UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PLAN OF STUDY OF THE HYDROLOGY OF THE MADISON LIMESTONE AND ASSOCIATED ROCKS IN PARTS OF MONTANA, NEBRASKA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

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Old West Regional Commission

Montana Bureau of Mines and Geology

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North Dakota State Water Commission

South Dakota Division of Geological Survey

Wyoming State Engineer

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Abstract

A major part of the United States' coal reserves is in the Fort Union coal region of the Northern Great Plains. Large-scale development of these reserves would place a heavy demand on the area's limited water resources.

Surface water is poorly distributed in time and space. Its use for coal development in parts of the area would require storage reservoirs and distribution systems, whereas in the rest of the area surface water is fully appropriated and its use would deprive present users of their supply.

Preliminary studies by the U.S. Geological Survey and State agencies in Wyoming, Montana, and South Dakota indicate that the Madison Limestone and associated rocks might provide a significant percentage of the total water requirements for coal development.

This report briefly summarizes the present knowledge of the geohydrology of the Madison and associated rocks, identifies the need for additional data, and outlines a 5-year plan for a comprehensive study of the hydrology of these rocks.

Introduction

In this report, figures for measures are given both in English units and in metric units (with the exception of tables, which contain English units only). Factors for converting English units to metric units are shown in the following table:

English	Multiply by	Metric
short ton	0.907	t (tonne)
acre-ft/year (acre-feet per year)	.00123	hm^3/year (cubic hectometres per year)
gal/min (gallons per minute)	.0631	ℓ/s (litres per second)
ft (feet)	.305	m (metres)
mi^2 (square miles)	2.59	km^2 (square kilometres)
in (inches)	25.4	mm (millimetres)
ft^2/day (feet squared per day)	.0929	m^2/day (metres squared per day)
(gal/min)/ft (gallons per minute per foot)	.207	(ℓ/s)/m (litres per second per metre)
ft/mi (feet per mile)	.189	m/km (metres per kilometre)

A major part of the United States' coal reserves--an estimated 1.5 trillion short tons (1.4 trillion t) of coal (Northern Great Plains Resources Program, 1975)--is in the Fort Union coal region of the Northern Great Plains (fig. 1). Major development of the coal, which may include on-site steam-power generation, gasification, liquefaction, and slurry-pipeline transport of coal from this area, would place a heavy demand on the area's limited water resources. Large quantities of water will be needed--estimates exceed 200,000 acre-ft/year (250 hm^3/year).

Surface water is poorly distributed in time and space. Its use for coal development in parts of the area would require storage reservoirs and distribution systems, whereas in the rest of the area surface water is fully appropriated and its use would deprive present users of their supply.

Paleozoic rocks, which include the Madison Limestone, its equivalents, and associated rocks--hereafter called the Madison aquifer--underlie the Fort Union coal region and adjacent areas in Wyoming, Montana, the Dakotas, and Nebraska. Preliminary studies by the U.S. Geological Survey and State agencies in Wyoming, Montana, and South Dakota indicate that these rocks might provide a significant percentage of the total water requirements for coal development. The available data indicate that well yields from the Madison aquifer range from about 20 gal/min (1.3 ℓ/s) to 9,000 gal/min (570 ℓ/s); most are less than 1,000 gal/min (63 ℓ/s). The Madison presently supplies water for domestic, stock, municipal, industrial,

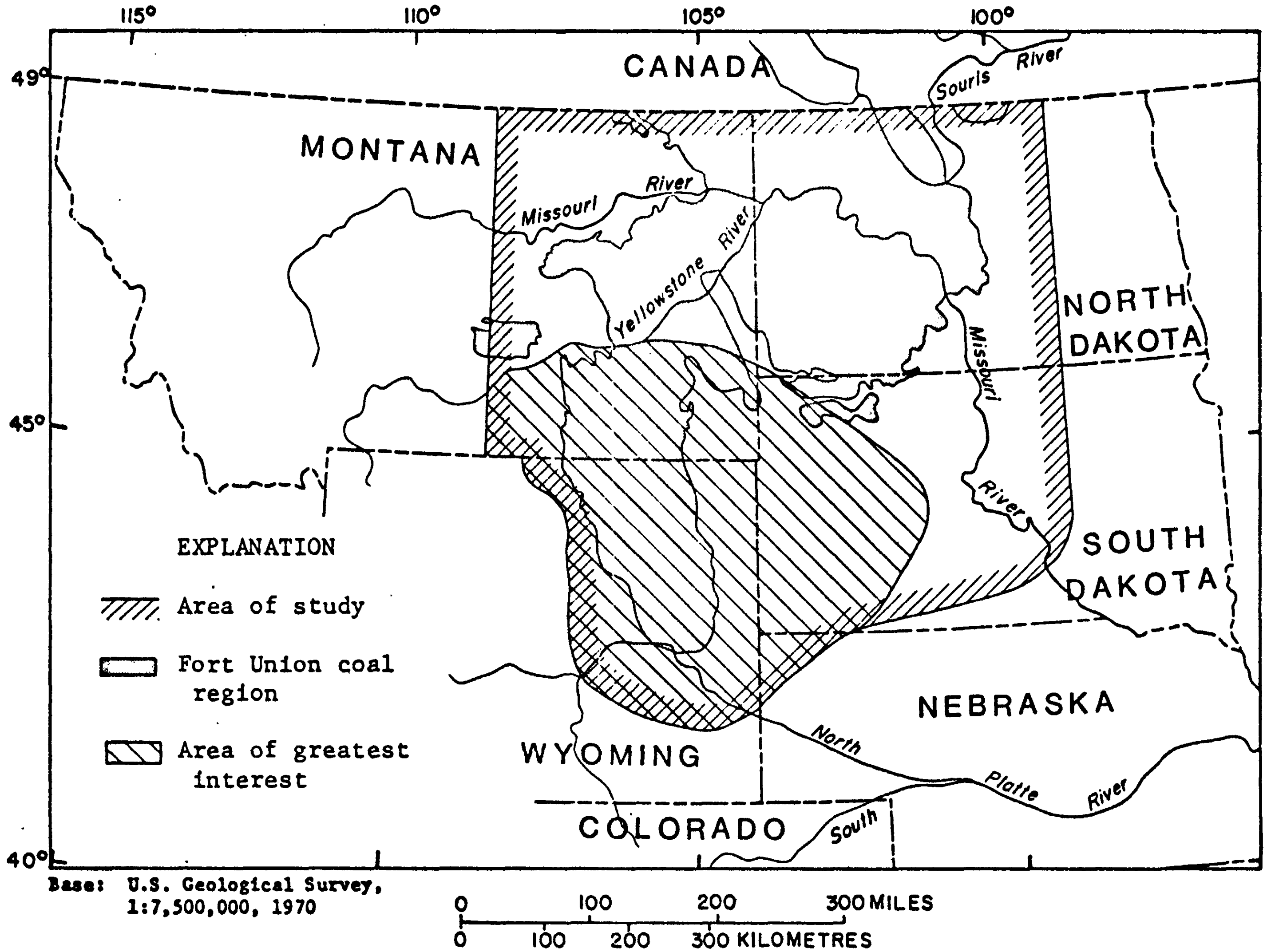


Figure 1.--Location of study area and Fort Union coal region.

and oil-field water-flood uses but large-scale withdrawals could result in hydrologic and economic problems, such as decline in potentiometric head, depletion of flow of streams and springs, or deterioration of quality of water from existing wells. Large declines in potentiometric head in the Midwest, Wyo., area caused by ground-water withdrawal for the past 15 years is the main result of development that has occurred to date (1975).

Additional data on the Madison aquifer are needed to evaluate its potential as a source for water supplies and to provide the necessary information for an orderly development of the aquifer. The cost of obtaining these data will be high because of the large areal extent of the Madison, its complex hydrologic nature, and its great depth (2,000 to 16,000 ft (610 to 4,880 m)) below the land surface in much of the area.

