. Only those parts of the publications that are relevant to the quantity or quality of shallow ground water in the Powder River Basin are described. Mine plans for coal and uranium mines (many of which contain detailed, local hydrologic information) and publications containing pertinent geologic information, but no hydrologic information, are not included.

Topics for which further study is needed were identified on the basis of differing interpretations or deficiencies in information provided by the publication. Specific investigations to address the deficiencies are not defined.

History of Investigations of Shallow Ground Water

Prior to about 1974, most investigators described ground-water resources of specific areas; few hydrologic processes were investigated. Nearly all investigations by Federal agencies were conducted under the U.S. Geological Survey Federal-State Cooperative Water-Resources Investigations Program, primarily in cooperation with the Wyoming State Engineer. Publications that describe typical investigations prior to about 1974 are Morris (1956) and Whitcomb and others (1966). The statewide series of Hydrologic Investigations Atlases emphasizing ground-water resources (scale 1:250,000) was completed by about 1974; Hodson and others (1973) prepared the atlas for the Powder River Basin.

The period 1974-83 was one of extensive exploration and mining of coal and uranium resources in the Powder River Basin in Wyoming. Many ground-water investigations during this period were basin-wide and related to the development of energy resources. Most of the investigations were part of the Coal-Hydrology and Regional Aquifer-System Analysis programs of the USGS, with continued cooperative support from State and other Federal agencies, especially the U.S. Bureau of Land Management. Investigations by academic and private organizations also increased during this period. Typical publications of investigations completed during the period (some were published after 1983) are Feder and others (1977), Hotchkiss and Levings (1986), Lowry and Rankl (1987), and Downey and Dinwiddie (1988). By 1983 the regional programs of the USGS had been completed or terminated, and the number of ground-water investigations had decreased substantially.

Since 1983, the objectives of new investigations generally have been to obtain more detailed information about hydrologic processes; to assess hydrologic effects of mining and reclamation; or to determine the occurrence, movement, and quality of ground water. Although fewer than in previous years, the investigations tend to be more quantitative than in the past. The Wyoming State Engineer remains the principal cooperating agency for ground-water investigations in Wyoming; however, the Wyoming Department of Environmental Quality and the U.S. Bureau of Land Management also participated in investigations during the 1980s. Publications that are representative of the focus of investigations since 1983 are Martin and others (1988), Naftz (1990), and Crist (1991).

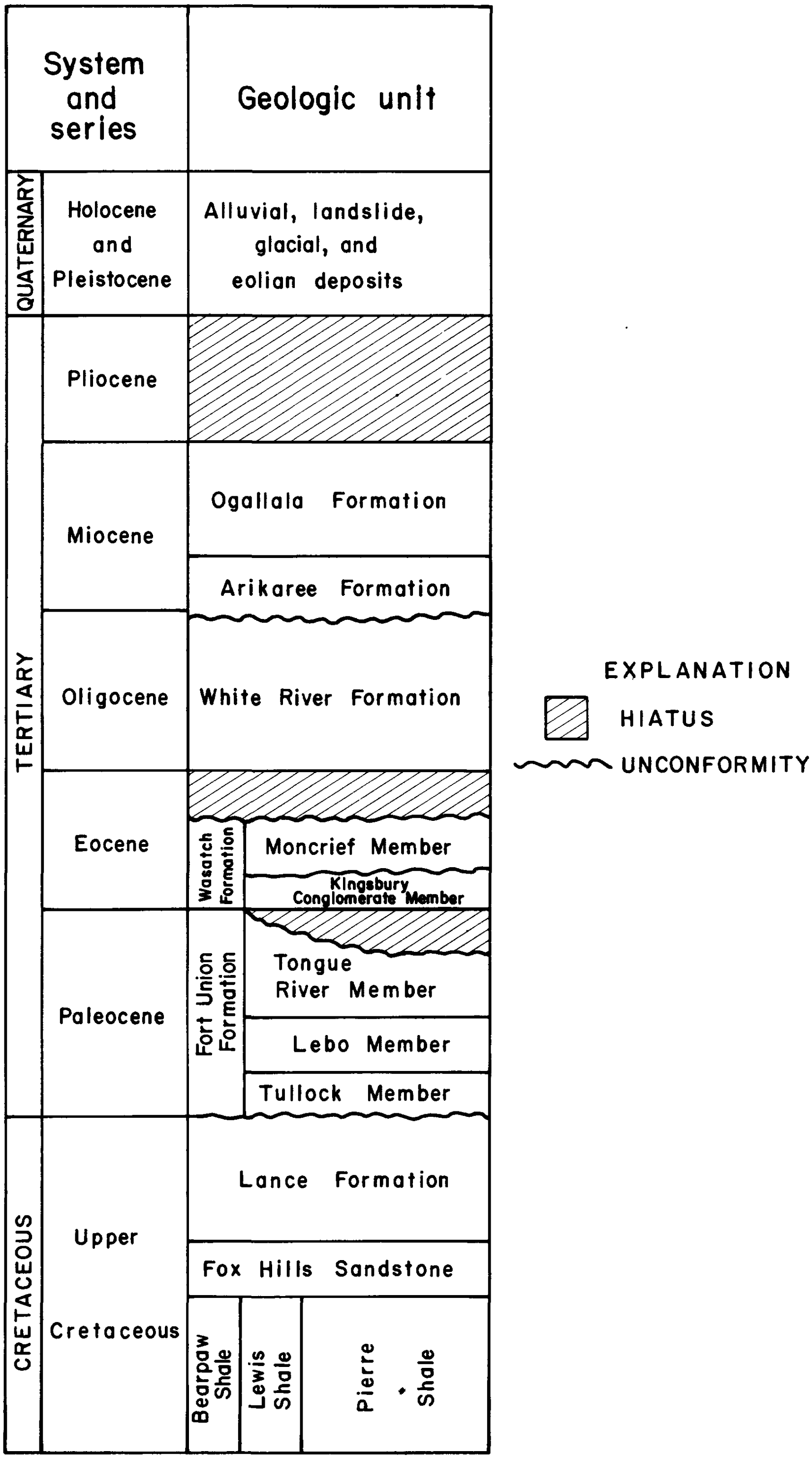
Physiographic and Hydrogeologic Setting

The ground-water hydrology of the Powder River Basin is controlled by the basin's physiography and geology. These topics are summarized briefly in this section. They are described in greater detail in many publications, including Wyoming Water Planning Program (1972), Hodson and others (1973), Feathers and others (1981), and Lowry, Wilson, and others (1986).

The Wyoming part of the basin is flanked on the east by the Black Hills, on the south by the Laramie Mountains, and on the west by the Bighorn Mountains (fig. 1). Plains, rolling hills, and tablelands characterize much of the land surface. Major streams crossing the basin are the Tongue, Powder, Belle Fourche, Cheyenne, and North Platte Rivers. Headwaters of the Tongue and Powder Rivers are in the Bighorn Mountains; headwaters of the Belle Fourche and Cheyenne Rivers are on the plains east of the Bighorn Mountains. The North Platte River flows across the southern end of the basin. Most other streams are ephemeral; some have reaches with intermittent flow.

The land is semiarid. Precipitation, controlled by the topography, averages 12 to 14 in/yr over most of the area, but as much as 25 in/yr falls on the Bighorn Mountains. Mean-annual pan evaporation is much greater than precipitation--about 60 to 65 in/yr (Martner, 1986, p. 177). The high rate of evaporation can cause concentration of salts in soils, so water that percolates through the soils to recharge the ground-water system in some places can become mineralized.

The basin is an asymmetrical syncline--the north-plunging axis is closer to the west side. The Upper Cretaceous and Tertiary rocks discussed in this report are nearly flat-lying across most of the basin. Geologic units in the Powder River Basin range in age from Precambrian to Quaternary. The shallower units of primary interest for this report (fig. 2) are the Fox Hills Sandstone and Lance Formation of Late Cretaceous age, the Fort Union Formation of Paleocene age, the Wasatch Formation of Eocene age, other locally present Tertiary rocks, and Quaternary alluvium. Most of these formations consist of interbedded fine- to medium-grained sandstone, shale, siltstone, clay, and coal. Coal generally is abundant in the upper part of the Fort Union



Modified from Love and others (1987)

Figure 2.--Stratigraphy of the shallow geologic units in the Powder River Basin, northeastern Wyoming.

Formation (Tongue River Member), and underlies most of the central part of the basin. The Wyodak coal bed (in places called the Wyodak-Anderson coal bed), in the Tongue River Member, is mined extensively; some mining also takes place in the School coal bed (Wasatch Formation) in the southern part of the study area. Extensive uranium deposits are found in the Wasatch Formation. The White River Formation of Oligocene age, the Arikaree Formation of late Oligocene (?) and early Miocene age, and the Ogallala Formation (minor outcrops) of Miocene age crop out in the extreme southern part of the basin.

Relative terms are used in this report to indicate the stratigraphically or lithologically controlled areal extent of hydrogeologic units, ground-water flow, or effects of human activities on ground-water quantity or quality. Regional extent or effects generally are considered to cover the entire structural basin (more or less). Local extent or effects are limited to an area of a few square miles, such as a mine site. Subregional indicates an area of intermediate size--several hundred square miles. The same terms were used, but not defined, in many of the publications described.

The lithology of the shallow geologic units in the basin is complex and heterogeneous. On a local scale, a complicated system of many aquifers and confining units, in varying degrees of communication, exists. Ground water can be obtained mainly from alluvial deposits, sandstone lenses, and coal beds. Sufficient water for stock-watering and domestic use (10-20 gal/min) generally can be obtained from wells less than 500 ft deep (Lowry, Wilson, and others, 1986, p. 90), but aquifer properties vary spatially because of large variations in lithology. Transmissivity ranges from about 1 (gal/d)/ft [0.13 ft^2/d] in sandstone to 3,000,000 (gal/d)/ft [400,000 ft^2/d] in clinker (Feathers and others, 1981, p. 5).

On a regional scale, the Wasatch Formation and the upper part of the Fort Union Formation (fig. 2) have been considered by some investigators (Hotchkiss and Levings, 1986; Bloyd and others, 1986; Koch and others, 1982) to compose one aquifer. These investigators also assume that the Lebo Member of the Fort Union Formation generally acts as a confining unit, and in most of the area, that the Lance Formation and Fox Hills Sandstone are hydraulically connected to form one aquifer.

Ground-water quality varies areally and with depth, and the water quality in isolated local systems can be different from the regional water quality. The following description is modified from Feathers and others (1981, p. 4-5) and Feder and others (1977). In general, water in the uppermost aquifers (above the Lebo Member) has a pH less than 8.0. Dissolved-solids concentrations range from 250 to 6,500 mg/L (milligrams per liter), and dominant ions are calcium, magnesium, sulfate, and bicarbonate. In the deeper Lance-Fox Hills aquifer, the pH is greater than 8.0. Dissolved-solids concentrations in water from the Lance-Fox Hills aquifer range from 350 mg/L in outcrop areas to 3,500 mg/L in the central part of the basin; dominant ions are sodium and bicarbonate. Concentrations of selenium, fluoride, radium-226, and gross alpha radiation in ground water from the basin commonly exceed maximum contaminant levels--the concentrations of contaminants that can cause adverse human health effects and are enforceable for public drinking-water supplies--as defined by U.S. Environmental Protection Agency drinking-water regulations (U.S. Environmental Protection Agency, 1990, p. 41-43). Occasionally, concentrations of nitrate, mercury, and lead in ground-water samples exceed the maximum contaminant levels. Concentrations of iron and manganese occasionally exceed secondary maximum contaminant levels--the concentrations of contaminants that can adversely affect the odor, taste, or appearance of water, are not health based, and are not enforceable for public drinking-water supplies as defined by U.S. Environmental Protection Agency drinking-water regulations (U.S. Environmental Protection Agency, 1990, p. 41-43).

TYPES OF INFORMATION IN PUBLICATIONS

For quick reference, the location of the study area and the types of hydrogeologic and ground-water information contained in the 76 publications are indicated in table 1. The publications are listed alphabetically by author and by year. More detailed descriptions of the publications are located at the back of this report, on the pages listed in the first column of table 1.

The location of the study area described by each publication--the entire Powder River structural basin in Wyoming, or all or part of a county or counties--is indicated in the first section of table 1. The study area may be larger than the area indicated.

The types of hydrogeologic information--geology, lithology, and water-yielding characteristics--in each publication are listed in the second section of table 1. The format of the information (maps, geologic or hydrologic sections, stratigraphic columns, well logs, tables or text, or statistical summaries) also is noted. Water-yielding characteristics include hydraulic conductivity, transmissivity, specific yield, storage coefficient, well yield, and specific capacity. In many publications, especially U.S. Geological Survey Water-Supply Papers, this information is combined in a single table.

The type and format of ground-water quantity and quality information in each publication are listed in the third section of table 1. Quantity information categorized in this section includes use; occurrence; and movement, recharge, and discharge. The format of the information is noted as map, geologic or hydrologic section, trend or prediction, text or tabular summary, or uninterpreted data. If the publication contains water-level data or a potentiometric-surface map, that information is indicated under the "Occurrence" column. Only explicit information about ground-water movement and areas of recharge and discharge, such as arrows or flow lines drawn on a map, or shading indicating recharge and discharge areas, is identified in the "Movement, recharge, discharge" column. If the user must infer movement from a potentiometric-surface map, only the "Occurrence" column is noted. Water-quality information includes dissolved solids, major-ion chemistry, and constituents of special concern. The most common constituents of special concern noted in the literature for the Powder River Basin are selenium, uranium, boron, and fluoride. The format of the information is noted in table 1 as map, geologic or hydrologic section, statistical summary, trend or prediction, text or tabular summary, or uninterpreted data. If individual analyses of water samples from one or more wells or springs are presented in a table, it is noted in table 1 by a "D." The designation "T" in this section of table 1 is used only for text discussions of water quality or, for example, discussions of ranges of dominant-ion and dissolved-solids concentrations listed in a more general table that describes water-yielding characteristics of geologic units.

