PLAN OF STUDY FOR THE REGIONAL AQUIFER SYSTEMS ANALYSIS OF THE UPPER COLORADO RIVER BASIN IN COLORADO, UTAH, WYOMING, AND ARIZONA

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4184

Lakewood, Colorado
1983

UNITED STATES DEPARTMENT OF THE INTERIOR

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METRIC CONVERSIONS

For the reader who prefers to use metric units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	*By*	*To obtain metric unit*
foot (ft)	3.048×10^{-1}	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon per minute (gal/min)	6.309×10^{-5}	cubic meter per second

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ABSTRACT

Water shortages are expected in the Upper Colorado River Basin because of increasing water demands for various uses. Ground-water supplies can help to reduce water shortages but ground-water reservoirs have not been studied in detail. The regional aquifer systems analysis of the Upper Colorado River Basin is a study of the major ground-water resources of the region. Aquifers occur in the sedimentary rock sequence in basins and uplifted regions, in volcanic-rock regions, and in stream-valley alluvium. The project work will include collection and compilation of existing geologic, geophysical, hydrologic, and geochemical data. These data will be used to designate and describe aquifers and to prepare simulation models. The models will be used to assess the hydrologic characteristics of the aquifer systems and to estimate the hydrologic effects of discharge from, or recharge to, selected aquifers.

INTRODUCTION

Problem and Objectives

Although qualitative regional and basinwide ground-water appraisals have been conducted by the U.S. Geological Survey, quantitative appraisals of regional aquifer systems have been lacking. The National Water Commission recommended that quantitative regional assessments of ground water be made, and the Regional Aquifer Systems Analysis (RASA) program of the Geological Survey was started in 1975 to provide the required information. As used in the RASA program, a regional aquifer system has been defined by Bennett (1979):

> "A regional aquifer system * * * may be of two general types: it may comprise an extensive set of aquifers and aquitards (confining beds) which are hydraulically connected, or it may represent a set of essentially independent aquifers which share so many common characteristics that they can be studied efficiently in a single exercise."

Preliminary evaluation of the Upper Colorado River Basin indicates that both types of systems may be present. This report establishes a work plan for the RASA of the Upper Colorado River Basin in Colorado, Utah, Wyoming, and Arizona that began in fiscal year 1982.

A map of the study area within the Upper Colorado River Basin is shown in figure 1. The basin has a surface drainage area of about 113,500 mi^2 in western Colorado, eastern Utah, southwestern Wyoming, northeastern Arizona, and northwestern New Mexico. About 14,600 mi^2 of the Upper Colorado River Basin were excluded from the study. The area excluded, the upper part of the San Juan River basin, will be part of a separate RASA study.

The objectives of the RASA program for the Upper Colorado River Basin are to provide regional assessments of major aquifer systems for which data are available. These assessments will include:

(1) Classification of stratigraphic sequences into those intervals that constitute aquifers and those that constitute confining beds.
(2) Maps that portray the areal extent of aquifers, aquifer thickness, and overburden thickness.
(3) Hydrologic and geochemical characteristics of regional flow systems.
(4) Analyses of the regional flow systems under steady-state conditions.
(5) The estimated hydrologic and geochemical response of regional aquifer systems to hypothetical patterns of withdrawal or injection.

Water shortages and distribution problems in the basin are becoming critical. States represented within the Upper Colorado River Basin are required to deliver surface water to the Lower Basin States and Mexico. Water use is increasing in the upper basin because of additional agricultural, municipal, and industrial demands. The expected increase in water use for oil-shale and coal development in the upper basin may cause water shortages, especially during years of below-normal precipitation and runoff. Ground-water reservoirs may contain large volumes of water that could be developed to partly satisfy water demands in the upper basin. Therefore, an investigation of major ground-water reservoirs is needed for the Upper Colorado River Basin.

The quality of water in the Colorado River is poor in some reaches because of return flow from other uses and the discharge of saline ground and surface water into the river system. In addition, waste water may be injected into ground-water reservoirs for disposal; this could result in the degradation of surface water. A quantitative description of hydrologic systems also is needed to aid in the evaluation of measures to improve water quality and the effects of additional ground-water development on the quality of the Colorado River.