This report briefly summarizes the present knowledge of the geohydrology of the Madison aquifer, identifies the need for additional data, and outlines a 5-year plan for a comprehensive study of the Madison.

The study area includes eastern Montana, western North and South Dakota, a small part of northwestern Nebraska, and northeastern Wyoming (fig. 1). It comprises about 188,000 mi^2 (487,000 km^2) of which 59,000 mi^2 (153,000 km^2) is in Montana, 50,000 mi^2 (129,000 km^2) in North Dakota, 45,000 mi^2 (117,000 km^2) in South Dakota, 2,000 mi^2 (5,000 km^2) in Nebraska, and 32,000 mi^2 (83,000 km^2) in Wyoming. The area of greatest interest, however, is the Powder River Basin of Montana and Wyoming and the area surrounding the Black Hills in Wyoming, Montana, the Dakotas, and Nebraska. This area is about 68,000 mi^2 (176,000 km^2) in extent, and is bounded on the south by the Laramie Mountains, on the west by the Bighorn Mountains, and on the north by the Yellowstone River. The eastern part includes the Black Hills and the gently sloping plains to the east.

The study area is drained by the Missouri River, its major tributaries, and the Souris River. Altitudes range from about 1,500 ft (460 m) along the Missouri River in South Dakota to 14,000 ft (4,300 m) in the Bighorn Mountains, Wyoming. In the area of greatest interest, altitudes range from about 1,800 ft (550 m) along the Cheyenne River in South Dakota to about 14,000 ft (4,300 m) in the Bighorn Mountains. The maximum altitude in the Black Hills is about 7,200 ft (2,200 m).

The climate is continental, characterized by cold winters and hot summers, and large extremes and rapid changes in weather. Precipitation ranges from about 10 in (250 mm) in the central part of the Powder River Basin to 30 in (760 mm) in the mountains. Most of the precipitation occurs from March through July; general rains occur throughout the area in May and June and thunderstorms prevail during the summer. Precipitation from November through May is usually snow, and blizzards are common.

The regional geology of the area is summarized by the Rocky Mountain Association of Geologists (1972); the geology of the Williston Basin by Sandberg (1962); the geology of the Powder River Basin by Beikman (1962); and that of the northern Black Hills by Robinson and others (1964). The geology of the Madison Group is described by Sloss (1950), Nordquist (1953), Andrichuk (1955), Mickelson (1956), Gries and Mickelson (1964), and Sando (1972 and 1974). The geology of the Devonian rocks is described by Sandberg and Hammond (1958), and that of the Ordovician rocks in the Powder River Basin by Richards and Nieschmidt (1961). Most of these reports are regional studies and contain little lithologic and structure information that can be related directly to the hydrology.

Hydrologic studies include Whitcomb and others (1958), Gries and Crooks (1968), Swenson (1968), Miller (1969), Gries (1971), U.S. Bureau of Reclamation (1972), Feltis (1973), Rahn and Gries (1973), Hodson and others (1973), Hodson (1974), and the Wyoming State Engineer (1974). Water quality is discussed by Crawford (1942). Few of these reports contain quantitative information on the hydraulic properties of the aquifer; on the recharge to, movement through, and discharge from the aquifer; or on the relation of the aquifer to springs, streams, and the underlying and overlying aquifers.

Current geohydrologic studies of the Madison aquifer being made by the U.S. Geological Survey, most in cooperation with the State and Federal agencies, include:

1. Availability of water from the Madison Group (Montana District of the U.S. Geological Survey in cooperation with the Montana Bureau of Mines and Geology and Old West Regional Commission)--The purposes of the study are to evaluate existing data and techniques and to develop a plan for a comprehensive investigation of the Madison. A preliminary report describing the water resources of the Madison in southeastern

Montana is in preparation. The information will be used to plan drilling and aquifer-testing programs.

2. Evaluation of recharge to the Madison Limestone, northeastern Wyoming (Wyoming District of the U.S. Geological Survey in cooperation with the Wyoming State Engineer, sponsored by Old West Regional Commission)--The purpose of the study is to evaluate recharge to the Madison Limestone. Stream-gaging stations have been established at 32 locations on streams in the Bighorn Mountains, Black Hills, and the northern end of the Laramie Mountains to determine water losses or gains from these streams crossing outcrops of the Madison aquifer around the perimeter of the Powder River Basin. Also three sets of streamflow measurements will be made each year on 30 additional streams at sites upstream and downstream from the outcrop of the Madison and associated rocks.

3. Hydrology of Paleozoic rocks in the Powder River Basin and adjacent area, northeastern Wyoming (Wyoming District, U.S. Geological Survey program)--The purpose of the study is to evaluate the Paleozoic rocks in the Powder River Basin in Wyoming as a potential source of water for energy development, primarily coal development and attendant conversions to both gaseous and liquid forms of energy and the generation of electric power. The principal effort will concentrate on the Madison Limestone, but both the underlying and overlying rocks, mostly carbonate or sandstone, will be included.

4. Hydrology of the aquifer(s) in the Madison Group, South Dakota (South Dakota District, U.S. Geological Survey program in cooperation with Old West Regional Commission)--The purposes of the study are to delineate the water resources of the Madison Group, to determine the hydrologic regimen of the aquifers in the Madison and underlying and overlying limestones, and to predict the probable results of the large withdrawals of water from the Madison.

5. Preliminary evaluations and development of a plan of study, Madison Limestone aquifer, Northern Great Plains (U.S. Geological Survey program in cooperation with Old West Regional Commission)--The purpose of the study is to prepare a systematic plan for evaluating the water-supply potential of the Madison Limestone and associated rocks. Also, this study has coordinated the current U.S. Geological Survey investigations of the Madison being made by the district offices of the Water Resources Division and has consolidated their results. As aids in the development of the study plan, a liaison committee was formed, a preliminary digital simulation model of the aquifer was developed, and studies using surface and borehole geophysics were begun to test methods that may show permeability patterns in the Madison aquifer.

The members of the liaison committee were drawn from agencies of State governments that have an active interest in or responsibility for control or development of water from the Madison aquifer. These agencies include Montana Bureau of Mines and Geology, Montana Department of Natural Resources and Conservation, North Dakota State Water

Commission, South Dakota Division of Geological Survey, and Wyoming State Engineer. The purpose of the committee is to maintain open communication between the investigating hydrologists and State officials relative to all aspects of the study--progress, problems, and significant results.

A preliminary digital simulation model was developed and used to analyze regional ground-water flow in the Madison aquifer in the area of greatest interest. Although the many factors that affect the ground-water flow in the Madison are not clearly defined or understood, the present model can be used to make preliminary estimates of the range of the possible effects that anticipated developments of the Madison aquifer might impose on the water level, recharge, discharge, and pattern of flow. It can also serve as a guide to additional data collection and to the location of monitoring wells. The model and its development are described in a separate report now in preparation.

Preliminary results of the study using existing borehole geophysical data to help determine some of the hydrologic parameters in the Madison aquifer look promising. Suites of good quality geophysical logs from Madison Limestone and Minnelusa Formation oil tests geographically distributed in the area were selected for analysis. Porosity, lithology, and water quality were examined. Maps of structure, thickness, porosity, lithology, and pore-fluid resistance were prepared for parts of the Minnelusa and the same parameters were tabulated for the Madison. However, additional borehole and surface geophysical data, and further analysis of available data, are needed to fully evaluate their use to extend point information between wells and to relate lithology, porosity, and water quality to the identification of permeability zones in the Madison aquifer.

In addition to these cooperative studies, some State agencies and private companies are evaluating the Madison aquifer as a potential source for water supplies or are evaluating the yield of the Madison at specific sites. The South Dakota School of Mines and Technology is studying the geology and hydrology of the Black Hills. The Wyoming State Engineer prepared a report for the Wyoming Legislature (December 1974) describing the Madison and the need for additional information. The University of Wyoming is mapping geology, gaging streams, and inventorying springs in the Bighorn Mountains. Private companies are test drilling and evaluating well yields and water-level declines in the Madison aquifer near Buffalo, Douglas, Lusk, and Upton, Wyo., and near Colstrip and Hardin, Mont.