Table 1.--Location of study areas, and types of hydrogeologic and

[Symbols for location of study area: *, entire area or more; o, part of area.
C, stratigraphic column, measured section, or drillers log; D, uninterpreted data
or contoured hydrologic map; P, trends, predictions, hydrographs, or comparisons
text or tabular summary (tables containing uninterpreted data are indicated by
be located for examination]

		Location of study area								
			County							
Page No.[1]	Publication (author and year of publication)	Powder River Basin	Campbell	Converse	Crook	Johnson	Natrona	Niobrara	Sheridan	Weston
21	Armentrout and Wilson, 1987	*								
21	Babcock and Morris, 1954						o			
22	Ballance and Freudenthal, 1975; 1976; 1977	*								
23	Bloyd and others, 1986		o	o	o	o			o	o
23	Breckenridge and others, 1974		*							
25	Brown, 1980		o							
26	Crist, 1991		o							
27	Crist and Lowry, 1972						*			
27	Daddow, 1986		o	o		o	o		o	
28	Dahl and Hagmaier, 1976			o						
28	Dana, 1962 [NLE]									
29	Davis, 1975		o							
29	Davis and others, 1980		o							
30	Davis and Rechard, 1977		o							
30	Divis and Tarquin, 1981 [NLE]									
31	Downey and Dinwiddie, 1988	*								
32	Druse and others, 1981	*								
32	Feathers and others, 1981	*								
34	Feder and others, 1977	*								
34	Fogg and others, 1991		o	o		o			o	
35	Freudenthal and others, 1974	*								
36	Gillette Area Groundwater Monitoring Organization, 1987		o	o						
36	Ground-Water Subgroup, 1974		o							
37	Hadley and Keefer, 1975		o							
38	Hagmaier, 1971	*								
39	Hodson, 1971a		*	o	*	*	o	o	*	*
39	Hodson, 1971b		*							
40	Hodson and others, 1973	*								
41	Hotchkiss and Levings, 1986	*								
42	Jordan and others, 1984		o							

ground-water information contained in selected publications

Abbreviations for hydrogeologic and ground-water information in report:
(tabular or on map; data on map not contoured); M, geologic, structure-contour,
of present and historical conditions; S, statistical or graphical summary; T,
D); X, geologic or hydrogeologic section. NLE, a copy of the report could not

Hydrogeologic information			Ground-water information					
			Quantity			Quality		
Geology	Lithology	Water-yielding characteristics	Use	Occurrence[2]	Movement, recharge, discharge	Dissolved solids	Major-ion chemistry	Constituents of special concern
					T			
MT		T		T		T		T
				DP				
MTX	T	T		M	T[3]	MT[4]		MT[4,5]
CMX	T	T				DT	T	
X	C	T		MP	PT			
T	T		P	MPT				
MX	T	T	D	D		M	D	T[6]
T				DM	T			
CMTX	T				TX		T	T[7]
MTX	C	D		DMPX	T			
X	D	D		X	P	DP	DS	D[8]
	X	D		PX		D	D	D[8]
MTX[9]	T			M	MT	MT	T	
					DPT[10]	PT[10]	DT[10]	D[10,11]
MT	CT	T	DT	MT	MT	MT	ST	MS[12]T[13]
						ST	ST	ST
MTX	T	T	T	DMP	PT	PT	PT	PT[14]
			DPT					
				DMP		D	D	D[14]
MT	T	T		DMPT	MT	DT	DT	DT
X				M[15]PTX				
M	T	T		D	TX	D	DPSX	DMTX[7]
	C					D	D	D[8]
	CD	D[16]		D				
M	CT	T	T	DT		DT	DT	
MT	CT	DM[17]ST		M	T[3]			
		T[18]			T			

Table 1.--Location of study areas, and types of hydrogeologic and

		Location of study area								
			County							
Page No.[1]	Publication (author and year of publication)	Powder River Basin	Campbell	Converse	Crook	Johnson	Natrona	Niobrara	Sheridan	Weston
43	Keefer and Hadley, 1976		o							
44	Kennedy and Green, 1988; 1990	*								
44	Kennedy and Oberender, 1987	*								
45	King, 1974		o							
45	Koch and others, 1982	*								
46	Kohout, 1957					o				
47	Lageson and others, 1980						*			
48	Lane and others, 1972 [NLE]									
48	LaRocque, 1966	*								
49	Larson, 1984	*								
49	Larson, 1988		o							
50	Larson and Daddow, 1984	*								
50	Lenfest, 1984	*								
51	Lenfest, 1987	*								
51	Lewis and Hotchkiss, 1981	*								
52	Littleton, 1950		o							
53	Lowry, 1973		o							
53	Lowry and Cummings, 1966								*	
54	Lowry and others, in press			o						
55	Lowry and others, 1986									*
55	Lowry and Rankl, 1987		o							
56	Lowry, Wilson and others, 1986		o	o	o	o	o	o	o	o
57	Martin and others, 1988		o	o						
58	Melancon and others, 1979 [NLE]									
58	Morris, 1956			o						
59	Naftz, 1990		o							
60	Ragsdale, 1982	*								
60	Ragsdale and Oberender, 1985	*								
60	Rahn, 1976		o	o						
61	Rankl and Lowry, 1990	*								
62	Ringen, 1973; 1974	*								
62	Ringen and Daddow, 1990					o			o	
64	Stevens, 1978	*								
64	U.S. Department of the Interior, 1974	*								
65	U.S. Geological Survey, 1990	*								

ground-water information contained in selected publications--Continued

Hydrogeologic information				Ground-water information				
				Quantity		Quality		
Geology	Lithology	Water-yielding characteristics	Use	Occurrence[2]	Movement, recharge, discharge	Dissolved solids	Major-ion chemistry	Constituents of special concern
M[19]T				M	M	M		
				DP				
				DP				
M		T		M	M	MT[20]		
	TX	DST		DMP	T[3,21]	DT		M[7]T
T	T	T	T	DT	T	D	SD	DT[22]
MT	T	T				S	S	
		M		M				
						ST	ST	ST
						D	D	D[8,14]
						D	D	D
					T			
	X	T		P	T			
M	CT	T						
CX	T	T	D	T		DT	DT	T
CM		MT		M	T			
MT	CT	T		DP		DT	DST	DT
MT	T			MPT	TX[21]	DT	D	D
M	C	T		D		D	DT	D[23]
CM		T		DMP	T[3]	D	DS	D[14]
CMTX	CMTX	MT	T	M[24]	T[3,21]	ST	ST	ST
M	CT	ST	T	P	T	PST	PST	PST[14,25]
MT	C	T		T				
	X				TX		S	DS[26]
				DP				
				DP				
	CX	DST			D[18]	DT	DST	D[14]
MT					ST[21]X		SP	
				D				
X	CDT	T		T	ST[21]	DS	DS	
				DP				
CTX	T	DT	T	DMP	MT	DT	DT	D[8]
				D		D	D	D

Table 1.--Location of study areas, and types of hydrogeologic and

			Location of study area							
			County							
Page No.[1]	Publication (author and year of publication)	Powder River Basin	Campbell	Converse	Crook	Johnson	Natrona	Niobrara	Sheridan	Weston
65	Wallace and Crist, 1989	*								
66	Wells, 1982	*								
67	Wendell and others, 1976					*				
68	Whitcomb, 1965							*		
68	Whitcomb and others, 1966					o				
69	Whitcomb and Morris, 1964				o					
70	Whitcomb and others, 1958		o		o					o
70	Wyoming Water Planning Program, 1972	*								

[1] Page number in "Descriptions of reports of investigations" at back of this report.
[2] This category includes water-level data and potentiometric-surface maps.
[3] Direction of ground-water movement can be inferred from potentiometric-surface map.
[4] Includes information for both pre- and post-mining conditions.
[5] Includes information for pH, sulfate, nitrate, manganese, and boron.
[6] Includes information for specific conductance, iron, selenium, and flouride.
[7] Includes information for uranium.
[8] Includes information for nitrate, iron, and boron.
[9] Includes maps of thickness of hydrogeologic units.
[10] Can be inferred from baseflow data presented.
[11] Includes information for nutrients, boron, iron, and organic carbon.
[12] Includes information for dissolved solids, sulfate, chloride, and iron.
[13] Includes information for selenium and fluoride.

ground-water information contained in selected publications--Continued

Hydrogeologic information			Ground-water information					
			Quantity			Quality		
Geology	Lithology	Water-yielding characteristics	Use	Occurrence[2]	Movement, recharge, discharge	Dissolved solids	Major-ion chemistry	Constituents of special concern
C	T		MT	PT				
	D			D		D	D	D
CMX	T	T		T		S	S	
CTX	CT	T		D	T	DT	DT	DT
CTX	T	T		DP	T	DT	DST	DT
CMT	CT	DT		T		DT	DT	
TX	CT	T		P				
CM	C	DM[27]T	PST	T	T	T	DT	D

[14] Includes information for trace metals.
[15] Map shows areas where ground water would be drained or water levels substantially lowered due to mining.
[16] Specific-capacity data presented for some wells.
[17] Includes map of estimated transmissivity.
[18] Includes infiltration data.
[19] Isopach of coal; structure contours on base of coal.
[20] Dissolved-solids concentrations inferred from specific-conductance data.
[21] Also discusses relation between ground water and surface water.
[22] Includes information for salinity hazard, hardness, and boron.
[23] Includes specific-conductance information.
[24] Coal aquifers only.
[25] Includes information for sulfate, selenium, and fluoride.
[26] Includes information for selenium.
[27] Aquifer properties briefly described on geologic map.

INDICATIONS FOR FURTHER STUDY

Information necessary to address basic water-supply concerns--such as geology and lithology, generalized aquifer properties, depth to water, water-level fluctuations, and dissolved-solids and major-ion concentrations--is contained in many of the publications of previous investigations (table 1). The occurrence and quality of ground water in the basin are reasonably well documented. However, reliable information about hydrologic and geochemical processes in the basin is scarce. Specific topics for which information is lacking or for which there are different interpretations include:

- The identification of the dominant ground-water flow process--whether there is a regional flow system, a subregional flow system, a group of independent local flow systems, or a combination of all three
- The volume, rate, and location of recharge and discharge, and the processes by which they occur
- The importance of local heterogeneity in defining hydrologic properties and processes in the basin
- The duration of effects of mining and other human activities--whether they are likely to be temporary or permanent
- The effects of geochemical processes, such as dissolution of minerals by flow through spoil material at surface mines, on water quality

These topics are discussed in more detail in the following paragraphs.

Information about ground-water movement and flow paths--regional, sub-regional, and local--is scarce. Ground-water movement was not addressed in many of the early descriptive water-supply investigations. There may be measurable regional flow, as suggested by several investigators, including King (1974), Feathers and others (1981), Hotchkiss and Levings (1986), and Downey and Dinwiddie (1988); however, Rankl and Lowry (1990), and Lowry and others (in press) maintain that regional flow is very small in comparison with local flows, and vertical flow components are generally greater than horizontal flow components in a series of isolated local systems. The relative importance of local flow systems compared to a regional flow system has implications for ground-water management--the areal extent of adverse effects of human activities on the ground-water system would be more limited if local flow systems were dominant than if the regional flow system were dominant.

Differing results concerning the amount of and mechanisms for ground-water recharge in the basin are apparent in the literature. Amount of recharge can be affected by many processes including rate of infiltration of precipitation, rate of evapotranspiration, and leakage. Jordan and others (1984, p. 15-16) reported that a rapid rate of infiltration (2 in/hr) was necessary to calibrate a deterministic model of an ephemeral stream in the basin. Feathers and others (1981) and Brown (1980), in contrast, report recharge by infiltration to be less than 1 in/yr. Rankl (1990) modeled infiltration as part of an investigation of runoff in small, ephemeral streams, but did not address the amount that actually reaches the underlying aquifers. King (1974) and Feathers and others (1981) suggest that, in addition to infiltration of precipitation, the ground-water system is recharged at the margins of the basin and at outcrop areas, and by leakage downward from overlying aquifers.

The amount and location of ground-water discharge also is subject to different interpretations. Potentiometric-surface maps in King (1974) and Hotchkiss and Levings (1986) indicate regional ground-water flow toward streams. However, other investigators, including Ringen and Daddow (1990, p. 39) provide evidence that the stream/alluvium system of the Powder River is isolated from bedrock. Armentrout and Wilson (1987, pl. 1); Lowry, Wilson, and others (1986, p. 44-45, 54-55); Rankl and Lowry (1990); and Lowry and others (in press) also found little or no evidence of ground-water contribution to streamflow in the basin. According to some investigators, additional discharge occurs toward the north, and to topographic valleys (King, 1974, sheet 1; Feathers and others, 1981 (p. 5-6); Hotchkiss and Levings, 1986 (p. 23); Downey and Dinwiddie, 1988 (p. A25)). Further study is needed to improve the conceptual model of regional, subregional, and local ground-water movement, recharge, and discharge.