Previous Investigations

Previous ground-water investigations in the project area within Colorado were either reconnaissance or local studies. Boettcher (1973) described ground water in the northern and central parts of western Colorado. Local studies were made by Brogden and Giles (1976a, 1976b, and 1977), Brogden and others (1977), and Giles (1980).

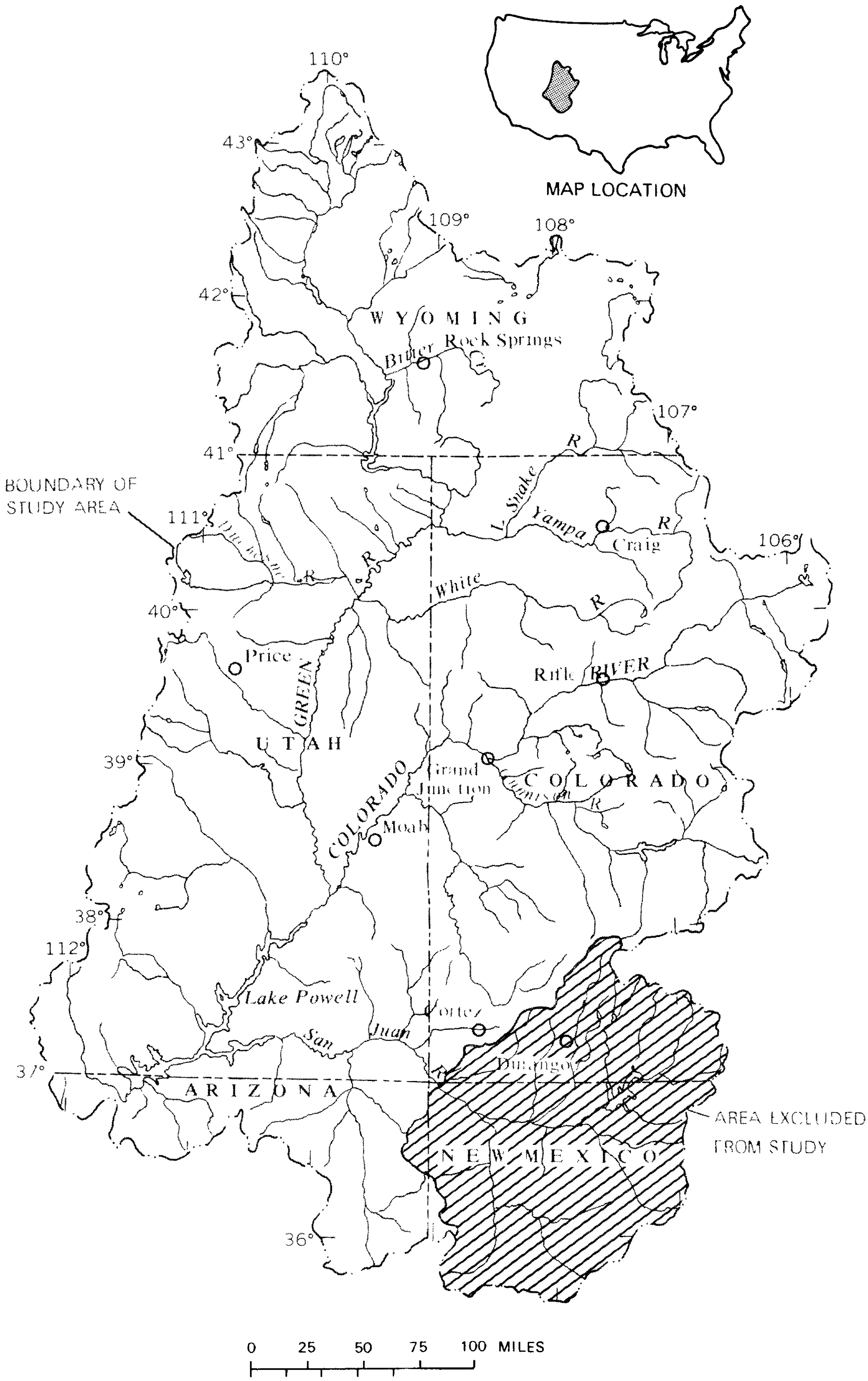

Figure 1.--Location of the study area within the Upper Colorado River Basin.