Summary of available data

Before a conceptual model of the operation of the Madison aquifer and its response to applied stresses (pumping) can be described, the geologic framework must be understood. Study of the water-supply potential of the Madison aquifer probably will require that the beds above and below the aquifer be studied also. Recharge to and discharge from the Madison aquifer are dependent in part on the hydraulic characteristics of the overlying and underlying beds as well as on the hydraulic characteristics of the Madison aquifer.

The nomenclature and correlation of the Paleozoic rocks that may constitute the Madison aquifer are summarized in table 1. In Wyoming the Madison Limestone consists of the rocks from the base of the Mississippian up to the base of the Amsden Formation or its equivalents. The Pahasapa Limestone is equivalent to part of the Madison Limestone in the Black Hills and western South Dakota as is the Guernsey Formation in the Hartville Uplift. In Montana, North Dakota, and central South Dakota these rocks are the Madison Group and consist of, in ascending order, the Lodgepole Limestone, the Mission Canyon Limestone, and the Charles Formation. These three units are not identified in Wyoming.

The structural features, listed in table 2 and shown on figure 2, may significantly affect the movement of water in the Madison aquifer and the well yields. Folding and faulting probably have fractured the rocks and increased their permeability. Later solution by circulating water has enlarged these fractures. The thickness of the Madison aquifer is not uniform over the area as some formations were not deposited everywhere or they were removed by erosion before deposition of overlying rocks.

Table 2 gives a general description of the Madison aquifer and presents the current status of information about such hydrologic parameters as outcrop areas, porosity, storage, vertical and horizontal permeability, transmissivity, potentiometric head, yields of wells, water use, and water quality.

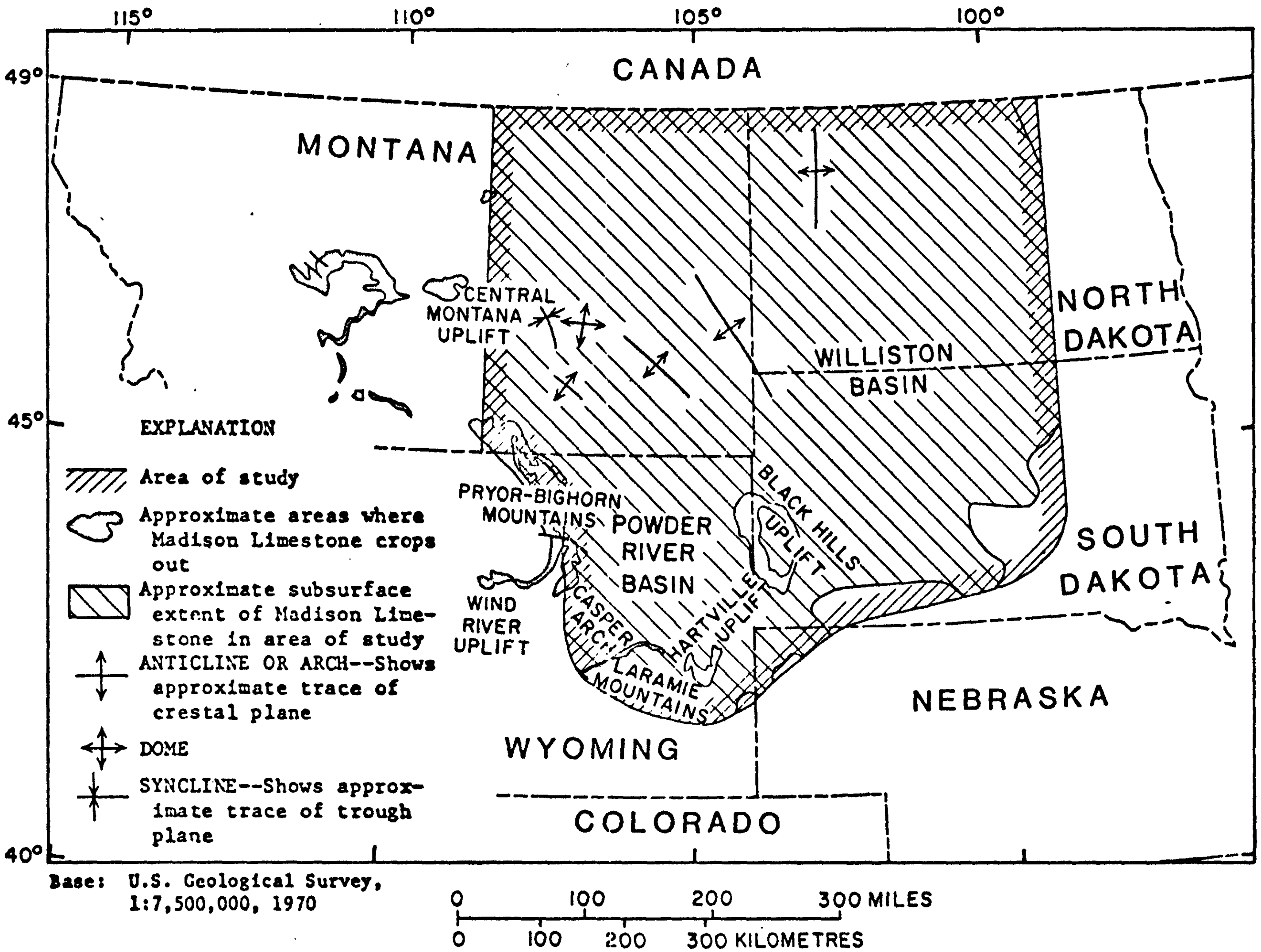


Figure 2.--Outcrops and subsurface extent of Madison Limestone and major tectonic features.

Data are primarily from oil tests within the study area. Some information is available from water wells (fig. 3), but many of these wells were originally drilled as oil tests and then completed as water wells.

Many oil tests have been drilled to the Madison aquifer. Most did not completely penetrate the aquifer, but were drilled to develop oil fields or were exploration tests on known geologic structures. Few of the data from these tests were collected for hydrologic purposes, but they are useful in defining the geologic framework and some of the aquifer characteristics such as water quality and temperature, porosity, and potentiometric head.

The first few oil tests drilled in an area generally yield the most data. Most of these provide information on formation tops and depths, well cuttings, a suite of geophysical logs, lithologic logs, and cores and core analyses. Drill-stem tests were made in some of the oil tests where the data were necessary to interpret geophysical logs or to plan production or secondary-recovery operations. A few chemical analyses are available of water produced with oil and of water recovered from drill-stem tests.

Most of the available geologic and hydrologic information has been compiled for the Madison aquifer in the Powder River Basin and it is being compiled for the South Dakota part of the area of greatest interest. These compilations include maps showing (1) the configuration of the top of the Madison in the Powder River Basin (Swenson and others, in press) and in the Black Hills area (L. W. Howells,