More work is necessary to determine how much of an effect local heterogeneities have on the ground-water flow system of the Powder River Basin, and better definition is needed of the discontinuous sandstone and coal beds that comprise locally important aquifers. Although the geology and lithology of the region has been described in many publications, the regional-scale publications are too generalized to identify local heterogeneities. Local detail is especially important for modeling and management purposes. Modeling studies were done by Koch and others (1982), Bloyd and others (1986), Hotchkiss and Levings (1986), and Downey and Dinwiddie (1988); they had to generalize the complex local geology of the area because of the regional scale of their investigations. The scale also was too coarse to show interactions with streams or the three-dimensional and local nature of the flow system. Hotchkiss and Levings (1986, p. 66) concluded that "The large standard error of estimate precludes [their] model from use as a means for assessing or managing local water problems. Future studies could concentrate on understanding the flow system of specific subareas. Insights into the regional flow system gained during the present modeling effort might be helpful in modeling these smaller areas." The development of models and algorithms to deal with local heterogeneities is the subject of current research by M.B. Allen, University of Wyoming (written commun., 1990).

Another topic in which heterogeneity indirectly plays a part is in determining the regional applicability of results of investigations that were local in scope. Many specific sites have been investigated, mostly for water supplies and for environmental-impact assessments at individual mine sites. Most of these investigations did not address the extent to which local conditions are representative of conditions elsewhere in the basin.

Other questions not fully resolved are whether identified hydrologic effects of economic development, especially surface mining of coal and other resources, are likely to be temporary or permanent, and to what extent proper mining practices and reclamation practices can mitigate these effects. Many investigations, such as Bloyd and others (1986), Martin and others (1988), and Fogg and others (1991) were not of sufficient duration to determine answers to these questions. Follow-up investigations and long-term monitoring would help to define whether effects of development are temporary or permanent.

More knowledge also is needed regarding geochemical processes. Effects of flow paths and lithology on ground-water quality, for example, are not well understood. Although few studies of these processes have been done, one recent example is the investigation of geochemical changes in water flowing through spoil materials at surface mines by Naftz (1990).

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DESCRIPTIONS OF SELECTED PUBLICATIONS

The descriptions of selected publications listed in table 1 consist of complete bibliographic information for the publications and summaries of significant findings or other pertinent comments. These descriptions are ordered by author and year of publication; however, they are presented title-first, rather than in standard bibliographic-citation format, to assist readers who wish to scan this section by subject matter. Unless specific page numbers for statements are presented, the information referenced was taken from the abstract, executive summary, summary, or conclusions section of the publication. Comments or interpretations of the compilers of this report are shown in square brackets.

The remarks sections have variable contents, depending on the type of information in the publication. Information presented in some of the remarks may seem redundant, because they are intended to summarize the significant ground-water-related conclusions of the publications, and in some cases, several authors have come to the same conclusions. In other cases, where there are differing interpretations in the literature, remarks about a publication may contradict remarks from other publications. Limited remarks are included for publications that are defined adequately by the title and the information in table 1, or whose conclusions are difficult to summarize in a short text (for example, a map publication). A few publications appear to be relevant, on the basis of their titles, but because copies could not be located for examination, no remarks are included for those publications.

TITLE: **An assessment of low flows in streams in northeastern Wyoming**

AUTHOR(S): Armentrout, G.W., Jr., and Wilson, J.F., Jr.

YEAR OF PUBLICATION: 1987

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 85-4246

PAGES: 30; 1 plate

REMARKS: Records from 128 streamflow-gaging stations in northeastern Wyoming were examined. Seven-day low flows were calculated for stations with sufficient record. Most streams that originate in the foothills and plains had no flow during part of every year (p. 20), indicating that there was negligible storage of surface or ground water in the basin for sustaining the flow. [Because the streams dry up, it can be inferred that there is no substantial ground-water discharge to streams.]

TITLE: **Ground water in the vicinity of Edgerton, Wyoming**

AUTHOR(S): Babcock, H.M., and Morris, D.A.

YEAR OF PUBLICATION: 1954

PUBLISHER AND SERIES: U.S. Geological Survey open-file report (no number)

PAGES: 9

REMARKS: The publication describes geology, occurrence of ground water, aquifer properties, and water quality in the alluvium, Lance Formation, Fox Hills Sandstone, and some deeper formations. The primary objective was to locate a source of water for the town of Edgerton. The authors concluded (p. 8), "Water of good quality can be obtained in sufficient quantities for domestic, stock, and small-scale municipal use from the Fox Hills sandstone [sic] east of Edgerton. * * * Sufficient water for domestic and stock use can be obtained also from the Lance and [deeper] formations east of Edgerton."

TITLE: **Ground-water levels in Wyoming, 1974**

AUTHOR(S): Ballance, W.C., and Freudenthal, P.B.

YEAR OF PUBLICATION: 1975

PUBLISHER AND SERIES: U.S. Geological Survey open-file report (unnumbered)

PAGES: 186

TITLE: **Ground-water levels in Wyoming, 1975**

AUTHOR(S): Ballance, W.C., and Freudenthal, P.B.

YEAR OF PUBLICATION: 1976

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 76-598

PAGES: 170

TITLE: **Ground-water levels in Wyoming, 1976**

AUTHOR(S): Ballance, W.C., and Freudenthal, P.B.

YEAR OF PUBLICATION: 1977

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 77-686

PAGES: 187

REMARKS: These publications present water-level measurements for wells in the U.S. Geological Survey observation-well network. Water-level ranges and hydrographs of water levels are included. Other publications of ground-water levels are: Kennedy and Green (1988; 1990); Kennedy and Oberender (1987); Ragsdale (1982); Ragsdale and Oberender (1985); Ringen (1973; 1974); and Stevens (1978).

TITLE: **Investigation of possible effects of surface coal mining on hydrology and landscape stability in part of the Powder River structural basin, northeastern Wyoming**

AUTHOR(S): Bloyd, R.M., Daddow, P.B., Jordan, P.R., and Lowham, H.W.

YEAR OF PUBLICATION: 1986

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 86-4329

PAGES: 101

REMARKS: The investigators used three approaches: (1) A surface-water model was used to simulate changes in streamflow and in dissolved-solids and sulfate concentrations, assuming less than and greater than average rainfall for premining, during-mining, and postmining conditions; (2) landscape stability analysis; and (3) a ground-water-flow model. The ground-water modeling effort was not successful; the authors' reasons (p. 2) indicate areas where more study is needed:

> The attempt to define and simulate the ground-water system in the area using a ground-water-flow model was unsuccessful; the steady-state ground-water-flow model could not be calibrated. The modeling effort failed principally because of insufficient quantity and quality of data to define the spatial distribution of aquifer properties; the hydraulic-head distribution within and between aquifers; and the rates of ground-water recharge and discharge, especially for steady-state conditions.

TITLE: **Campbell County, Wyoming--Geologic map atlas and summary of land, water, and mineral resources**

AUTHOR(S): Breckenridge, R.M., Glass, G.B., Root, F.K., and Wendell, W.G.

YEAR OF PUBLICATION: 1974

PUBLISHER AND SERIES: The Geological Survey of Wyoming County Resource Series, no. CRS-3

PAGES: 9 sheets

REMARKS: In addition to data indicated in table 1, this publication contains sheets with information on petroleum and natural gas production, tables and text on "History and Future of Oil and Gas in Campbell County," and maps of land and mineral ownership and land use. Other maps depict soil type, and locations of clinker outcrops, sand and gravel, and uranium deposits. One sheet contains a map showing locations of coal resources, outcrops, and existing mines. This sheet also has short texts on coal resources--coal-bearing rocks underlie more than 99 percent of the county, but only 315 mi^2 (6.6 percent of the county) contain coal at a shallow enough depth to be economically mined by surface methods as of publication date--and a history and forecast for coal mining [now somewhat dated].

Of particular interest from a ground-water perspective, the publication contains a map of mean-annual precipitation, which ranges from 10-12 in. in parts of the southern part of the county to 16-18 in. in the northeast and central parts. The publication describes the trace-element geochemistry of the coal and related rocks--the metals associated with the Wyodak aquifer [Wyodak-Anderson coal bed in the Tongue River Member of the Fort Union Formation] include arsenic, beryllium, copper, lead, mercury, selenium, and uranium.

The water-resources sheet contains a map showing dominant ions in ground water and dissolved-solids concentrations. A table listing lithology, water-yielding characteristics, and major water-quality characteristics for geologic formations in the basin is included. [The information may be useful on a reconnaissance basis, but may be too generalized to be useful for site-specific studies.] Other maps on this sheet show depth to top of the Fox Hills Sandstone and the Madison Limestone of Mississippian age, and surface-water drainage. Much of the information on this sheet is from Hodson and others (1973).

Other publications in this series are:

Converse County (Lane and others, 1972)

Johnson County (Wendell and others, 1976)

Natrona County (Lageson and others, 1980)

TITLE: **Regional hydrogeology of the Gillette, Wyoming area (with a discussion of cumulative regional impacts of surface coal mining and reclamation), <u>in</u> Proceedings, Second Wyoming Mining Hydrology Symposium**

AUTHOR(S): Brown, J.D.

DATE OF PUBLICATION: 1980

PUBLISHER AND SERIES: Wyoming Water Resources Research Institute, University of Wyoming, Laramie

PAGES: 10-42

REMARKS: Regional potentiometric-surface maps constructed for the overburden [all rocks above the Wyodak-Anderson coal, including the Wasatch Formation and locally present alluvial aquifers] and the coal indicate that recharge occurs over most of the land surface. Recharge to the overburden was estimated to be 1 to 5 percent of the annual precipitation, or 0.15 to 0.75 in/yr; recharge to the coal is primarily by downward leakage through the overburden. Discharge occurs primarily along stream drainages. Transmissivity of the coal seam was calculated to be 500 to 7,000 (gal/d)/ft [70 to 900 ft^2/d] on the basis of aquifer tests of 24 hours or longer. Long-term aquifer tests generally could not be conducted in the overlying Wasatch Formation because of excessive drawdowns in the pumped wells; therefore, single-well slug tests, which tend to underestimate transmissivity, were done. Transmissivity estimated from these slug tests was less than 10 (gal/d)/ft [1.3 ft^2/d]. Transmissivity in clinker deposits was estimated to be 10,000 to 1,000,000 (gal/d)/ft [1,300 to 130,000 ft^2/d], but because these deposits are highly localized and contain water with dissolved-solids concentrations that generally ranged from 2,000 to 3,000 mg/L, they were considered not useful as sources of water supply.

The author concluded (p. 40) that "The shallow ground-water systems in the Gillette, Wyoming area must be considered as local systems rather than as regional systems." He further concluded that cumulative drawdowns caused by mining will be minimal in the overburden and that cumulative drawdowns greater than 10 ft in the coal will extend no more than a few miles west of the westernmost mine cut.

TITLE: **Evaluation of ground-water-level changes near Gillette, northeastern Wyoming**

AUTHOR(S): Crist, M.A.

YEAR OF PUBLICATION: 1991

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 88-4196

PAGES: 2 sheets (map report)

SCALE: 1:100,000

REMARKS: Ground water in the 220 mi^2 study area is used for municipal supply, waterflooding oil fields, facilities at surface coal mines, rural-domestic supply, and stock watering. The population of Gillette increased from 3,150 in 1950 to 15,000 in 1985. Local users are concerned that pumping may be causing water-level declines, and that withdrawals from deep aquifers may affect water levels in shallow aquifers.

The principal aquifers investigated in the study, from shallowest to deepest, were the Wasatch Formation, the Fort Union Formation, and the combined Lance Formation and Fox Hills Sandstone. Selected hydrographs indicate that water levels in wells completed in the Wasatch Formation were stable until about 1961, then declined between 1965 and 1974, as the population of Gillette increased. Water-level data for the Wasatch are not available for 1975-82. Water levels in one observation well have been rising since 1983 (in 1981 pumpage of water from the Wasatch for municipal supply was discontinued). Water levels in wells completed in deeper aquifers have been declining. In the immediate vicinity of Gillette, water levels in 17 wells completed in the upper part of the Fort Union Formation declined an average of 120 ft between 1972 and 1985.

The author states (sheet 1) that "The distribution of data points shows poor correlation of hydraulic head with depth [for wells completed in the Fort Union Formation and the Lance Formation and Fox Hills Sandstone] * * * suggesting that vertical ground-water flow is downward and that the deeper aquifers potentially can be recharged from overlying beds. However, because of the interbedding of sandstone, shale, and coal; the discontinuous sandstone beds; and the wide range of hydraulic heads, vertical hydraulic connection probably is poor." Pumping from the lower part of the Fort Union Formation is not expected to affect water levels substantially in the upper part, but long-term monitoring is needed to verify this assertion. [For an earlier investigation of the same area, see the description for Littleton (1950).]

TITLE: **Ground-water resources of Natrona County, Wyoming**

AUTHOR(S): Crist, M.A., and Lowry, M.E.

YEAR OF PUBLICATION: 1972

PUBLISHER AND SERIES: U.S. Geological Survey Water-Supply Paper 1897

PAGES: 92; 3 plates

REMARKS: Only the extreme northeast corner and an area along the eastern border of Natrona County are in the Powder River Basin, so much of the summary material in the publication may not be applicable to studies of the Powder River Basin. Data presented in the publication for the northeast corner of the county indicate that the Fox Hills Sandstone is a principal aquifer (p. 60). The formation is about 700 ft thick, but transmissivity is small. Three aquifer tests resulted in estimates of transmissivity in the northeast part of the county of 10 and 22 ft^2/d for the combined Lance Formation and Fox Hills Sandstone, and 214 ft^2/d for the sandstone alone (p. 61). Dissolved-solids concentrations generally were between 1,200 and 2,000 mg/L; predominant ions were sodium, sulfate, and bicarbonate (p. 20-21).