Simulation models of the ground-water systems in the Piceance basin of western Colorado were constructed by Weeks and others (1974), Robson and Saulnier (1981), and Taylor (1982). These models describe simulations of the hydrologic system and mine drainage of oil-shale aquifers within the Piceance basin.

Several studies described or summarized ground water in Utah and the adjacent northeastern corner of Arizona. Thomas (1952) described aquifers and ground-water conditions in a reconnaissance along the Green River in Utah and Colorado. Feltis (1966) compiled available data on water in bedrock in the Colorado Plateau in Utah. Cooley and others (1969) described the regional hydrogeology of the Navajo and Hopi Indian Reservations in southeastern Utah and northeastern Arizona. Hood (1976) described the characteristics of aquifers in the northern Uinta basin. Water-resource studies related to coal (Eychaner, 1981) were made in Arizona on the southern margin of the region. The Navajo Sandstone and related sandstone aquifers in Utah are described in a series of studies that include a report by Hood and Danielson (1981).

Summary appraisals of the ground-water hydrology, flow systems, and water quality for the project area in Wyoming were prepared by Welder and McGreevy (1966), Welder (1968), Lines and Glass (1973), Collentine and others (1981), and Ahern and others (1981). In addition, Zimmerman (U.S. Geological Survey, written commun., 1981) compiled hydrologic data for some 1,700 water wells, including 500 water-quality analyses, within the study area. Areally restrictive studies of the ground-water hydrology at a few specific localities also are available. No simulation models have been prepared for the aquifer systems within the project area in Wyoming. The existing studies and data compilations provide the foundation for the present investigation.

Approach

The major emphasis of the RASA of the Upper Colorado River Basin will be on the consolidated sedimentary aquifers of Paleozoic, Mesozoic, and Tertiary age. Available geologic and hydrologic information will be used to select major aquifer sequences for intensive study. Less emphasis will be put on unconsolidated aquifers and aquifers in igneous and metamorphic rocks. The data for the RASA program will be assembled by integrating existing hydrologic, geologic, geochemical, and geophysical information with newly collected data. However, most of the information used in the study will be derived from existing data. It is likely that hydrologic information will be meager for some aquifers in certain regions. The hydrologic characteristics of those aquifers will be estimated in order to complete the regional analysis of aquifer systems, because project funds are inadequate for exploratory drilling.

The available information will be analyzed and interpreted using statistical and simulation techniques in order to derive the maximum amount of knowledge about the ground-water systems of the project region. Details of the methods of interpretation of the available information to be used are given in the Plan of Study.

HYDROLOGIC FRAMEWORK

The Upper Colorado River Basin includes parts of four physiographic provinces: the Middle Rocky Mountains, the Wyoming Basin, the Southern Rocky Mountains, and the Colorado Plateaus (Fenneman, 1946). The basin also was divided into major drainage and physiographic subdivisions by Iorns and others (1965), as shown in figure 2. The major aquifers within each subdivision (Price and Arnow, 1974) are listed in table 1.

Many of the unconsolidated sedimentary deposits of Quaternary age in major stream valleys are hydraulically connected to streams and also may be connected to underlying bedrock aquifers. These deposits are aquifers in parts of the valleys and tributary valleys of the following streams (fig. 1): Green River, Yampa River, White River, Duchesne River, Colorado River, Gunnison River, and San Juan River.

The major aquifers are consolidated sedimentary rocks of Paleozoic, Mesozoic, and Tertiary age. Periodic tectonic activity has divided the study area into numerous structural basins, uplifts, and platforms (fig. 3) that are further deformed by faulting and fracturing. The older bedrock aquifers are deeply buried at the basin centers, but are exposed along the basin margins and the uplift centers. Much of the upper sedimentary sequence has been removed by erosion in the uplifted regions; owing to laterally changing depositional environments, the stratigraphic section does not necessarily remain uniform over the entire study area.