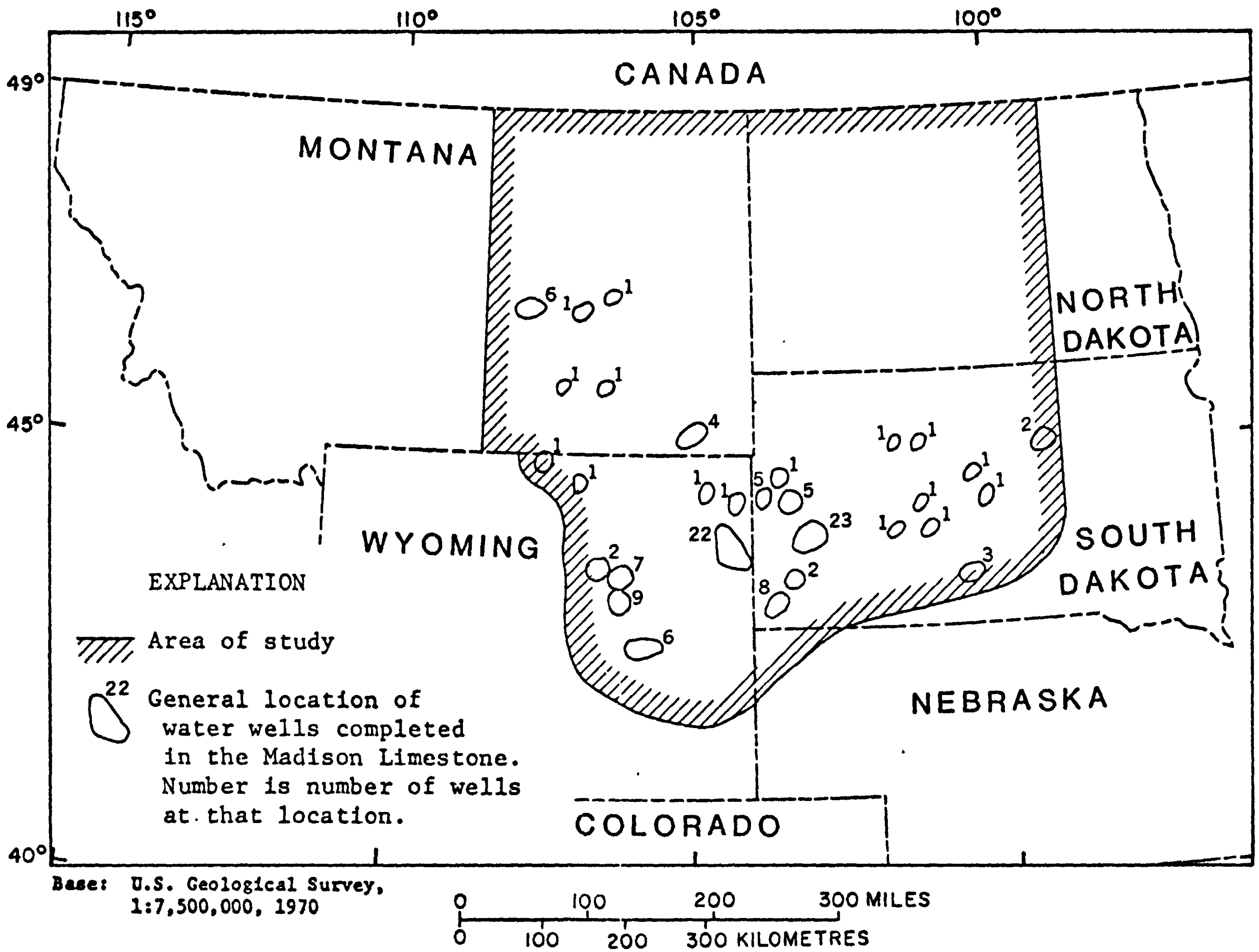


Figure 3.--General locations of water wells completed in the Madison Limestone.

written commun., 1975); (2) the thickness of the Madison in the Powder River Basin (Swenson and others, in press) and in the Black Hills area (L. W. Howells, written commun., 1975); (3) the potentiometric surface of the Madison in the Powder River Basin (Swenson and others, in press), in the Black Hills area (Gries, 1971), and in the area of greatest interest (L. F. Konikow, written commun., 1975); and (4) the quality of the water (dissolved-solids concentration) in the Powder River Basin (Swenson and others, in press), in the Black Hills area (L. W. Howells, written commun., 1975), and in the study area (fig. 4).

Deficiencies of data

Most of the available geologic and hydrologic data in the study area are from oil and gas exploration. Because the oil tests were drilled primarily on known geologic structures or to develop oil fields, much of the data are limited to the areas of these structures and oil fields. Except in the Williston Basin most of the oil tests are not deep enough to reach the Madison, and of those that are drilled to the Madison, only a few completely penetrate the aquifer. In the Powder River Basin, the oil tests that penetrate the aquifer are near the edges of the basin. There are fewer than one test per 600 mi^2 (1,550 km^2) in the northern end of the Powder River Basin and less than one test per 1,000 mi^2 (2,600 km^2) in the central and southern parts of the basin.

Where oil tests have penetrated the Madison aquifer, information to define the top and the thickness is generally available. If a suite of geophysical logs and drill-stem tests were made, water-quality,

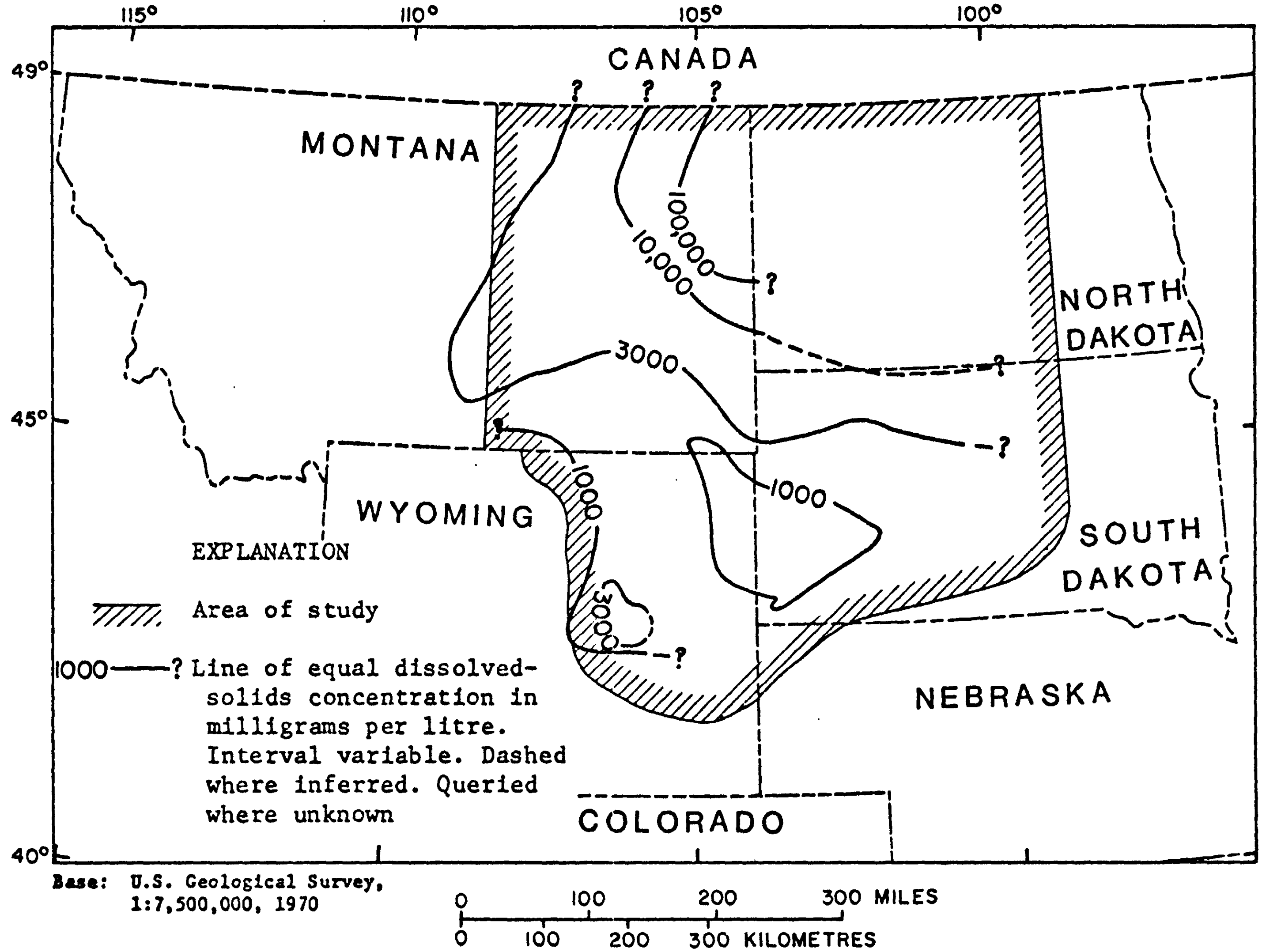


Figure 4.--Generalized dissolved-solids concentration of water from the Madison Limestone.

temperature, porosity, and potentiometric-head data may be available. However, the oil tests are not adequately spaced to provide the geologic information necessary for a regional hydrologic study of the aquifer.