TITLE: **Potentiometric-surface map of the Wyodak-Anderson coal bed, Powder River structural basin, Wyoming, 1973-84**

AUTHOR(S): Daddow, P.B.

YEAR OF PUBLICATION: 1986

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 85-4305

PAGES: 1 sheet

SCALE: 1:250,000

REMARKS: The author states that previous water-level maps of shallow aquifers in the Powder River Basin in Wyoming were based on water levels in wells completed in different, often discontinuous, stratigraphic intervals within thick sequences of sedimentary rocks. The publication includes a map of the water levels in the areally extensive Wyodak-Anderson coal bed (in the Tongue River Member of the Fort Union Formation). Potentiometric-surface contours indicate that movement of water generally is toward the northwest; however, in places the flow might follow available fractures, in preference to the regional gradient.

TITLE: **Genesis and characteristics of the southern Powder River Basin uranium deposits, Wyoming, in Geology and energy resources of the Powder River Basin**

AUTHOR(S): Dahl, A.R., and Hagmaier, J.L.

YEAR OF PUBLICATION: 1976

PUBLISHER AND SERIES: Wyoming Geological Association Guidebook, 28th Annual Field Conference

PAGES: 243-252

REMARKS: This article describes the role of ground water in the origin and deposition of uranium in sandstone beds in the Wasatch Formation, in Converse County. According to the authors (p. 244), "Transportation and precipitation of uranium * * * is directly related to groundwater [sic] movement * * * . Regional groundwater [sic] recharge and discharge areas of the present ground-water flow systems (Hagmaier, 1971) are interpreted to have been at approximately the same locations as those of the early Tertiary groundwater-flow [sic] systems, * * * ." Changes in water chemistry as the water moved through the sandstone beds are described. [Most of this article was drawn from Hagmaier (1971).]

TITLE: **Groundwater reconnaissance of the State of Wyoming**

AUTHOR(S): Dana, G.F.

YEAR OF PUBLICATION: 1962

PUBLISHER AND SERIES: Wyoming Natural Resources Board, Cheyenne

PAGES: (not available)

REMARKS: A copy of the publication could not be located for examination.

TITLE: **Results of a hydrological investigation of AMAX's Belle Ayr Mine and vicinity near Gillette, Wyoming**

AUTHOR(S): Davis, R.W.

YEAR OF PUBLICATION: 1975

PUBLISHER AND SERIES: Wyoming Water Resources Research Institute Water Resources Series, no. 57, University of Wyoming, Laramie

PAGES: 35

REMARKS: This publication was the first in a series documenting research done at AMAX's Belle Ayr Mine. The authors concluded that the study area is representative of the eastern Powder River Basin, based on regional water-table data. The Wyodak coal bed [in the Tongue River Member of the Fort Union Formation] and the Wasatch and Fort Union aquifers all appeared to have similar aquifer properties. Transmissivity ranged from 1,353 to 6,175 (gal/d)/ft and averaged 3,218 (gal/d)/ft [181 to 825 ft^2/d (average, 418 ft^2/d)], and the average storage coefficient was 0.0046.

Alluvial valleys appeared to be areas of ground-water discharge. However, except for the Belle Fourche River, none of these valleys contains perennial streams (p. 19). In some losing reaches of Caballo Creek, surface flow probably became subsurface flow through the alluvium; in other reaches, most of the flow was lost to evapotranspiration.

TITLE: **Shallow ground water distribution and movement as influenced by surface coal mining in the eastern Powder River Basin, Wyoming**

AUTHOR(S): Davis, R.S., Hasfurther, Victor, and Rechard, P.A.

YEAR OF PUBLICATION: 1980

PUBLISHER AND SERIES: Wyoming Water Resources Research Institute Water Resources Series, no. 77, University of Wyoming, Laramie

PAGES: 46

REMARKS: The publication is one of a series documenting research done at AMAX's Belle Ayr Mine. The study was site-specific, but the authors suggested that the results can be generalized to the entire eastern Powder River Basin. Although (p. 3) " * * * major chemical characteristics of water in the spoil aquifers are not appreciably different from water in undisturbed aquifers, there does appear to be an increase in trace element content. * * * The reclaimed spoil will have about the same aquifer characteristics as coal in areas of thin overburden where fracture systems are better developed."

TITLE: **Effects of surface mining upon shallow aquifers in the eastern Powder River Basin, Wyoming**

AUTHOR(S): Davis, R.W., and Rechard, P.A.

YEAR OF PUBLICATION: 1977

PUBLISHER AND SERIES: Wyoming Water Resources Research Institute Water Resources Series, no. 67, University of Wyoming, Laramie

PAGES: 47

REMARKS: This publication is one of a series investigating effects of surface mining on shallow aquifers in the Powder River Basin. The work described in this publication was done at AMAX's Belle Ayr mine. In addition to the information described in table 1, the authors describe recharge to the coal aquifer based on fluctuations in water levels in 1976. Recharge by leakage from the overlying Wasatch aquifers is described as insignificant, and nearly all recharge occurs either through alluvial deposits where Caballo Creek crosses outcrops of the coal aquifer, or through the coal/scoria [coal/clinker] interface. The authors provide a clear description of the mechanism (p. 27): "The most important properties of alluvium and scoria [clinker] with respect to recharge of the coal are probably their capacity to accept large amounts of precipitation, transfer it quickly beyond the reach of evapotranspiration, and provide a reservoir for slowly transferring the water to the coal throughout the drier parts of the year." The authors do not indicate whether results obtained at this site are representative of the entire eastern Powder River Basin.

TITLE: **The geohydrologic regime of the Powder River Basin**

AUTHOR(S): Divis, S.A., and Tarquin, P.A.

YEAR OF PUBLICATION: 1981

PUBLISHER AND SERIES: Environmental Science Associates, Wheat Ridge, Colorado

PAGES: 109

REMARKS: A copy of the publication could not be located for examination.

TITLE: **The regional aquifer system underlying the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming--Summary**

AUTHOR(S): Downey, J.S., and Dinwiddie, G.A.

YEAR OF PUBLICATION: 1988

PUBLISHER AND SERIES: U.S. Geological Survey Professional Paper 1402-A

PAGES: 64; 3 plates

REMARKS: Professional Paper 1402 is a series of publications on the results of the Northern Great Plains Regional Aquifer-System Analysis. The entire Powder River Basin is a small part of the 300,000-mi^2 study area. Chapter A summarizes the findings of the investigation. Other chapters contain greater detail about the geologic framework (chapter B), geochemistry of ground water (chapter C), freshwater heads and ground-water temperatures (chapter D), and geohydrology of bedrock aquifers, including the use of a digital model to simulate the regional flow system (chapter E).

The uppermost of five major regional aquifers studied by the authors comprises the shallow aquifers of interest for this report. The "predevelopment (before 1950)" potentiometric surface (p. A25) indicates that this regional aquifer is recharged in and near the highland areas in the western and southwestern part of the study area, and water moves generally eastward and northeastward toward areas of discharge in Canada, North Dakota, and South Dakota. The largest heads mapped (p. A25) are in the southwestern part of the Powder River Basin near Glenrock. In the Powder River Basin part of the study area, flows are generally northward into Montana, and eastward toward the Cheyenne River. Water temperatures in the uppermost aquifer in the Powder River Basin range from less than 20 ^{o}C to more than 60 ^{o}C (p. A29); the dominant anion is bicarbonate (p. A42).

TITLE: **Base flow and chemical quality of streams in the Northern Great Plains area, Montana and Wyoming, 1977-78**

AUTHOR(S): Druse, S.A., Dodge, K.A., and Hotchkiss, W.R.

YEAR OF PUBLICATION: 1981

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 81-692

PAGES: 60; 1 plate

REMARKS: Base-flow discharge and chemical-quality measurements were made at 233 sites during three periods of base flow during 1977-78. The sampling dates were selected to quantify differences in discharge during periods of maximum and minimum evapotranspiration, and to exclude evapotranspiration and irrigation effects (p. 3). On October 17, 1978 [during a period of minimum evapotranspiration], there was a loss of 14 ft^3/s in the upper Powder River between Sussex and Arvada, Wyoming, and a gain of 6 ft^3/s on the lower Powder River between Arvada, Wyoming, and Moorhead, Montana [Moorhead is a few miles north of the Wyoming-Montana State line]. Except for August-September 1978 [a period of maximum evapotranspiration and irrigation], there were few differences in water discharge, chemical character, or dissolved-solids concentration in the major subbasins in the study area.

Conditions for 1978 were compared with long-term records for precipitation and runoff. Both precipitation and discharge were greater than normal in most of the basin, and base flows at selected stations during the investigation were several times greater than the median discharge based on period of record (p. 6-7).

TITLE: **Occurrence and characteristics of ground water in the Powder River Basin, Wyoming**

AUTHOR(S): Feathers, K.R., Libra, Robert, and Stephenson, T.R.

YEAR OF PUBLICATION: 1981

PUBLISHER AND SERIES: Wyoming Water Resources Research Institute report, University of Wyoming, Laramie

PAGES: 171, 4 appendices (v. I); 8 plates (v. II)

REMARKS: This is one of a Statewide series of publications funded by the U.S. Environmental Protection Agency to obtain background information for protection of ground-water resources from contamination caused by injection of wastes. The publication, compiled mostly from information in published reports, contains an extensive bibliography. Of four major bedrock aquifers identified by the authors in the Powder River Basin (p. 2), the upper two--the "Lower Tertiary Wasatch/Fort Union aquifer system" and the "Upper Cretaceous Fox Hills/Lance aquifer system"--and several local or minor aquifers, are of interest in the present assessment. For the major aquifers, the authors summarized published information to describe water use, quality, aquifer properties, recharge, movement, and discharge. The authors reported that aquifer recharge rates, ground-water flow paths, and the extent of interformational mixing are not well known (p. 2).

The "Lower Tertiary Wasatch/Fort Union aquifer system" is the most important source of ground water for rural-domestic, stock, and municipal supply in the central part of the basin.

> Recharge occurs principally through outcrop infiltration but downward water leakage may also occur. Topographic valleys are important discharge points. Although shallow water circulation is under topographically controlled water table conditions, deeper strata have dominantly stratigraphically controlled horizontal flow. Hydrologic conditions vary from water table to fully confined between and within individual water-bearing zones (p. 5-6).

The "Upper Cretaceous Fox Hills/Lance aquifer system" is used for industrial applications in the northeast part of the basin and municipal supplies in the southwest and northeast (p. 4). The authors assumed a regional or basinwide flow system, and defined the primary source of recharge to this aquifer as downward leakage from overlying aquifers. Some recharge occurs by infiltration of precipitation on outcrops. Discharge is mostly through subsurface flow to the north; there also is some discharge to major stream valleys (p. 5).

Other shallow aquifers described by these authors range in age from middle Tertiary to Quaternary. These are described as locally important water sources where they are present in the southeast, west, and south parts of the basin. The primary recharge mechanism is infiltration of precipitation on outcrops. Water from the Quaternary alluvial aquifers probably comes from the adjacent river (p. 4-7).

Transmissivity and water chemistry vary widely in the basin, mostly because of the varying lithologies. Transmissivity varies from about 1 (gal/d)/ft [0.13 ft^2/d] in the sandstone to 3,000,000 (gal/d)/ft [400,000 ft^2/d] in the clinker. Dissolved-solids concentrations range from 250 mg/L in outcrop areas to 6,500 mg/L in the central part of the basin, and show the greatest variation between shallow wells [which presumably are part of isolated local flow systems (p. 142), rather than the deeper regional system, which shows less variation]. The publication also contains trilinear plots showing the change in major-ion composition of ground water with depth.

TITLE: **Geochemistry of ground waters in the Powder River coal region, in Geochemical survey of the western energy regions, fourth annual progress report**

AUTHOR(S): Feder, G.L., Lee, R.W., Busby, J.F., and Saindon, L.G.

YEAR OF PUBLICATION: 1977

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 77-872

PAGES: 173-179

REMARKS: Samples from 20 sites within the basin (4 in Wyoming and 16 in Montana) were collected and analyzed. All samples were from geologic formations above the Pierre Shale. Average depth of sampling was about 100 meters (325 ft). Only wells used for domestic or livestock water supply were sampled. The water chemistry was found to change with depth. In shallow recharge areas, the pH was less than 8.0 and the dominant ions were calcium, magnesium, sulfate, and bicarbonate. In deeper zones and in discharge areas, the pH was greater than 8.0 and the dominant ions were sodium and bicarbonate.

[The samples collected in Wyoming for this investigation were from Campbell and Sheridan Counties. However, the authors generalized the findings for the entire Powder River Basin in Wyoming and Montana, and hypothesized that geochemical processes found here are similar to those operating in other coal regions in the Northern Great Plains.]

TITLE: **Geohydrology and potential effects of coal mining in 12 coal-lease areas, Powder River structural basin, northeastern Wyoming**

AUTHOR(S): Fogg, J.L., Martin, M.W., and Daddow, P.B.