Paleozoic Aquifers

Aquifers of Paleozoic age are widespread in the project area but are absent in the Uinta and Uncompahgre uplifts due to erosion. Probable major aquifers of Paleozoic age in Colorado include the Leadville Limestone. Teller and Welder (1983) report that numerous large springs issue from the Leadville Limestone in the White River uplift. These springs suggest that the Leadville may be permeable because of fracture and solution cavities that are visible in outcrops. The Weber Sandstone, also known as the Weber Quartzite, also may be a major regional aquifer. However, hydrologic data for other formations will be compiled and analyzed in order to search for other aquifers within the sequence of Paleozoic rocks that has a maximum total thickness of nearly 5,000 ft.

Sedimentary rocks of Paleozoic age in eastern Utah and northeastern Arizona range in age from Cambrian to Permian. For most of the area, little is known of the strata of Cambrian and Devonian age. The results of numerous petroleum tests and the work by Hanshaw and Hill (1969) indicate that limestone and dolomite of Mississippian age probably constitute an extensive regional aquifer. In northeastern Utah, the Weber Quartzite or sandstone of Pennsylvanian and Permian age is an important aquifer. In east-central and southeastern Utah, the Cutler Formation contains massive sandstone aggregating about 1,000 ft in thickness. Near the western edge of the region this section is referred to as an equivalent of the Coconino Sandstone; that section grades eastward into several units, including the White Rim Sandstone Member and the Cedar Mesa Sandstone Member of the Cutler Formation.