In addition, information is virtually nonexistent for the determination of regional values for recharge, discharge, transmissivity, storage, vertical leakage, water use, and water-level fluctuations. Values for these parameters are necessary to evaluate the water-supply potential of the Madison aquifer.

To overcome the deficiencies in the base data, it will be necessary to further evaluate the available data; collect new surface and subsurface hydrologic, geologic, geophysical, and geochemical data; analyze and evaluate these data and use them to make predictions of the possible effects that proposed withdrawals may have on the hydrologic system; and monitor water-supply developments and refine predictions.

Plan of study

Objectives

The objectives of this proposed study are to:

1. Determine the quantity of water that may be available from the Madison aquifer.

2. Define the chemical and physical properties of the water.

3. Determine the effects of existing developments on the potentiometric head, storage, recharge and discharge, springs, streamflow, and the pattern of ground-water flow.

4. Predict the probable hydrologic effects of proposed withdrawals of water for large-scale developments at selected rates and locations.

5. Determine the locations of wells and the type of construction and development of deep wells that would obtain optimum yields.

6. Design a network of observation wells and stream gages to monitor the effects of additional developments on the hydrologic system.

The resulting study should provide a better understanding of the aquifer and answer some of the questions that are being asked about the Madison.

1. How much water can be withdrawn from the aquifer?

2. How much water will the aquifer yield to individual wells?

3. Where and how deep should wells be drilled for maximum yield?

4. What will the development costs be?

5. What is the water quality in the aquifer?

6. Will large-scale development affect springs and streamflow--if so, where, how much, and how soon?

7. Will large-scale development cause land subsidence?

8. Will development affect existing industrial, municipal, and domestic uses from the Madison aquifer or from aquifers above the Madison?

9. What will be the long-term effects of development on aquifer storage, water levels, and water quality?

10. Will large-scale development of water in one State affect water users in adjacent States--if so, where, when, and how much?

11. What well design, construction, and development techniques will give optimum yields for wells deeper than 5,000 ft (1,500 m)?

The evaluation of the Madison aquifer will be primarily in the area of greatest interest (fig. 1). However, data collection and analysis will extend into northern Montana, North Dakota, and South Dakota because the aquifer extends into these States (figs. 1 and 2).

Approach

To accomplish the objectives of the study, it is necessary to understand the stratigraphy and structure of the region, determine the boundaries of the aquifer and the geologic parameters that control the permeability, and map or otherwise define these parameters, translate the geologic parameters into hydrologic terms, determine the steady-state movement of water through the aquifer, predict the effects of various patterns of water-supply development on the potentiometric surface, recharge, discharge, springs, and streamflow, determine changes in quality of the water that could result from these developments, and operate a monitoring system and refine predictions. The approach would be:

1. Determine stratigraphy, structure, boundaries of aquifer, porosity, permeability, and storage distribution, and significance of adjacent formations.

a. Study geologic history, outcrops, cores, drill-stem-test data, water-quality data, subsurface and surface geophysical data, and lithologic logs.

b. Correlate lineaments with well production and drill-stem-test data.

c. Determine facies trends that correlate with permeability and porosity.

d. Construct simple models to test hypotheses.

2. Map geologic parameters that are found to control or correlate with the hydrologic parameters. Maps of the aquifer may include but are not restricted to:

a. Areal extent

b. Configuration of top

c. Thickness

d. Continuity

e. Extent and orientation of fracturing

f. Lithofacies

g. Porosity

h. Degree of erosion and karst development

i. Geophysical data

j. Geochemical data

3. Translate geologic parameter maps into hydrologic maps.

a. Shallow and deep test drilling and hydrologic testing

b. Quantify relations determined in (1) above.

c. Map transmissivity and storage distribution and hydrologic boundaries for each aquifer zone and adjacent formations.

4. Determine steady-state movement of water through aquifer.

a. Refine potentiometric map with new data (head, temperature, salinity, etc.).

b. Reconcile quality-of-water and head data.

c. Determine head variations with depth.

d. Refine and verify steady-state model.

5. Predict transient response of potentiometric surface, recharge, discharge, springs, and streamflow to various patterns of development.

a. Refine digital model (adjust transmissivity, storage, aquifer boundaries, leakance).

b. Verify model (use data from water-well fields and oil and gas fields).

6. Determine changes in water quality that could result from various patterns of development.

a. Incorporate solute transport model.

b. Verify model.

c. Predict changes in response to selected pumping rates and locations.

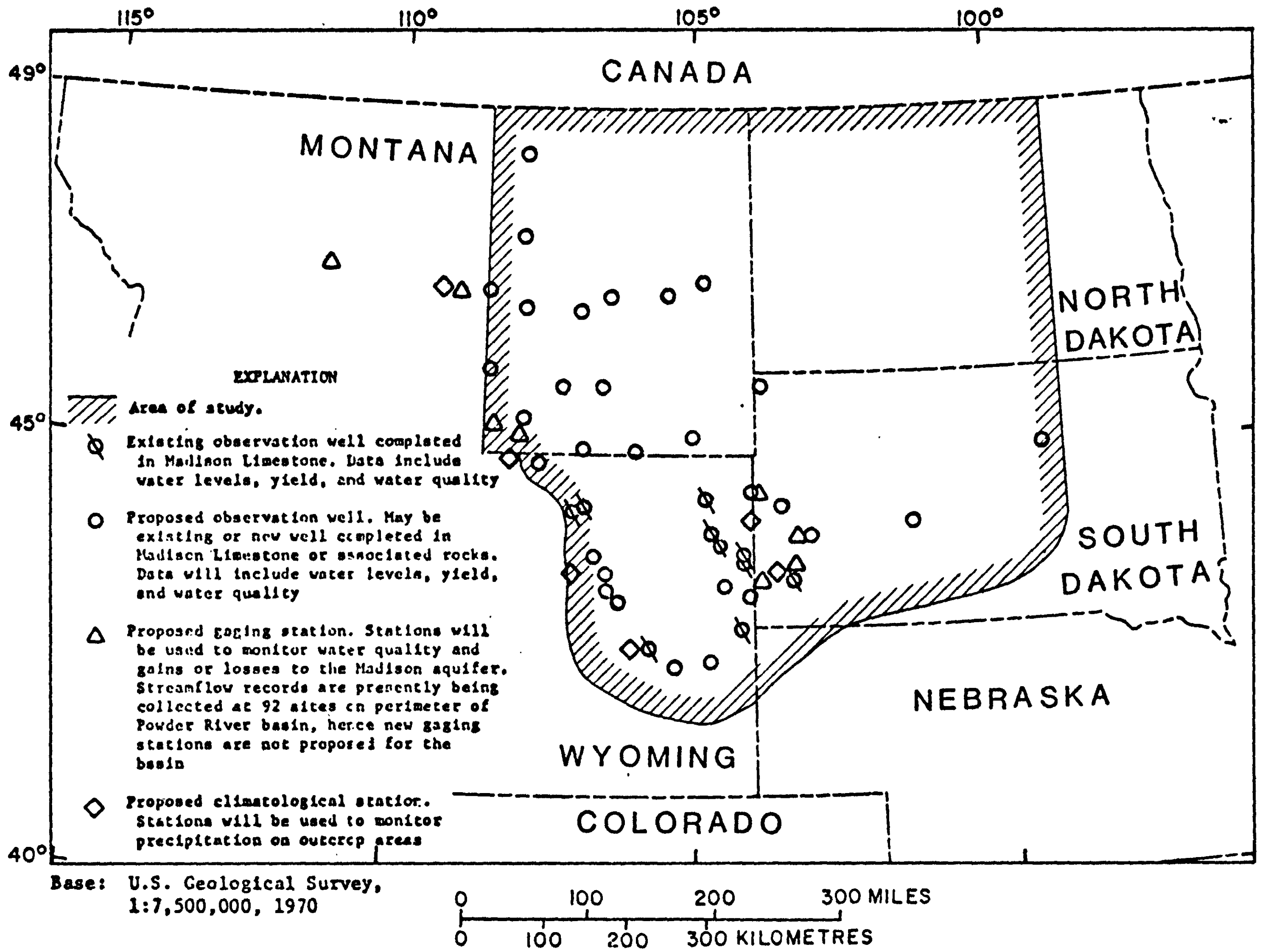
7. Refine and operate monitoring system (fig. 5), and refine digital model and predictions.

a. Water level in wells

b. Gaging stations on springs and streams

c. Water-quality sampling stations

d. Precipitation stations



Base: U.S. Geological Survey, 1:7,500,000, 1970

Figure 5.--Locations of existing observation wells and proposed locations for observation wells, stream-gaging stations, and climatological stations (existing stream-gaging stations in Powder River basin too numerous to plot).