YEAR OF PUBLICATION: 1991

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 87-4102

PAGES: 49; 2 plates

REMARKS: The geohydrology of 12 coal-lease areas is described in relation to the type of mining proposed for each area. Recharge and discharge areas, direction of ground-water flow, and possible effects of mining are identified. Local ground-water-flow systems, which develop where ground water flows from a topographic high to an adjacent low, and which have flow paths of a few thousand feet, are most likely to be affected by coal mining. If areas to be mined contain large outcrop areas of clinker, mining probably will decrease recharge to the local ground-water-flow system. If large outcrop areas of clinker are not present, mining probably will increase recharge to the local ground-water-flow system. Mining near discharge areas might decrease discharge to flowing wells and springs. Mining also will affect the quality of ground water available in the lease areas. Concentrations of dissolved solids in water from spoil aquifers generally are two to three times greater than in water from undisturbed coal aquifers. Concentrations of calcium, sulfate, nitrate, and selenium also are expected to be substantially larger in water from spoil aquifers than in water from undisturbed aquifers (p. 41-43).

TITLE: **Coal development alternatives--an assessment of water use and economic implications**

AUTHOR(S): Freudenthal, D.D., Ricciardelli, Peter, and York, M.N.

YEAR OF PUBLICATION: 1974

PUBLISHER AND SERIES: Wyoming Department of Economic Planning and Development report

PAGES: 101; 7 appendices with separate pagination

REMARKS: The publication focuses on socio-economic aspects of coal-development alternatives. "Coal mining is presented in terms of water utilized, land disturbed, employment required and associated population, and environmental implications" (p. iii). Specific processes for using the coal are described in similar terms and compared. Both processes involving shipping the coal out of State in its original form, and processes that convert the coal to another form of energy within the State are discussed. The scope of the publication was limited; the authors state (p. 11) that "Environmental concerns are not the major emphasis of this report. * * * Primary consideration was given to potential contamination of water by the [coal-development] processes. Once again, no attempt was made to predict actual levels of contamination or harmful effects."

TITLE: **Gillette Area Groundwater Monitoring Organization annual report 1987** (1987 report used as an example; reports published annually since at least 1982)

AUTHOR(S): Gillette Area Groundwater Monitoring Organization •

YEAR OF PUBLICATION: 1987

PUBLISHER AND SERIES: Gillette Area Groundwater Monitoring Organization annual report

PAGES: (unnumbered)

SCALE: 1 inch = approximately 1 mile

REMARKS: The publication contains a compilation of hydraulic-head data from more than 1,200 ground-water monitoring wells at 20 coal surface-mine sites. Water-quality data for backfill (spoils) also are included. Potentiometric surfaces and water-level changes are contoured; no text discussion, interpretation, or summary is provided.

TITLE: **Shallow ground water in selected areas in the Fort Union coal region--a preliminary appraisal of the impacts of surface mining on the shallow ground water resource**

AUTHOR(S): Ground-water Subgroup of Water Work Group, Northern Great Plains Resource Program

YEAR OF PUBLICATION: 1974

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 74-371

PAGES: 132

REMARKS: Ground water in the Lance-Fox Hills aquifer flows generally northward and discharges by upward leakage along the valleys of the Yellowstone River in Montana and the Tongue and Powder Rivers in Wyoming and Montana. In the Wasatch and Fort Union Formations, ground-water movement is controlled mainly by local topography. Water enters the system along interstream divides and moves downward and laterally toward the nearby valleys. Much of the ground water is discharged at springs, seeps, or wells, but some enters the alluvium along the stream valleys where it augments streamflow or underflow and eventually is dissipated by evapotranspiration.

The authors concluded that surface mining might decrease discharges in nearby springs and streams, and that surface mines located in the alluvium might decrease the amount of ground water in the alluvium and degrade the quality and decrease the quantity of streamflow. Special precautions might be needed to prevent contamination of underlying aquifers where mines are located in recharge areas. The most detrimental effect of mining on the ground-water system might be contamination by dissolved materials leached from excavated overburden or spoils.

TITLE: **Map showing some potential effects of surface mining of the Wyodak-Anderson coal, Gillette area, Campbell County, Wyoming**

AUTHOR(S): Hadley, R.F., and Keefer, W.R.

YEAR OF PUBLICATION: 1975

PUBLISHER AND SERIES: U.S. Geological Survey Miscellaneous Investigations Map I-848-F

PAGES: 1 sheet

SCALE: 1:125,000

REMARKS: The publication delineates areas where all aquifers above the base of the Wyodak-Anderson coal bed [in the Tongue River Member, Fort Union Formation] probably will be drained in the vicinity of mining operations. These areas form an irregular band from less than 1 to about 6 mi wide that crosses the study area from north-northwest to south-southeast and passes a few miles east of the city of Gillette. Surrounding this band is the area in which the coal aquifer will be drained and water levels in shallow aquifers less than 200 ft deep will be "moderately" affected. West of this area, and including the city of Gillette, is a band 2 to 5 mi wide, paralleling the band where all aquifers will be drained, but less irregular in shape, in which water levels in wells completed in the Wyodak-Anderson coal bed will be affected but water levels in wells completed in shallower aquifers probably will not be affected.

TITLE: **Groundwater flow, hydrochemistry, and uranium deposition in the Powder River Basin, Wyoming**

AUTHOR(S): Hagmaier, J.L.

YEAR OF PUBLICATION: 1971

PUBLISHER AND SERIES: unpublished Ph.D. dissertation, University of North Dakota, Grand Forks

PAGES: 166

REMARKS: The objective of this investigation was to relate ground-water flow to the uranium geology in the Powder River Basin. The author reconstructed the Tertiary ground-water-flow system, located the recharge and discharge areas, related this flow to processes affecting uranium transport and deposition, and compared Tertiary ground-water flow and hydrochemistry in the basin with those of the present.

The following quotation is from the abstract of the publication:

> The relation between regional groundwater flow, hydrochemistry, and uranium distribution in the Powder River Basin indicates that uranium was deposited during the Tertiary Period in groundwater recharge areas where the groundwater changed from a sulfate-bicarbonate water to a bicarbonate-rich water.
>
> The regional recharge and discharge areas of present-day groundwater-flow systems have about the same location as the recharge and discharge areas of the Tertiary groundwater-flow systems. The present-day groundwater is recharged in the eastern, western, and especially in the southern margins of the basin and is discharged in the valley of the Powder River, especially in the north. * * *
>
> The Tertiary groundwater-flow systems had a larger longitudinal flow component than present-day groundwater-flow systems. The present-day topography causes a large lateral and vertical groundwater-flow component toward the large river valleys. The topography during the Tertiary was a result of deposition and had little relief, whereas, the present-day topography is a result of erosion and has large relief.

> The groundwater chemistry of this area during the Tertiary was probably similar to that of today because the groundwater flowed through the same sediment as present-day groundwater. * * * An abrupt decrease in sulfate concentration [as ground water moves along the regional flow path from the southern recharge area to the northern discharge area] occurs where the sulfate is removed from solution * * * [probably] due to a strong reducing environment, which may be caused by sulfate-reducing bacteria.

Major unoxidized uranium deposits in the basin occur near the transition zone where sulfate is precipitated.

TITLE: **Chemical analyses of ground water in the Powder River Basin and adjacent areas, northeastern Wyoming**

AUTHOR(S): Hodson, W.G.

YEAR OF PUBLICATION: 1971a

PUBLISHER AND SERIES: Wyoming Department of Economic Planning and Development report

PAGES: 20

REMARKS: Chemical analyses of water samples from 490 wells and springs are presented without interpretation.

TITLE: **Logs of wells in Campbell County, Wyoming**

AUTHOR(S): Hodson, W.G.

YEAR OF PUBLICATION: 1971b

PUBLISHER AND SERIES: Wyoming State Engineer's Office, Wyoming Water Planning Program Report No. 8

PAGES: 210

REMARKS: The publication presents 1,200 lithologic logs with no interpretation.

TITLE: **Water resources of the Powder River Basin and adjacent areas, northeastern Wyoming**

AUTHOR(S): Hodson, W.G., Pearl, R.H., and Druse, S.A.

YEAR OF PUBLICATION: 1973

PUBLISHER AND SERIES: U.S. Geological Survey Hydrologic Investigations Atlas HA-465

PAGES: 4 sheets

SCALE: 1:250,000

REMARKS: The authors infer that ground-water recharge and discharge were in balance, as shown by slight annual water-level fluctuations in observation wells. Prior to 1973, before major coal mining began, most ground-water development had been for stock and domestic purposes; hence, wells were drilled to have sufficient yield for those needs only.

Availability and chemical quality of ground water are described for each formation. Potential yields to wells in the alluvium range from a few gal/min to more than 1,000 gal/min, depending on saturated thickness, grain size, and sorting. Water quality also varies widely; dissolved-solids concentrations range from 100 to more than 4,000 mg/L, but generally are between 500 and 1,500 mg/L (sheet 3).

The Wasatch Formation yields water from lenticular sandstone. Expected yields can be as much as an order of magnitude greater in the southern part of the basin (500 gal/min or more) than in the northern part (10 to 50 gal/min). In general, dissolved-solids concentrations range from 500 to 1,500 mg/L and are less in the southern than in the northern part of the basin. Dominant water types are sodium sulfate and sodium bicarbonate.

The Fort Union Formation yields water from fine-grained sandstone, jointed coal, and clinker beds, with maximum yield of about 150 gal/min. Water quality is similar to that in the overlying Wasatch Formation.

The Lance Formation generally yields less than 20 gal/min, although yields of several hundred gallons per minute may be possible for the complete section. Dissolved-solids concentrations generally range from 500 to 1,500 mg/L; there is no consistent water type.

Yields from the Fox Hills Sandstone vary from as much as 200 gal/min in the eastern part of the basin to less than 100 gal/min in the western part of the basin. Dissolved-solids concentrations generally are less than 1,000 mg/L in the east and range from 1,000 to 2,000 mg/L in the west; no dominant water type is prevalent.

TITLE: **Hydrogeology and simulation of water flow in strata above the Bearpaw Shale and equivalents of eastern Montana and northeastern Wyoming**

AUTHOR(S): Hotchkiss, W.R., and Levings, J.F.

YEAR OF PUBLICATION: 1986

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 85-4281

PAGES: 72

REMARKS: Five hydrogeologic units above the Bearpaw Shale (three aquifers and two confining layers) were studied. Some of the hydrogeologic units were named on the basis of rocks that are present only in Montana. From youngest to oldest, they are the Tongue River aquifer [includes Wasatch, White River, and Arikaree Formations where present], the Lebo confining layer, the Tullock aquifer [includes part of the lower part of the Fort Union Formation], upper Hell Creek confining layer [includes part of the upper part of the Lance Formation], and Fox Hills-lower Hell Creek aquifer [includes part of the lower part of the Lance Formation] (p. 10). Potentiometric-surface maps prepared for the units indicate that, in general, the deeper aquifers have larger hydraulic heads than do the shallower aquifers. Thus, the authors concluded that the study area is a [regional] discharge area [of the larger Northern Great Plains area?], except near outcrop areas (p. 23). For the shallowest hydrogeologic units, the major sources of recharge were identified as infiltration of water from precipitation on areas of outcrop and infiltration from losing streams. [A subregional flow system is superimposed on the regional system. For the subregional system,] discharge areas are outflow along the northeastern boundary of the study area [in Montana], loss of ground water to gaining streams, springs and seeps, evapotranspiration, and pumpage.

A water budget computed during the modeling phase of the investigation indicated that the shallowest hydrogeologic unit also loses water by leakage to the underlying confining layer [Lebo Member of the Fort Union Formation and equivalents] (p. 62). Both the modeled and the measured potentiometric-surface maps for all five of the hydrogeologic units indicate a generally northward regional flow in the Wyoming part of the basin (p. 57-61). Although the scale of the model is such that detail is insufficient to show stream-aquifer interaction, the potentiometric surface indicates there should be substantial discharge to the Powder River from the aquifer.

TITLE: **An assessment of cumulative impacts of coal mining on hydrology in part of the Powder River structural basin, Wyoming--a progress report**

AUTHOR(S): Jordan, P.R., Bloyd, R.M., and Daddow, P.B.

YEAR OF PUBLICATION: 1984

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 83-4235

PAGES: 25

REMARKS: The publication presents preliminary results of a model study assessing the effects of surface mining of coal on streamflow in the Caballo Creek drainage. The authors refer to this drainage as "typical" of others in the Powder River structural basin (p. 5). "Three model simulations show little, if any, change in streamflow between premining and postmining conditions and very little change between premining and during-mining conditions. The principal reasons for the absence of change are the small fraction of the drainage area that is mined and the rapid rate of infiltration used in the model for all three conditions" (p. 1).

The authors present a conceptual model of the ground-water-flow system (p. 11). Recharge to the aquifers above the Wyodak-Anderson coal bed is assumed to come from infiltration of precipitation and streamflow, and to average 0.2 in/yr. Principal recharge to the coal is assumed to occur at outcrop areas; recharge to the underburden (Lebo Shale Member of the Fort Union Formation) is from an unidentified source in the southern part of the study area. Under natural conditions, the general direction of ground-water flow is from south to north. There is also some downward flow between the layers--from the overburden into the coal, and possibly from the coal into the underburden.

TITLE: **Land and natural resource information and some potential environmental effects of surface mining of coal in the Gillette area, Wyoming**

AUTHOR(S): Keefer, W.R., and Hadley, R.F.

YEAR OF PUBLICATION: 1976

PUBLISHER AND SERIES: U.S. Geological Survey Circular 743

PAGES: 27

REMARKS: In addition to information noted in table 1, the publication contains a summary data table with information on trace-element geochemistry of the coal and overburden. The potentiometric-surface map and maps showing direction of ground-water movement and dissolved-solids concentrations are from King (1974). The section on environmental effects includes discussions of land disturbance, topographic changes (the average land-surface elevation is predicted to drop by 60 ft), effects on ground-water levels, changes in surface-drainage patterns, and geochemical changes. Much of this material is from King (1974) and Hadley and Keefer (1975). Geochemical changes most likely will result from bringing deeply buried rock closer to the surface and (or) exposing overburden to natural cycles of leaching, weathering, and erosion. Some analyses indicate that larger concentrations of some trace elements are present in deeper overburden than in near-surface materials. The implications are unclear--the authors note that even if large concentrations of some metals are present in the formation, this does not necessarily imply that toxic concentrations in ground water would result from oxidation and leaching.