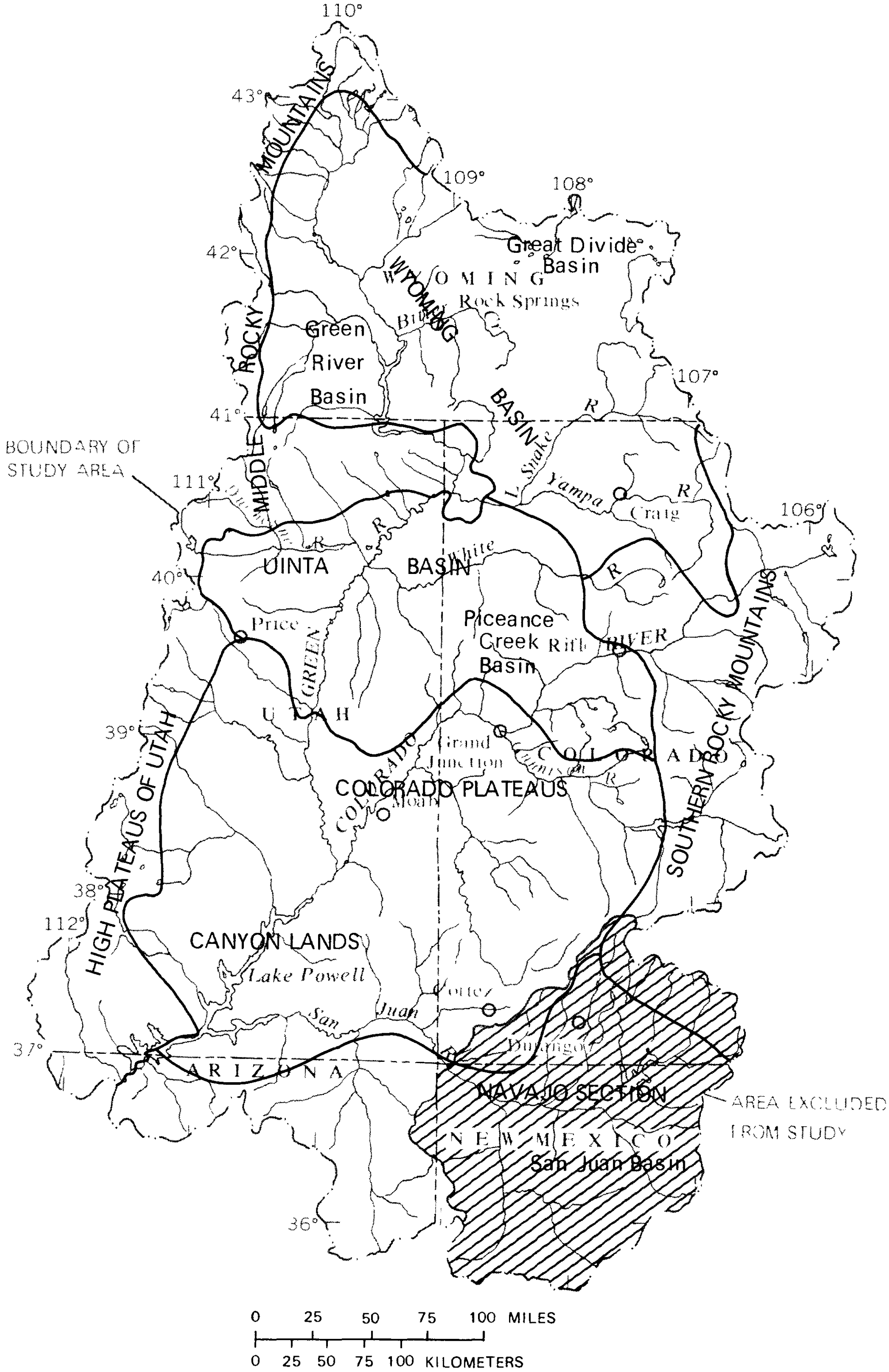

Figure 2.--Drainage and principal physiographic subdivisions of the Upper Colorado River Basin.

Table 1.--*Principal aquifers of the Upper Colorado River Basin*

[Regions are shown on figures 2 and 3. Modified from Price and Arnow (1974)]

WYOMING BASIN PROVINCE

A. West-central part of Green River basin

- Quaternary
  - Unconsolidated sedimentary deposits
    - Stream alluvium
    - Eolian deposits
    - Glacial outwash deposits
    - Terrace or pediment deposits
- Tertiary
  - Browns Park Formation
  - Bridger Formation
  - Green River Formation
  - Wasatch Formation
- Cretaceous
  - Almond and Ericson Formations, undivided
  - Rock Springs Formation
  - Frontier Formation
  - Dakota Formation or Bear River Formation
- Jurassic and Triassic
  - Nugget Sandstone or Navajo Sandstone
- Permian
  - Phosphoria Formation or Park City Formation
- Permian and Pennsylvanian
  - Weber Sandstone
  - Wells Formation
- Pennsylvanian and Mississippian
  - Darwin Member (Mississippian) of the Amsden Formation (Pennsylvanian and Missippian)
- Pennsylvanian
  - Morgan Formation
- Mississippian
  - Madison Limestone (includes Mission Canyon and Lodgepole Limstones
  - Deseret Limestone (in south)
- Devonian
  - Darby Formation
- Ordovician
  - Bighorn Dolomite
- Cambrian
  - Flathead Sandstone
- Precambrian
  - Uinta Mountain Group

B. Great Divide and Washakie Basins

- Quaternary
  - Unconsolidated sedimentary deposits (mostly alluvial, lacustrine, or eolian in origin)
- Tertiary
  - North Park Formation or Browns Park Formation
  - Green River Formation
  - Wasatch Formation or Battle Spring Formation
  - Fort Union Formation
- Cretaceous
  - Lance Formation
  - Fox Hills Sandstone
  - Almond and Ericson Formations, undivided
  - Mesaverde Formation (east part of the area)
  - Rock Springs Formation
  - Frontier Formation
  - Cloverly Formation and Dakota Sandstone
- Jurassic
  - Sundance Formation
- Jurassic (?) and Triassic (?)
  - Nugget Sandstone
- Triassic
  - Chugwater Formation
- Pennsylvanian
  - Tensleep Sandstone
- Mississippian
  - Madison Limestone
- Cambrian
  - Flathead Sandstone

Table 1.--*Principal aquifers of the Upper Colorado River Basin*--Continued

MIDDLE ROCKY MOUNTAINS PROVINCE

C. South flank of Uinta Mountains

Quaternary
  Unconsolidated sedimentary deposits
  Glacial outwash
Tertiary
  Duchesne River Formation
Cretaceous
  Dakota Sandstone
Jurassic(?) and Triassic(?)
  Nugget Sandstone
Permian
  Park City Formation
Pennsylvanian
  Weber Quartzite
  Morgan Formation
Mississippian
  Carbonate rocks, undifferentiated