Personnel requirements

The estimated man-year requirements for the study are shown in the following table. For each of the fiscal years 9 man-years are available from personnel already on the rolls, so that the additional personnel needed for each fiscal year is the difference between the total shown each fiscal year and the 9 on the rolls, that is, 10 for the 1976 fiscal year, 12 for the 1977 and 1978 fiscal years, and 13 for the 1979 and 1980 fiscal years.

Discipline	Man years per fiscal year					
	On rolls[1/]	1976	1977	1978	1979	1980
Geologists	3	4	4	4	4	4
Engineers	1	2	2	2	2	2
Geophysicists	.5	2	2	2	3	3
Geochemists	.5	2	2	2	2	2
Microbiologist	0	1	1	1	1	1
Hydrologists	1	2	2	2	2	2
Technicians	3	6	8	8	8	8
Total	9	19	21	21	22	22

[1/]Currently assigned to Madison or related study.

Cost estimates

The estimated cost of the 5-year study of the Madison is 11.4 million dollars. The breakdown of the estimate is shown below:

Item	Fiscal year (cost in thousands of dollars)				
	1976	1977	1978	1979	1980
Personnel[1/]	$ 680	$ 720	$ 720	$ 760	$ 760
Oil and Gas Branch	30	60	60	120	30
Geophysical data:					
Surface	20	30	30	100	10
Borehole	10	20	20	30	10
Grants	25	25	25	25	25
Special equipment and supplies	70	130	40	40	10
Computer time	10	20	20	20	30
Analytical services	100	200	200	200	50
Test drilling and testing	1,355	1,360	1,600	1,600	0
Total	$2,300	$2,565	$2,715	$2,895	$ 925

1/ Includes support costs, such as overhead, travel, trucks, supervisory and clerical assistance, and so forth.

Work plan (by fiscal years)

The following work plan is contingent on the availability of funds, manpower, and contractors. Continuing evaluation of the results of the many phases of the program could also necessitate some realignment of the plan. Reports and maps will be prepared and published as interpretations and compilations are completed. Certain phases of the program may be done in cooperation with, or by grants and contracts to, Federal and State agencies, private companies, and universities.

1976 fiscal year (ending September 30, 1976)

1. Compile and further evaluate available data (emphasis on study area outside of Powder River Basin).

2. Prepare drilling specifications.

3. Continue evaluation of surface and borehole geophysics as hydrologic tools to extend point data between wells and to determine and delineate permeability zones.

4. Collect and analyze water samples (wells, streams, springs, precipitation), and interpret results.

5. Determine sites for and construct additional gaging and climatological stations for monitoring system.

6. Evaluate existing wells for monitoring system.

7. Use preliminary digital model to estimate the range of possible effects that anticipated developments of the Madison aquifer might impose on water levels, recharge, discharge, and pattern of flow. Evaluate proposed monitoring-well locations based upon these possible effects.

8. Operate monitoring system.

9. Collect available data from current test drilling by oil and coal companies.

10. Begin petrologic studies of surface exposures and cores to determine the geologic parameters that control development of porosity and permeability in Madison aquifer.

11. Study modern carbonate sedimentation and relate to Madison aquifer.

12. Refine and extend existing maps (configuration of top, thickness, potentiometric surface, quality of water).

13. Extend geohydrologic mapping on surface and in subsurface to include other Paleozoic rocks that may constitute part of the Madison aquifer.

14. Begin construction of maps of geologic parameters that control or correlate with hydrologic parameters.

15. Conduct short seminar to discuss and outline work assignments and plans to complete various phases of the program.

16. Begin test drilling and aquifer testing.

1977 fiscal year

Continue items 1, 3, 4, 8-14, and 16.

Complete items 5-7.

17. As data become available, extend and refine digital model to include area outside of present model boundaries and to include other Paleozoic rocks that may be part of aquifer. Test hypotheses used to modify model.

18. Compile and publish geohydrologic maps, basic data, and technical reports as data become available.

19. Evaluate program and reorient any phase, if necessary.

20. Make seepage runs and dye studies on selected reaches of streams.

21. Continue geochemical studies.

22. Prepare preliminary geochemical model.

23. Relate and integrate results of geohydrologic studies.

24. Prepare progress report.

1978 fiscal year

Continue items 1, 3, 4, 8-14, 16-21, and 23.

Complete items 11 and 24.

25. Evaluate data collected from monitoring system and modify system as needed.

26. Combine geochemical model and digital flow model.

27. Evaluate all data and define limit and extent of aquifer (both horizontally and vertically).

28. Prepare progress report.

1979 fiscal year

Continue items 8, 9, 17, 18, 23, 25, and 27.

Complete items 3, 4, 10, 12-14, 16, 19-21, and 28.

29. Relate results of all phases of program to operation of aquifer

system (ground water, surface water, precipitation, and water quality).

30. Refine and verify models.

31. Predict responses of aquifer to selected stresses.

32. Prepare progress report.

1980 fiscal year

Continue items 8, 9, and 30.

Complete items 18, 23, 25, 29, 31, and 32.

33. Compile and analyze results of 5-year study and relate to geohydrology of aquifer. Prepare recommendations for continuing and additional studies if needed.

34. Using models, make short- and long-term predictions of responses of various schemes of development of aquifer. Prepare recommendations for development alternatives.

35. Present results of studies at technical seminars.

36. Complete final report.

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Table 1.--Correlation diagram showing the rocks that may constitute the Madison aquifer

System	Series	Laramie Mountains, Wyo. (West)	Hartville Uplift, Wyo. (East)	Black Hills and eastern Powder River Basin, S. Dak. and Wyo.	Bighorn Mountains and western Powder River Basin, Mont. and Wyo. (West–East)	Southeastern Montana (West–East)	Central and northern Montana (South–North)	Williston Basin, N. Dak. (South–North)	Williston Basin, S. Dak. (West–East)
Permian									
Pennsylvanian		Casper Formation	Hartville Formation	Minnelusa Formation	Tensleep Sandstone; Amsden Formation	Tensleep Sandstone; Amsden Formation; Minnelusa Formation	Tensleep Sandstone; Amsden Formation	Minnelusa Formation	Minnelusa Formation
Mississippian	Upper					Big Snowy Group, undivided	Big Snowy Group, undivided	Big Snowy Group, undivided	
	Upper and Lower	Madison Limestone	Guernsey Formation	Pahasapa Limestone	Madison Limestone	Madison Group: Charles Formation; Mission Canyon Limestone; Lodgepole Limestone	Madison Group: Charles Formation; Mission Canyon Limestone; Lodgepole Limestone	Madison Group: Charles Formation; Mission Canyon Limestone; Lodgepole Limestone	Madison Group: Charles Formation; Mission Canyon Limestone; Lodgepole Limestone
Devonian	Upper		Guernsey Formation	Englewood Formation	Three Forks Formation; Jefferson Formation; Birdbear Formation; Duperow Formation; Jefferson Group; Souris River Formation	Three Forks Formation; Jefferson Group, undivided; Souris River Formation	Bakken Formation; Three Forks Formation; Jefferson Group, undivided; Souris River Formation	Bakken Formation; Three Forks Formation; Jefferson Group, undivided; Souris River Formation	Three Forks Formation, Jefferson Group, and Souris River Formation, undivided
	Middle					Dawson Bay and Beartooth Butte Formations, undivided	Dawson Bay Formation, Elk Point Group, and Beartooth Butte Formation, undivided	Dawson Bay Formation, Elk Point Group, and Beartooth Butte(?) Formation, undivided	
	Lower								
Silurian						Interlake Formation	Interlake Formation	Interlake Formation	
Ordovician	Upper			Whitewood Dolomite	Bighorn Dolomite	Bighorn Dolomite; Stony Mountain Formation; Red River Formation	Stony Mountain Formation; Red River Formation	Stony Mountain Formation; Red River Formation	
	Middle			Winnipeg Formation		Winnipeg Formation	Winnipeg Formation	Winnipeg Formation	
	Lower			Deadwood Formation[1]		Deadwood Formation[1]	Deadwood Formation[1]	Deadwood Formation[1]	