TITLE: **Ground-water levels in Wyoming, 1978 through September 1987**

AUTHOR(S): Kennedy, H.I., and Green, S.L.

YEAR OF PUBLICATION: 1988

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 88-187

PAGES: 132

TITLE: **Ground-water levels in Wyoming, 1980 through September 1989**

AUTHORS: Kennedy, H.I., and Green, S.L.

YEAR OF PUBLICATION: 1990

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 90-106

PAGES: 132

TITLE: **Ground-water levels in Wyoming, 1976 through 1985**

AUTHOR(S): Kennedy, H.I., and Oberender, C.B.

YEAR OF PUBLICATION: 1987

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 87-456

PAGES: 122

REMARKS: Many of the observation wells listed in these three publications are in agricultural areas; coverage is sparse in the Powder River Basin in formations of interest. Other publications of ground-water levels are: Ballance and Freudenthal (1975; 1976; 1977); Ragsdale (1982); Ragsdale and Oberender (1985); Ringen (1973; 1974); and Stevens (1978).

TITLE: **Maps showing occurrence of ground water in the Gillette area, Campbell County, Wyoming**

AUTHORS: King, N.J.

YEAR OF PUBLICATION: 1974

PUBLISHER AND SERIES: U.S. Geological Survey Miscellaneous Investigations Map I-848-E

PAGES: 1 sheet

SCALE: 1:125,000

REMARKS: Aquifers that are less than 500 feet deep in the study area are "* * * composed largely of interbedded sandstone, siltstone, mudstone, and shale; all contain some coal" (pl. 1). The units are generally similar in their water-bearing characteristics. The potentiometric surface in the southern part of the study area slopes generally eastward, echoing the topography. In the northern part of the area, the slope is generally northward. Water levels generally decline with increasing depth. Water quality "* * *seem[s] to reflect lithologic changes within the formations that underlie the area* * *" (pl. 1), and improves with depth.

The maps in this publication, especially the potentiometric-surface map showing the direction of ground-water movement, have been reproduced in several publications on the Powder River Basin including Feathers and others (1981), Ground Water Subgroup (1974), Keefer and Hadley (1976), and several others.

TITLE: **Monitoring and modeling the shallow ground-water systems in the Powder River Basin**

AUTHOR(S): Koch, Donald, Ringrose, C.D., Moore, R.C., and Brooks, D.L.

YEAR OF PUBLICATION: 1982

PUBLISHER AND SERIES: Hittman Associates, Englewood, Colo: report to U.S. Bureau of Mines

PAGES: 359; appendices A through U in separate volume

REMARKS: The authors investigated regional impacts of mining on the ground-water system by establishment of a regional ground-water monitoring network and development of regional and subregional ground-water flow and quality models that incorporated components dealing with ground-water contributions to surface flow, runoff, and recharge. The basin was modeled as a large, homogeneous, unconfined aquifer, with a leaky confining bed beneath (p. V-55). The authors adopted this approach on the basis of the coarse scale of the model (each node represents 38.5 mi^2) and an assumption of the existence of a regionally continuous flow system (p. V-55).

The models indicated that drawdowns might extend west from the mines as far as 40 km [24 mi] (p. V-75), but impacts would be insignificant on a regional scale. The authors expected impacts to be small, because the mines in the Powder River Basin all are located in recharge areas and because topographic variations in the basin are larger than mine depths (p. V-81). [The authors do not explain why locations in recharge areas are better than locations in intermediate or discharge areas.] After reclamation, the authors expect the regional ground-water-flow system to return to its premining configuration (p. V-82). Impacts of mining on regional ground- and surface-water quality are expected to be negligible because of the large distances and slow movement of ground water in the basin. Impacts are expected to be "significant" [not quantified or defined in the publication] in the immediate vicinity of the mines.

TITLE: **Geology and ground-water resources of the Kaycee irrigation project, Johnson County, Wyoming, <u>with a section on</u> Chemical quality of the water**

AUTHOR(S): Kohout, F.A.; water-quality section: F.H. Rainwater

YEAR OF PUBLICATION: 1957

PUBLISHER AND SERIES: U.S. Geological Survey Water-Supply Paper 1360-E

PAGES: 321-374; plates 22-23

REMARKS: The investigation was made prior to the extension of irrigation in the Kaycee area, to aid in evaluating drainage and water-quality effects. The authors concluded that waterlogging problems, already present in some of the area, could develop in as much as 25 percent of the Kaycee study area.

TITLE: **Natrona County, Wyoming** [Geologic map atlas and summary of land, water, and mineral resources]

AUTHOR(S): Lageson, D.R., DeBruin, R.J., Hausel, W.D., Glass, G.B., Ver Ploeg, A.J., and Stephenson, T.R.

YEAR OF PUBLICATION: 1980

PUBLISHER AND SERIES: The Geological Survey of Wyoming County Resource Series, no. CRS-6

PAGES: 8 sheets

SCALE: 1:250,000 and 1:500,000

REMARKS: The publication is structured similarly to that of Breckenridge and others (1974). Separate sheets show a Landsat image of the county; petroleum, uranium, coal, and mineral resources; and "environmental" information, including streamflow, climate and precipitation, and geologic hazards. A section on water resources contains a geologic map showing aquifers (formations that have the potential to be developed for a ground-water source); pie charts showing the relative proportion of major ions and the approximate range of dissolved-solids concentrations for both surface and ground water; and a table showing lithology, water-yielding characteristics, and water quality for each formation in the county. Much of the information presented in this section is from Hodson and others (1973).

Other publications in this series are:

Campbell County (Breckenridge and others, 1974)

Converse County (Lane and others, 1972)

Johnson County (Wendell and others, 1976)

TITLE: **Geologic map atlas and summary of economic mineral resources of Converse County, Wyoming**

AUTHOR(S): Lane, D.W., in collaboration with Root, F.K., and Glass, G.B.

YEAR OF PUBLICATION: 1972

PUBLISHER AND SERIES: The Geological Survey of Wyoming County Resource Series, no. CRS-1

PAGES: 22

REMARKS: A copy of the publication could not be located for examination. Other publications in this series are:

Campbell County (Breckenridge and others, 1974)

Johnson County (Wendell and others, 1976)

Natrona County (Lageson and others, 1980)

TITLE: **General availability of ground water and depth to water level in the Missouri River basin**

AUTHOR(S): LaRocque, G.A., Jr.

YEAR OF PUBLICATION: 1966

PUBLISHER AND SERIES: U.S. Geological Survey Hydrologic Investigations Atlas HA-217

PAGES: 1 sheet

SCALE: 1:2,500,000

REMARKS: The map shows information for those areas where the water quality is expected to be "generally satisfactory for most ordinary uses" [the limiting water-quality values were not quantified], and depth to water is shown for areas in which expected well yields are greater than 50 gal/min. The alluvial river valleys are the only areas in the Powder River Basin that fit these criteria for water supply. [Later investigators (Ringen and Daddow, 1990) have indicated that the alluvium is not separate from the stream. Water rights might become an issue if the Powder River alluvium were to be considered as a water source, since the river is fully appropriated.]

TITLE: **Ground-water quality in Wyoming**

AUTHOR(S): Larson, L.R.

YEAR OF PUBLICATION: 1984

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 84-4034

PAGES: 71

REMARKS: Dissolved-solids concentrations are summarized by aquifer for each county in the State. Also, dissolved-solids, nitrate, fluoride, iron, manganese, and selenium concentrations are summarized, by aquifer, on a statewide basis.

TITLE: **Coal-spoil and ground-water chemical data from two coal mines; Hanna Basin and Powder River Basin, Wyoming**

AUTHOR(S): Larson, L.R.

YEAR OF PUBLICATION: 1988

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 88-481

PAGES: 18

REMARKS: These data were collected as part of an investigation of methods used to predict postmining water quality of aquifers affected by surface mining of coal (see Naftz, 1990). The study sites were the combined Medicine Bow-Seminoe Number 1 Mines (outside the Powder River Basin) and the Cordero Mine in Campbell County. The tabulated data consist of X-ray diffraction, saturated paste-extract, and sulfur-forms analyses of spoils samples; chemical analyses of water samples from batch-mixing experiments; and common-constituent and trace-constituent analyses of water samples from wells in spoil and coal aquifers.

TITLE: **Ground-water-quality data from the Powder River structural basin and adjacent areas, northeastern Wyoming**

AUTHOR(S): Larson, L.R., and Daddow, R.L.

YEAR OF PUBLICATION: 1984

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 83-939

PAGES: 56; 1 plate

REMARKS: Major-ion data for 748 ground-water sites [not all of which are in the shallow aquifers of interest for the present report], trace-metal data for 220 sites, and radiochemical data for 65 sites are presented in three tables without interpretation.

TITLE: **Evapotranspiration rates at selected sites in the Powder River Basin, Wyoming and Montana**

AUTHOR(S): Lenfest, L.W., Jr.

YEAR OF PUBLICATION: 1984

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 82-4105

PAGES: 23

REMARKS: The following quotation is from the publication abstract:

> Evapotranspiration rates for the 1978 growing season were estimated by the Blaney-Criddle method for 12 sites within the Powder River Basin. The mean rate was 12.7 in., standard deviation 2.0 in. Discharge from alluvial aquifers was calculated by multiplying the rate of evapotranspiration by the net surface area where evapotranspiration occurs. Average discharge in 1978 ranged from 0.03 to 0.31 (ft^3/s)/mi of river reach. The net surface area has a greater effect on the discharge than does the rate of evapotranspiration.

TITLE: **Recharge of shallow aquifers through two ephemeral-stream channels in northeastern Wyoming, 1982-83**

AUTHOR(S): Lenfest, L.W., Jr.

YEAR OF PUBLICATION: 1987

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 85-4311

PAGES: 29

REMARKS: A reach of the North Fork Dry Fork Cheyenne River near Glenrock, Wyoming, and a reach of Black Thunder Creek near Hampshire, Wyoming, were instrumented to quantify the recharge from the streams to the alluvial and bedrock aquifers. Computed losses from streamflow measurements ranged from 0.43 acre-ft/mi to 1.44 acre-ft/mi at North Fork Dry Fork Cheyenne River. Ground-water recharge computed using a convolution technique was estimated to be 26.5 acre-ft/mi at North Fork Dry Fork Cheyenne River, and ranged from 3.56 to 12.4 acre-ft/mi at Black Thunder Creek. Observation wells completed in the alluvial aquifer were dry during flow of the North Fork Dry Fork Cheyenne River, but water levels in observation wells completed in the bedrock aquifer rose in response to flow in both rivers.

TITLE: **Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming**

AUTHOR(S): Lewis, B.D., and Hotchkiss, W.R.

YEAR OF PUBLICATION: 1981

PUBLISHER AND SERIES: U.S. Geological Survey Miscellaneous Investigations Map I-1317

PAGES: 6 sheets

SCALE: 1:1,000,000

REMARKS: The shallow aquifer system of the basin is composed of five hydrogeologic units. The authors describe the units as "areally extensive." From youngest to oldest, they are the Tongue River-Wasatch aquifer, the Lebo confining layer, the Tullock aquifer, upper Hell Creek confining layer [upper part of the Lance Formation], and Fox Hills-lower Hell Creek [Lance] aquifer. The average sand content of the aquifers is 50 to 54 percent, which indicates that the units function as aquifers in most of the basin. Average sand content for the confining layers is 31 to 35 percent. Separate maps are provided for thickness, percent sand, and elevation of the base for each of the five units.

TITLE: **Ground-water conditions in the vicinity of Gillette, Wyoming, with a section on the quality of ground water**

AUTHOR(S): Littleton, R.T.; water-quality section: H.A. Swenson

YEAR OF PUBLICATION: 1950

PUBLISHER AND SERIES: U.S. Geological Survey Circular 76

PAGES: 43; 3 plates

REMARKS: The investigation was conducted to provide information for locating a supply of ground water "of better quality and greater quantity" for Gillette [the largest municipality in the Powder River Basin depending solely on ground water]. The population of Gillette then was about 3,150 (p. 1). A tabulation of records of 62 wells, test holes, and springs is included. Gillette, together with what then were called the Wyodak Manufacturing Co. and the Chicago, Burlington, and Quincy Railroad, has a long history of struggle to obtain a sufficient supply of water with tolerable dissolved-solids concentrations. The authors concluded (p. 28) that "It seems likely that enough water is available in the sandstones of the Wasatch and Fort Union formations [sic] to supply the city's present and future water needs." [Subsequent population growth of nearly five-fold has caused concern for decreasing water levels; see Crist (1991).]

TITLE: **Hydrology of the uppermost Cretaceous and the lowermost Paleocene rocks in the Hilight oil field, Campbell County, Wyoming**

AUTHOR(S): Lowry, M.E.

YEAR OF PUBLICATION: 1973

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 73-161

PAGES: 60; 5 plates

REMARKS: The publication contains detailed descriptions of the geology and potentiometric surface for a small area [about 5 by 10 mi]. The author attempted to model ground-water flow in the area in two dimensions, assuming flow was parallel to bedding planes. Because the model did not adequately represent ground-water flow, he concluded that there is a significant vertical component to the ground-water-flow system, and recharge to the Lance-Fox Hills aquifer in the center of the basin is largely from overlying formations (p. 47-48).