[1] Upper Cambrian and Lower Ordovician

Table 2.--Description of the Madison aquifer [illegible] adapted from Sandberg (1962), and Rocky Mountain Association of Geologists (1972))

Topic	Area of greatest interest	Northern Montana, excluding area of greatest interest	North Dakota	South Dakota, excluding area of greatest interest
Distribution of aquifer (outcrop areas, subsurface extent, and overlying and underlying beds)	Aquifer crops out in Bighorn, Pryor, and Laramie Mountains, Hartville Uplift, and Black Hills, and occurs in subsurface in rest of area. Madison rocks are overlain by Pennsylvanian rocks. They are underlain by Devonian rocks in northern part of area, Silurian rocks in a small area in the north-central part, Ordovician rocks in central part of area and east of Black Hills, Cambrian rocks in southern part of area and southeast of Black Hills, and Precambrian rocks southeast of Black Hills in eastern South Dakota.	Aquifer crops out in areas west of study area and occurs in subsurface in entire area. Madison rocks are overlain by [illegible] Pennsylvanian rocks in extreme southern part of area, Big Snowy Group rocks in central and northwestern parts, and Jurassic rocks in northeastern part. Madison rocks are underlain by Devonian rocks in most of area except for a small area in west-central part where they are underlain by Ordovician and Cambrian rocks.	Aquifer does not crop out but occurs in subsurface in entire area. Madison rocks are overlain by Big Snowy Group rocks in most of area except in northern and eastern parts where they are overlain by Pennsylvanian rocks and in extreme eastern part where they are overlain by Triassic and Jurassic rocks. Madison rocks are underlain by Bakken Formation except in extreme eastern and southern parts of area where they are underlain by Devonian rocks.	Aquifer does not crop out but occurs in subsurface in entire area. Madison rocks are overlain by Big Snowy Group rocks in northwestern part of area and Pennsylvanian rocks in rest of area except in eastern part where they are overlain by Cretaceous rocks. Madison rocks are underlain by Devonian rocks in entire area except in extreme southern and eastern parts where they are underlain by Ordovician and Precambrian rocks.
Structure and thickness of aquifer	Main structures are Bighorn, Pryor, and Laramie Mountains, Casper Arch, Powder River and Williston Basins, and Hartville, central Montana, and Black Hills Uplifts. (See figure 2.) Madison aquifer dips steeply into Powder River Basin from Bighorn Mountains on west and Laramie Mountains on south; folding and faulting are significant. Aquifer dips less steeply from Black Hills. Top of Madison rocks ranges from 10,000 ft below sea level (about 16,000 ft below land surface) in southwestern part of basin to land surface in outcrop. Madison rocks are 0 to 800 ft thick east of Black Hills, 200 ft thick at southern end of Powder River Basin, and 1,400 ft thick at northern end. Overlying rocks that may be part of aquifer are as much as 800 ft thick. Underlying rocks that may be part of aquifer are less than 100 ft thick at southern end of Powder River Basin, as much as 1,400 ft thick at northern end, and are absent in southern part of South Dakota.	Folding and faulting are significant in western half of area. Top of Madison rocks ranges from about 6,400 ft below sea level (8,500 ft below land surface) to land surface in outcrop just west of study area. Madison rocks are about 700 ft thick at northwestern edge of area and 2,100 ft thick at eastern edge.	Main structure is Williston Basin. Top of Madison rocks ranges from about 6,700 ft below sea level (10,000 ft below land surface) in the center of the basin to about 1,000 ft below sea level (3,000 ft below land surface) in eastern part. Madison rocks are about 2,300 ft thick in center of basin and about 400 ft thick in northeastern part.	Main structure is Williston Basin. Top of Madison rocks ranges from about 300 ft below sea level (2,300 ft below land surface) in southeastern part of area to 5,000 ft below sea level (8,500 ft below land surface) in northwestern part. Madison rocks are not present in southeastern part of area but are about 1,300 ft thick in the northwestern part.
Physical description of aquifer (lithology, and type and distribution of porosity and permeability (hydraulic conductivity development)	Madison rocks are mainly carbonate: in northern part of area, basal part is clayey, and upper part contains evaporites. Overlying Pennsylvanian rocks are carbonate, sandstone, and shale: basal part is calcareous or clayey; middle part contains mainly limestone, which is sandy toward top; and upper part is mainly sand and sandy limestone grading into limestone eastward. Devonian rocks are interbedded shale, sandstone, and carbonate at top, and carbonate containing thin shale and siltstone interbeds at base. Silurian rocks are carbonate. Ordovician rocks are mainly carbonate in upper part, sandstone in middle part, and interbedded sandstone, calcareous sandstone, and shale at base. Cambrian rocks are mainly sandstone containing some carbonate at top, and interbedded rocks in middle part. Development of porosity and permeability in Madison aquifer is poorly documented but seems to be related to solution and collapse-breccia zones associated with unconformities and fracturing. Porosity and permeability related to unconformities occur at top of Madison and Ordovician rocks, and to a lesser extent at top of Devonian and Cambrian rocks, in surface exposures in Bighorn and Laramie Mountains and in Black Hills. Porosity and permeability related to fracturing caused by folding and faulting occur along flanks of Bighorn and Laramie Mountains and in Black Hills. Oil-test records of lost-circulation zones, large yields from wells, and drill-stem tests indicate that porosity and permeability may be well developed in the subsurface. Dolomitization of carbonate and solution of evaporites may also be important factors controlling porosity and permeability. Geophysical logs indicate porosity, but individual zones have not been correlated in subsurface.	Madison rocks are mainly carbonate; basal part is clayey and upper part contains abundant evaporites. Big Snowy Group is mainly continental clastic rocks and has abrupt facies changes. Pennsylvanian rocks are mainly shaly carbonate and shale where they are in contact with Madison, and shaly carbonate and carbonate in rest of area. Jurassic rocks are mainly shale but some are sandstone. Devonian rocks are shale at top and carbonate at base and contain thick evaporites in north-eastern part of area. Silurian rocks are mainly carbonate. Ordovician rocks are mainly carbonate at top, sandstone and shaly sandstone in middle, and carbonate at base. Cambrian rocks are mainly sandstone in eastern part of area, and interbedded sandstone, shale, and carbonate in rest of area. Development of porosity and permeability in Madison aquifer is poorly documented but occurs in outcrops west of study area and is probably significant in subsurface where unconformities occur, or where solution of evaporites or enlargement of fractures has occurred. Drill-stem tests and borehole geophysical data are available in much of area but few have been analyzed.	Madison rocks are mainly carbonate: basal part is calcareous shale and shaly limestone in western part of area, and shaly limestone and limestone in eastern part: middle part is mainly carbonate containing evaporites at top and upper part is mainly evaporites containing interbedded carbonate. Big Snowy Group rocks are mainly calcareous shaly sandstone and sandy shale. Pennsylvanian rocks are mainly carbonate: basal part is shale, sandy shale, limy shale, sandstone, and carbonate with abrupt facies changes: middle part is limestone and shaly limestone: and upper part is shaly and sandy carbonate and carbonate. Devonian rocks are black shale in the northern part of area and sandstone, shale, and carbonate in the southern and eastern parts at the top, and mainly carbonate at base containing thick evaporites in the northern part. Silurian rocks are carbonate. Ordovician rocks are shaly limestone at top, carbonate in middle, shale and sandy shale at base. Cambrian rocks are sandstone in the eastern part of area and interbedded sandstone, shale, and limestone in the western part. Development of porosity and permeability in Madison aquifer is poorly documented, but is probably significant where unconformities, solution of evaporites, or enlargement of fractures occur in the subsurface. Drill-stem tests and borehole geophysical data are available but few have been analyzed.	Madison rocks are mainly carbonate: some evaporites occur near top in northern part of area. Big Snowy Group rocks are mainly calcareous sandy shale and sandy carbonate. Pennsylvanian rocks are mainly carbonate and clastic; basal part is similar to North Dakota section; middle part is shaly carbonate; and upper part is similar to North Dakota section but contains more clastics. Devonian rocks are mainly carbonate containing interbedded sandstone and shale in upper part, shale in middle part, and carbonate in lower part. Silurian and Upper Ordovician rocks are mainly carbonate. Middle Ordovician rocks are mainly shale and sandy shale. Lower Ordovician and Upper Cambrian rocks are mainly sandstone containing some calcareous sandstone at top.