TITLE: **Ground-water resources of Sheridan County, Wyoming**

AUTHOR(S): Lowry, M.E., and Cummings, T.R.

YEAR OF PUBLICATION: 1966

PUBLISHER AND SERIES: U.S. Geological Survey Water-Supply Paper 1807

PAGES: 77; 1 plate

REMARKS: Part of the county is not in the Powder River Basin; therefore, some of the general statements about ground water may not be applicable to the basin. The authors concluded that rocks of Tertiary age generally yield sufficient quantities of water for stock or domestic use. Water may occur under water-table, artesian, or a combination of artesian and gas-lift conditions. The conditions might vary over short distances because of the lenticular nature of the aquifer. Water generally is suitable for domestic purposes, although large iron and (or) dissolved-solids concentrations are present in some areas. Hydrogen sulfide also is a concern in some locations. Sodium-bicarbonate-type water makes much of the Fort Union Formation an unsuitable source of water for irrigation.

TITLE: **Assessment of the hydrologic system and hydrologic effects of uranium exploration and mining in the Southern Powder River Basin Uranium District and adjacent areas, Wyoming, 1983**

AUTHOR(S): Lowry, M.E., Daddow, P.B., and Rucker, S.J., IV

YEAR OF PUBLICATION: in press

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 90-4154

PAGES: (not available)

REMARKS: This publication describes the shallow hydrologic system in the study area, mining activities as of 1983, and potential adverse effects on quantity and quality of ground water used for domestic and stock-watering supplies. The study area covered most of the northern two-thirds of Converse County. Most water is developed from the Wasatch and Fort Union Formations; most uranium exploration and mining was in the Wasatch Formation. The authors concluded that shallow ground-water movement in the area has restricted vertical flow and there is little or no discharge to major streams [in contrast with the hypothesis of some investigators that there is a large component of vertical flow and substantial discharge to major streams]. No regional pattern of water-level change caused by exploration or mining was found. Stock-water and domestic-supply wells in all but one lease area were in shallower aquifers than those used for mine wells. At one lease area, pumpage for mine supplies and dewatering caused decreased artesian flow in some relatively deep agricultural wells completed in the same horizon as the mine wells. No adverse effects on water quality were found that might have been caused by vertical flow through incompletely plugged exploration holes. Many of the approximately 115,000 holes drilled by 1981 were unplugged or incompletely plugged; however, despite an extensive search, only a few holes were located and inspected.

TITLE: **Water resources of Weston County, Wyoming**

AUTHOR(S): Lowry, M.E., Head, W.J., Rankl, J.G., and Busby, J.F.

YEAR OF PUBLICATION: 1986

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 84-4079

PAGES: 33; 1 plate

REMARKS: The Fox Hills Sandstone and the Lance and Fort Union Formations were grouped into one geohydrologic unit. The areas of the geohydrologic units are shown on plate 1; also shown are locations of water wells and information about each well, including depth and the geohydrologic unit in which the well was completed. The hydraulic conductivity, estimated from tests of wells in other parts of the Powder River Basin, averaged 1.5 ft/d. However, the authors reported that wells with yields of 200 to 500 gal/min are possible in some areas with large thicknesses of the geohydrologic unit. The dominant ions are sodium, sulfate, and bicarbonate.

TITLE: **Hydrology of the White Tail Butte area, northern Campbell County, Wyoming**

AUTHOR(S): Lowry, M.E., and Rankl, J.G.

YEAR OF PUBLICATION: 1987

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 82-4117

PAGES: 47

REMARKS: Potentiometric-surface maps indicate that the study area is a regional discharge area. However, chemical quality of water in wells is characteristic of water found in recharge areas. The authors concluded that movement of water in the regional system is apparently small compared to local discharge.

Two aquifer systems, separated by the Lebo Member of the Fort Union Formation, are discussed. Regional movement in the lower system is northward through the study area (p. 33). Regional flow data for the upper system were available only for the Wyodak coal aquifer [in the Tongue River Member, Fort Union Formation] south of the study area. Recharge to the Wyodak coal aquifer occurs at the outcrop south of Gillette. Regional movement is northward. North of Gillette, the coal outcrop is a discharge area (p. 41). At the time this publication was prepared, only the Wyodak mine east of Gillette was operating; the rest of the system was in a predevelopment condition. The effects of mining on the hydrology are discussed briefly.

TITLE: **Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana**

AUTHOR(S): Lowry, M.E., Wilson, J.F., Jr., and others

YEAR OF PUBLICATION: 1986

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545

PAGES: 137

REMARKS: This publication, written for the nontechnical audience, has simplified text and many illustrations. In addition to information described in table 1, the publication covers physiography, economic development, surface-water quantity and quality, and suspended sediment. The publication has information about water-data sources and an extensive bibliography.

"Analysis of streamflow and water-level data indicates that discharge to streams from local ground-water systems is greater than discharge from a regional ground-water system" (p. 54). Although the water levels indicated that the Powder River should be gaining flow, analysis of records indicated the river is losing flow. The shapes of flow-duration curves also indicated no ground-water contribution to streamflow.

A map of the potentiometric surface in the School coal bed [in the Wasatch Formation] and the Wyodak-Anderson coal bed [in the Tongue River Member of the Fort Union Formation] shows flow towards the north and east in most of the area, but flow is westward near the Wyoming-Montana border (p. 93). The authors caution that this might not be a true representation of the regional potentiometric surface, because no data are available to determine how northward and westward flows are related. The publication also presents information about the availability and chemical quality of ground water, by geologic formation. Median dissolved-solids concentrations for the shallow aquifers ranged from 943 to 1,700 mg/L, but the range was very large--from 106 to more than 8,000 mg/L (p. 95).

TITLE: **Cumulative potential hydrologic impacts of surface coal mining in the eastern Powder River structural basin, northeastern Wyoming**

AUTHOR(S): Martin, L.J., Naftz, D.L., Lowham, H.W., and Rankl, J.G.

YEAR OF PUBLICATION: 1988

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 88-4046

PAGES: 201; 5 plates

REMARKS: In addition to the information described in table 1, the publication contains information about the area disturbed by mining in 1986, the projected maximum area to be disturbed by mining over the life of the mines, and a frequency distribution of hydraulic-conductivity measurements. Infiltration into reclaimed soils, sediment yield of reclaimed soils, and stability of reclaimed drainage basins also are addressed.

The areal extent of cumulative declines caused by mining is shown on a plate. The authors concluded (p. 26-28) that declines will not be significant in the Wasatch aquifer (which overlies the coal) beyond about 2,000 ft from the mine pit (p. 26). In the Wyodak coal aquifer [in the Tongue River Member of the Fort Union Formation], the area where cumulative drawdowns may exceed 5 ft extends 4 to 8 mi beyond the mine pit. Underlying aquifers are not expected to be substantially affected by mining, but might be affected by withdrawals from wells supplying facilities at the mines. The existence and quality of alternative sources of water also are discussed (p. 30-34).

Most postmining water is expected to be of suitable quality to meet the State standard for livestock watering, and to be of similar quality to that currently present in the study area. Increases in dissolved-solids concentrations in postmining ground water could be minimized by isolation of overburden material with large soluble-salt content to areas above the postmining ground-water table, decreasing rates of surface-water infiltration in the spoil aquifer, and isolation of spoil material with large soluble-salt content from clay-rich and organic-rich strata during backfilling (p. 2).

TITLE: **Assessment of energy resource development impact on water quality: the Tongue and Powder River basins**

AUTHOR(S): Melancon, S.M., Hess, B.C., and Thomas, R.W.

YEAR OF PUBLICATION: 1979

PUBLISHER AND SERIES: U.S. Environmental Protection Agency, Office of Research and Development report EPA-600/7-79-249

PAGES: 197

REMARKS: A copy of the publication could not be located for examination.

TITLE: **Reconnaissance of the geology and ground-water resources in the Cheyenne River drainage basin in northern Converse County, Wyoming**

AUTHOR(S): Morris, D.A.

YEAR OF PUBLICATION: 1956

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 56-83

PAGES: 14

REMARKS: This reconnaissance investigation was conducted to determine if adequate water of suitable quality for irrigation of hay was available in bottomlands along the mainstem and tributaries of the Cheyenne River. The publication includes information about the local ground-water characteristics of the Wasatch and Fort Union Formations and the alluvium along the valley of the Cheyenne River. The author concluded (p. 10) that the alluvium, particularly in buried channels, would be the best source of water for irrigation.

TITLE: **Geochemistry of batch-extract waters derived from spoil material collected at the Cordero coal mine, Powder River Basin, Wyoming**

AUTHOR(S): Naftz, D.L.

YEAR OF PUBLICATION: 1990

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 87-4200

PAGES: 58

REMARKS: Laboratory simulation of geochemical processes in saturated spoil materials at surface coal mines and actual postmining water quality were compared. Detailed mineralogical analyses of the spoil material were included in the laboratory simulations. The author used samples of spoil material and water from the spoil aquifer and the coal aquifer to conduct and evaluate batch-mixing experiments, which are used at some mines to predict postmining water quality. From the publication abstract (p. 1-2):

> Contact of water from the spoil aquifer with fresh spoil material caused only small changes in major-element concentrations and in pH, unless sulfide oxidation or contact with soluble salts * * * occurred. In contrast, large changes in major-element concentrations resulted when water from the coal aquifer contacted the spoil material. * * * samples obtained from the batch-mixing experiments using water from the coal aquifer contained smaller concentrations of calcium, magnesium, sodium, chloride, and sulfate compared to the water in the spoil aquifer. * * * The major-ion concentrations and pH obtained from the batch-mixing experiments using water from the coal aquifer possibly represent the long-term postmining ground-water quality in the spoil aquifer. [See Larson (1988) for the compilation of solid-phase and water-quality data collected at this mine and one other.]

TITLE: **Ground-water levels in Wyoming, 1971 through part of 1980**

AUTHOR(S): Ragsdale, J.O.

YEAR OF PUBLICATION: 1982

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 82-859

PAGES: 200

TITLE: **Ground-water levels in Wyoming, 1974 through 1983**

AUTHOR(S): Ragsdale, J.O., and Oberender, C.B.

YEAR OF PUBLICATION: 1985

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 85-403

PAGES: 194

REMARKS: Other publications of ground-water levels are: Ballance and Freudenthal (1975; 1976; 1977); Kennedy and Green (1988; 1990); Kennedy and Oberender (1987); Ringen (1973; 1974); and Stevens (1978).

TITLE: **Potential of coal strip-mine spoils as aquifers in the Powder River Basin**

AUTHOR(S): Rahn, P.H.

YEAR OF PUBLICATION: 1976

PUBLISHER AND SERIES: South Dakota School of Mines and Technology, Rapid City, report prepared for Old West Regional Commission

PAGES: 108; appendices I through VI in separate volume

REMARKS: Field and laboratory methods were used to determine hydrologic characteristics of spoils at six surface coal mines. Permeability was related to method of emplacement. Aquifer tests at two mine sites in western Sheridan County indicted an average permeability of 450 (gal/d)/ft [60 ft^2/d] and an average storage coefficient of 0.17 for a site with dragline-emplaced spoils, and an average permeability of 4 (gal/d)/ft [0.5 ft^2/d] and an average storage coefficient of 0.23 for a site with scraper-and-bulldozer-emplaced spoils. The abstract (p. 1) states, "Spoils emplaced by dragline show higher laboratory permeability than those emplaced by scraper or truck. This is presumably due to greater compaction caused by machinery moving over the surface of the spoils." [This statement from the abstract is not supported by data in table 5 (p. 102), which indicate slightly smaller average permeability for dragline-dumped spoils than for scraper and truck spoils, and an infiltration rate for dragline less than one-half of the rate for scraper and truck.] Areas with large proportions of alluvium or sandstone in the overburden had substantially larger values of laboratory permeability than those where overburden consists chiefly of siltstone or shale.

Water in spoils had greater concentrations of calcium, magnesium, sulfate, and dissolved solids than water from wells in the Tongue River Member of the Fort Union Formation. Sulfate concentrations in both natural ground water and spoils water, and dissolved-solids concentrations in spoils water, were considered excessive for drinking water and for irrigation.

TITLE: **Ground-water flow systems in the Powder River structural basin, Wyoming and Montana**

AUTHOR(S): Rankl, J.G., and Lowry, M.E.

YEAR OF PUBLICATION: 1990

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 85-4229

PAGES: 39; 1 plate

REMARKS: The authors evaluated evidence of flow systems in the alluvium, the Wasatch, Fort Union, and Lance Formations, and the Fox Hills Sandstone. Most aquifers are heterogeneous, mostly shale, with sandstone in isolated lenses. The authors anticipated finding northward regional ground-water flow that is controlled stratigraphically, on the basis of potentiometric data, but could not identify discharge from shallow wells or from the water quality of springs. The authors also examined base-flow data for streams, because the potentiometric data indicate that base flow should be present. Ground-water contribution to streamflow could not be identified in streamflow records examined in this investigation--alluvium and clinker affect streamflow more than the bedrock aquifers. The authors concluded (p. 37) that because there is no important regional flow system, impacts from surface mining and water development will be local; more work is needed to understand local and subregional flow systems and their relation to a regional system.

TITLE: **Records of ground-water levels in Wyoming, 1940-1971**

AUTHOR(S): Ringen, B.H.

YEAR OF PUBLICATION: 1973

PUBLISHER AND SERIES: Wyoming State Enginner's Office, Wyoming Water Planning Program Report No. 13

PAGES: 479

TITLE: **Ground-water levels in Wyoming, 1972-1973**

AUTHOR(S): Ringen, B.H.

YEAR OF PUBLICATION: 1974

PUBLISHER AND SERIES: Wyoming State Engineer's Office, Wyoming Water Planning Program Report No. 13, Supplement No. 1

PAGES: 158

REMARKS: These two data publications list water-level measurements for wells that have sufficient data to show a trend. Other publications of ground-water levels are: Ballance and Freudenthal (1975; 1976; 1977); Kennedy and Green (1988; 1990); Kennedy and Oberender (1987); Ragsdale (1982); Ragsdale and Oberender (1985); Stevens (1978).

TITLE: **Hydrology of the Powder River alluvium between Sussex, Wyoming and Moorhead, Montana**

AUTHOR(S): Ringen, B.H., and Daddow, P.B.

YEAR OF PUBLICATION: 1990

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 89-4002

PAGES: 48

REMARKS: The purpose of this investigation was to describe the hydrology and evaluate the potential for developing water supplies from the Powder River alluvium between Sussex, Wyoming and Moorhead, Montana. The authors concluded that the alluvium is in good hydrologic connection with the river, and that nearly all of the water in the alluvium is seepage from the river, stored during periods of high streamflow and discharged back to the river in the reach near Sussex during low flow. A substantial percentage of the pumped water produced by a well completed in the alluvium would be derived from the river. The percentage of the total water pumped that would be derived from the river increases with length of time the well is pumped or decreasing distance from the well to the river (p. 40).

Water quality in the alluvium was found to be similar to water quality in the river (p. 35-36). Dominant ions were sodium, calcium, and sulfate. The water quality generally is not acceptable for drinking (dissolved-solids concentrations exceed 1,500 mg/L). In contrast, water from selected wells in the bedrock (Wasatch Formation) in the vicinity of the Powder River was a sodium bicarbonate type, with dissolved-solids concentrations less than 600 mg/L (p. 36).

The authors concluded (p. 40) that:

> * * * the potential for developing water supplies from the alluvium along the Powder River is limited. The areal extent of the alluvium and the saturated thickness generally are not large. Water in the alluvium is supplied primarily by the river, which was dry periodically. Pumpage from wells completed in the alluvium is highly dependent on water derived directly from the river, particularly from wells close to the river. The quality of water in the alluvium also limits its use as a water supply, being unacceptable for drinking water, acceptable for most livestock, and marginal for irrigation or industrial use.

The authors also concluded (p. 39) that the bedrock (Wasatch and Fort Union Formations) is isolated from the alluvium and the river. [Other studies of the area (Hotchkiss and Levings, 1986; Hagmaier, 1971) indicated that the shallow aquifers should discharge to the river.]

TITLE: **Ground-water levels in Wyoming, 1977**

AUTHOR(S): Stevens, M.D.

YEAR OF PUBLICATION: 1978

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 78-605

PAGES: 203

REMARKS: Other publications of ground-water levels are: Ballance and Freudenthal (1975; 1976; 1977); Kennedy and Green (1988; 1990); Kennedy and Oberender (1987); Ragsdale (1982); Ragsdale and Oberender (1985); and Ringen (1973; 1974).

TITLE: **Proposed development of coal resources in the eastern Powder River coal basin of Wyoming**

AUTHOR(S): U.S. Department of the Interior

YEAR OF PUBLICATION: 1974

PUBLISHER AND SERIES: U.S. Department of the Interior [Bureau of Land Management], Cheyenne, Wyo.

PAGES: 6 volumes with separate pagination

REMARKS: No new ground-water investigations were conducted for this environmental impact statement, prepared prior to renewal of leasing of Federally owned coal in the Powder River Basin. The publication, however, contains a summary of work as of 1974 on water resources in major aquifers in both the Wyoming and Montana parts of the Powder River Basin, and an assessment of the effects of new coal mining on the water resources.

TITLE: **Water-resources data, Wyoming, water year 1989**
(1989 report used as an example; reports published annually)

AUTHOR(S): U.S. Geological Survey

YEAR OF PUBLICATION: 1990

PUBLISHER AND SERIES: U.S. Geological Survey Water-Data Report WY-89-1 (series unnumbered prior to 1975)

PAGES: 506

REMARKS: This is one example in a series of publications published for each year since 1961 (water-quality data were published in a separate volume prior to 1975). The water-resources data consist of records of stage, discharge, and water quality of streams; stage and contents of lakes and reservoirs; and water levels and water quality of ground water. Ground-water levels and artesian pressures in observation wells prior to 1975 were reported by geographic areas in a 5-year series of U.S. Geological Survey Water-Supply Papers. Data for Wyoming are in "Ground-Water Levels in the United States, Northwestern States."

TITLE: **Procedure for evaluating observation-well networks in Wyoming, and application to northeastern Wyoming, 1986**

AUTHOR(S): Wallace, J.C., and Crist, M.A.

YEAR OF PUBLICATION: 1989

PUBLISHER AND SERIES: U.S. Geological Survey Water-Resources Investigations Report 88-4215

PAGES: 29

REMARKS: The publication abstract states (p. 1):

> On the basis of an evaluation of activities likely to affect ground water in northeastern Wyoming, the most important monitoring needs in the area are related to: (1) Oil-field waterflooding, (2) surface mining of coal, (3) increasing municipal use of ground water, and (4) need for general resource information. The 18 observation wells in the existing (1986) network meet most of the needs identified. Seven additional wells need to be added to the network, whereas four wells in the network can be discontinued.

As of 1986, substantial water-level declines were recorded in one well completed in the Fort Union Formation of Paleocene age near Gillette, in one well completed in the Lance Formation and Fox Hills Sandstone of Late Cretaceous age near Gillette, and in one well completed in the Lakota Formation of Early Cretaceous age in northern Niobrara County. Substantial water-level rises were recorded in one well completed in the Wasatch Formation of Eocene age at Gillette and in one well completed in the Madison Limestone of Mississippian age in northern Niobrara County.

TITLE: **Ground-water data from selected wells in alluvial aquifers, Powder River Basin, northeastern Wyoming**

AUTHOR(S): Wells, D.K.

YEAR OF PUBLICATION: 1982

PUBLISHER AND SERIES: U.S. Geological Survey Open-File Report 82-856

PAGES: 35

REMARKS: The publication abstract states: "Data on selected wells completed in alluvial aquifers in the Powder River structural basin are presented without interpretation. Records of 300 wells, chemical analyses of water from 43 wells, and logs of 113 wells are listed in three tables. A map showing location of wells is included."

TITLE: **Johnson County, Wyoming--Geologic map atlas and summary of land, water, and mineral resources**

AUTHOR(S): Wendell, W.G., Glass, G.B., Breckenridge, R.M., Root, F.K., Lageson, David, and The Remote Sensing Laboratory, University of Wyoming

YEAR OF PUBLICATION: 1976

PUBLISHER AND SERIES: The Geological Survey of Wyoming County Resource Series, no. CRS-4

PAGES: 9 sheets

REMARKS: The format of this publication is similar to that of Breckenridge and others (1974). The sheets in this publication are titled "Petroleum and Natural Gas," "Land Use," "Land Forms," "Land and Mineral Ownership," "Minerals," "Coal," "Vegetation," "Geology," and "Water."

The sheet on water resources contains a map of major ions and dissolved-solids concentrations in ground and surface water. A table listing lithology, water-yielding characteristics, and major water-quality characteristics for geologic formations in the basin is included; the information may be useful on a reconnaissance basis. Other maps on this sheet show depth to top of the Fox Hills Sandstone and the Madison Limestone, and surface-water drainage. Much of the information in this section is from Hodson and others (1973).

Other publications in this series are:

Campbell County (Breckenridge and others, 1974)

Converse County (Lane and others, 1972)

Natrona County (Lageson and others, 1980)

TITLE: **Ground-water resources and geology of Niobrara County, Wyoming, <u>with a section on</u> Chemical quality of the ground water**

AUTHOR(S): Whitcomb, H.A.; chemical-quality section: T.R. Cummings

YEAR OF PUBLICATION: 1965

PUBLISHER AND SERIES: U.S. Geological Survey Water-Supply Paper 1788

PAGES: 101; 3 plates

REMARKS: Only the northwestern part of the county is in the Powder River Basin; the main focus of the investigation was the Arikaree Formation of Miocene age [mostly outside the Powder River Basin], "the only known source of large quantities of ground water in Niobrara County" (p. 2). However, the authors state (p. 2) that "appreciably large quantities of ground water probably move westward through the Fox Hills Sandstone and the Lance and Fort Union Formations into the Powder River Basin. * * * [The quality of] water from the Pierre Shale, Fox Hills Sandstone, Lance Formation, Fort Union Formation, and the alluvium seem [sic] suitable for stock supplies but may or may not be suitable for irrigation use, depending upon location. In general, for domestic use these supplies should be considered acceptable only if no other supplies are available."

TITLE: **Ground-water resources and geology of northern and central Johnson County, Wyoming**

AUTHOR(S): Whitcomb, H.A., Cummings, T.R., and McCullough, R.A.

YEAR OF PUBLICATION: 1966

PUBLISHER AND SERIES: U.S. Geological Survey Water-Supply Paper 1806

PAGES: 99; 2 plates

REMARKS: This publication includes a table of stratigraphy, lithology, and water-bearing characteristics of the principal formations in the study area. Hydrographs were used to show how water levels in shallow aquifers are affected by local and regional recharge and water levels in Lake DeSmet.

The authors concluded that most ground water enters the project area by precipitation, and leaves by evapotranspiration, underflow, and (or) streamflow. The Wasatch Formation is the principal source of ground water for the county. It yields "adequate" supplies to shallow stock and domestic wells. Dissolved-solids concentrations exceed drinking-water standards in many areas. Hydrogen sulfide sometimes is present. Water generally is unusable for irrigation because of high sodium, bicarbonate, or salinity hazard. Water quality ranges from good to poor for stock-watering supplies.

The shallow water in the Fort Union Formation is a sodium or calcium sulfate type, very hard, with dissolved-solids concentrations as large as 3,250 mg/L. Deeper water (more than 500 ft) is a sodium bicarbonate type, with dissolved-solids concentrations smaller than 1,250 mg/L, is soft, and has little sulfate. Cation-exchange softening and sulfate reduction are two processes postulated to cause this change.

TITLE: **Ground-water resources and geology of northern and western Crook County, Wyoming, <u>with a section on</u> Chemical quality of the ground water**

AUTHOR(S): Whitcomb, H.A., and Morris, D.A.; chemical-quality section: R.H. Langford

YEAR OF PUBLICATION: 1964

PUBLISHER AND SERIES: U.S. Geological Survey Water-Supply Paper 1698

PAGES: 92; 2 plates

REMARKS: Deep aquifers are the most important sources of ground water in the study area. There is limited information on the shallow systems of interest in the present assessment. From the publication abstract (p. 1-2):

> The shaly and silty Fox Hills Sandstone contributes small amounts of water to a few stock and domestic wells in a small area in the western part of the county. Many stock and domestic wells yield small quantities of water from relatively massive sandstone beds in the Lance and Fort Union Formations. Moderate supplies can be obtained from these formations locally. * * * Pumping [aquifer] tests of three wells in the Belle Fourche River valley [alluvium] indicate that quantities of water adequate for small-scale irrigation may be obtained locally.

TITLE: **Occurrence of ground water in the eastern Powder River Basin and western Black Hills, northeastern Wyoming, in Powder River Basin, Wyoming**

AUTHOR(S): Whitcomb, H.A., Morris, D.A., Gordon, E.D., and Robinove, C.J.

YEAR OF PUBLICATION: 1958

PUBLISHER AND SERIES: Wyoming Geological Association Guidebook, 13th Annual Field Conference

PAGES: 245-270

REMARKS: The authors prepared this generalized description of the occurrence of ground water by summarizing information from other publications. At the time this publication was prepared, ground-water investigations had been conducted in only a few small areas. The publication is organized by stratigraphic unit; discussions of units of Late Cretaceous age and younger are on p. 266-269.

TITLE: **Water and related land resources of northeastern Wyoming**

AUTHOR(S): Wyoming Water Planning Program

YEAR OF PUBLICATION: 1972

PUBLISHER AND SERIES: Wyoming State Engineer's Office, Wyoming Water Planning Program Report No. 10

PAGES: 209

REMARKS: This publication is one of a series of regional summaries prepared as part of the State Water Plan. About 770,000 acre-ft of ground water is available to wells in the alluvial aquifers in northeastern Wyoming, which includes the Powder River Basin. An additional 85 million acre-ft is available in the Wasatch-Fort Union aquifer within 1,000 ft of the land surface (p. 85). Additional ground water is available in deeper aquifers. Fifty-one percent of the municipal population depend exclusively on ground water; another two percent use ground water as a supplemental source. Ground water also is used for industrial applications (mostly waterflood operations to recover crude oil from the subsurface; 16,800 acre-ft in 1967), and irrigation. Fewer than 9,000 acres are irrigated with ground water as either the original or supplemental supply; annual use is less than 9,700 acre-ft for lands irrigated with ground water as the original supply (p. 90-91).

This publication also provides information on surface-water resources of northeastern Wyoming, water use (both surface and ground water) in relation to the economy, and potential sources of water to meet expected development needs. Water needs for future development were projected to be greater than water supplies available in northeastern Wyoming. No major increases were predicted for municipal, stock, domestic, or irrigation supplies for the period 1970-2020, but industrial needs were expected to increase by a factor of 20 during this period, necessitating the importation of water into the area.

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