Hydraulic characteristics (transmissivity, storage coefficient, and vertical hydraulic conductivity)	Transmissivity of Madison, estimated from an aquifer test in Montana, is 5,400 ft²/day, and estimated from specific capacity of one well in Wyoming, is 4,000 ft²/day. Flow-net analysis of potentiometric surface near Midwest, Wyo., indicates transmissivity of about 1,000 ft²/day. Data from drill-stem tests and water wells indicate both higher and lower values; all data have not been analyzed. Data to determine transmissivity are available for overlying rocks, but scarce for underlying rocks. Storage coefficient has been estimated to range between 2.5 X 10^{-4} and 10^{-5}. Vertical hydraulic conductivity is not known but probably is variable and very significant.	Transmissivity data have not been calculated for these areas. Many drill-stem tests are available for the Madison aquifer in northern Montana and western North Dakota; fewer tests are available for eastern North Dakota and South Dakota. Storage coefficient has been estimated to be about 10^{-4}. Vertical hydraulic conductivity is not known.			
Potentiometric surface and movement of water (shape, direction, altitude and depth, relation to springs and streams, and water-level changes)	Potentiometric data for Madison aquifer are mainly from drill-stem tests or water wells on flanks of Bighorn and Laramie Mountains and Black Hills; few data are available in central or deeper parts of basin. Data for Pennsylvanian rocks are most abundant; data for underlying rocks are available only for northern part of area. Potentiometric gradient is steep in western and southern parts of area, gentle from outcrops in Black Hills, and essentially flat in center of Powder River Basin. Potentiometric contours indicate water movement is from outcrop areas to center of basin and then northward; some water moves southeast around southern end of Black Hills and some moves into basin from Casper Arch. East of Black Hills water movement is east-northeast. Potentiometric surface is as much as 1,200 ft below land surface in high areas northeast of Casper, Wyo., and on interstream divides, above land surface along most major streams, and as much as 1,000 ft above land surface along Yellowstone River at northern end of area. Springs occur in outcrop areas of Madison aquifer and gaining and losing streams cross these outcrops. Potentiometric lows caused by pumping occur near Midwest, Glenrock, and Newcastle, Wyo., but data in rest of area are not sufficient to determine water-level changes, if any.	Potentiometric data for Madison aquifer are mainly from drill-stem tests. In eastern part of area data are available for both Madison and underlying rocks; in southern and southwestern parts few data are available. Data for overlying rocks are available in most of area. Potentiometric data for Madison indicate water movement is east-northeast; average gradient is about 15 ft/mi. Potentiometric surface is above land surface in much of area; springs occur in outcrops west of area and wells completed in aquifer along major streams will flow. Sufficient data to determine water-level changes are not available. Vertical head relationships in Madison aquifer have not been determined. Water from Madison aquifer is used mainly for secondary recovery of oil; some is used for stock water in study area and for irrigation west of area; total number of wells and total use are not known. Most data are from drill-stem tests; some are from water-supply wells. Largest confirmed reported yield from Madison is 270 gal/min; unconfirmed reported yield is about 1,400 gal/min.	Potentiometric data for Madison aquifer are mainly from drill-stem tests. Most available data are for western part of area. Interpretations have not been made.	Potentiometric data for Madison aquifer are mainly from drill-stem tests. Data indicate water movement is east-northeast. Potentiometric surface is above or near land surface in most of area.
Water use and well yields (use, yields, and specific capacities)	Water from Madison aquifer is used for municipal, stock, domestic, irrigation, fish hatchery, and industrial supplies; total number of wells is not known. Water use in 1973 was about 25,000 acre-ft in Wyoming and 3,600 acre-ft in Montana. Maximum measured yield from Madison was 7,200 gal/min on short-term test of well near Midwest, Wyo.; other well yields in Wyoming range from less than 50 gal/min to about 5,000 gal/min. Maximum yield in Montana was 1,300 gal/min at Bell Creek oil field. Data for overlying and underlying rocks have not been compiled. Specific capacities in Wyoming range from 0.25 to 49 (gal/min)/ft drawdown; for Midwest, Wyo., area, most were less than 2.5 (gal/min)/ft drawdown. Water-use, well-yield, and specific-capacity data have not been fully documented in South Dakota.	Water from Madison aquifer is used mainly for secondary recovery of oil; some is used for stock water in study area and for irrigation west of area; total number of wells and total use are not known. Most data are from drill-stem tests; some are from water-supply wells. Largest confirmed reported yield from Madison is 270 gal/min; unconfirmed reported yield is about 1,400 gal/min.	Water use and well yield for Madison aquifer are poorly documented; most data are from drill-stem tests. Some water is pumped with oil, and some is pumped from water wells and used mainly for secondary recovery of oil.	Water use and well yield for Madison aquifer are poorly documented; most data are from drill-stem tests. Wells, flowing as much as 100 gal/min from Madison, have been developed for stock and municipal supplies in central part of area. Specific capacity data are not available.
Water quality	Dissolved-solids concentration of water from Madison Limestone ranges from about 150 mg/l in Bighorn Mountains and Black Hills to as much as 5,000 mg/l in northeastern part of Powder River Basin. Most data are from wells near Midwest, Glenrock, Newcastle, Wyo., and Belle Creek, Mont.; other data are mainly from drill-stem tests. Data are not available for central part of Powder River Basin. Data for overlying rocks have not been compiled. Data are available for underlying rocks only in northern part of area. Quality of water in Madison aquifer east of Black Hills is poorly documented. Calcium, magnesium, and sulfate are major chemical constituents of water near edge of Powder River Basin; sodium and chloride concentrations increase basinward and to northeast. Detailed geochemical data are not available.	Dissolved-solids concentration of water from Madison Limestone ranges from about 1,430 mg/l from springs west of study area to more than 100,000 mg/l from wells in eastern part. Most data are from drill-stem tests, but some analyses are for water produced with oil. Data for water from rocks other than Madison have not been compiled. Calcium, magnesium, and sulfate are major chemical constituents of Madison water in the western and southwestern parts of area; sodium and chloride increase eastward, and are main constituents in eastern part. Detailed geochemical data are not available.	Water-quality data are available from drill-stem tests and from water pumped with oil; data are not compiled. Dissolved-solids concentration probably exceeds 35,000 mg/l and may be greater than 100,000 mg/l. Sodium and chloride are the major chemical constituents.	Little data are available; mainly from drill-stem tests. Water apparently contains less than 2,000 mg/l dissolved-solids in southern part of area, but contains larger amounts in northern part. Calcium, magnesium, and sulfate are the major chemical constituents.