UINTA BASIN SECTION

D. Eastern and central parts

Quaternary
  Unconsolidated sedimentary deposits (mostly alluvium)
Tertiary
  Duchesne River Formation
  Uinta Formation
  Green River Formation
  Wasatch Formation
Cretaceous
  Frontier Sandstone Member of Mancos Shale
  Mowry Shale
  Dakota Sandstone
Jurassic and Triassic
  Glen Canyon Sandstone
Permian
  Park City Formation
  Phosphoria Formation
Pennsylvanian
  Weber Sandstone (Quartzite)
  Morgan Formation
  Round Valley Limestone

HIGH PLATEAUS OF UTAH

E. Northern part

Quaternary
  Unconsolidated sedimentary deposits (mostly alluvium)
Tertiary
  Flagstaff Formation
Tertiary and Cretaceous
  North Horn Formation
Cretaceous
  Emery Sandstone Member of Mancos Shale
  Ferron Sandstone Member of Mancos Shale
Jurassic
  Carmel Formation
Jurassic and Triassic(?)
  Navajo Sandstone (Glen Canyon Group)
Triassic
  Wingate Sandstone (Glen Canyon Group)

F. Southern part

Quaternary
  Unconsolidated alluvial and lacustrine deposits (probably some extrusive igneous rocks)
Tertiary
  Igneous rocks
  Wasatch Formation
Cretaceous
  Kaiparowits Formation
  Wahweap Sandstone
  Straight Cliffs Sandstone
Jurassic
  Carmel Formation
Jurassic and Triassic(?)
  Navajo Sandstone (Glen Canyon Group)
Triassic
  Wingate Sandstone (Glen Canyon Group)

Table 1.--*Principal aquifers of the Upper Colorado River Basin*--Continued

CANYON LANDS

G. Henry Mountains vicinity	H. La Sal Mountains vicinity
Quaternary	Quaternary
Unconsolidated sedimentary deposits (mostly alluvium and dune sand)	Unconsolidated sedimentary deposits (mostly alluvium and dune sand)
Cretaceous	Cretaceous
Dakota Sandstone	Dakota Sandstone
Jurassic and Triassic(?)	Burro Canyon Formation
Navajo Sandstone (Glen Canyon Group)	Jurassic
Triassic	Entrada Sandstone
Wingate Sandstone (Glen Canyon Group)	Jurassic and Triassic(?)
Permian	Navajo Sandstone (Glen Canyon Group)
Coconino Sandstone	Triassic
	Wingate Sandstone (Glen Canyon Group)
	Permian
	Cutler Formation

NAVAJO SECTION

I. North-central part	J. Northeast part
Quaternary	Quaternary
Unconsolidated alluvium and dune sand (some igneous rocks)	Unconsolidated sedimentary deposits (mostly alluvium)
Tertiary	Tertiary
Chuska Sandstone	San Jose Formation
Cretaceous	Cretaceous
Dakota Sandstone	Dakota Sandstone
Jurassic	Jurassic
Recapture Shale Member of Morrison Formation	Entrada Sandstone
Salt Wash Sandstone Member of Morrison Formation	Permian
Summerville Formation	Cutler Formation
Cow Springs Sandstone	
Bluff Sandstone	
Jurassic and Triassic(?)	
Navajo Sandstone (Glen Canyon Group)	
Triassic(?)	
Moenave Formation	
Triassic	
Owl Rock Member of Chinle Formation	
Shinarump Member of Chinle Formation	
Permian	
Cedar Mesa Sandstone Member of Cutler Formation	
Mississippian	
Carbonate rocks, undifferentiated	

SOUTHERN ROCKY MOUNTAIN PROVINCE

K. North Park and Middle Park vicinity	L. Glenwood Springs-McCoy vicinity
Quaternary	Quaternary
Unconsolidated sedimentary deposits (mostly alluvium and glacial deposits)	Unconsolidated alluvium
	Mississippian
	Leadville Limestone

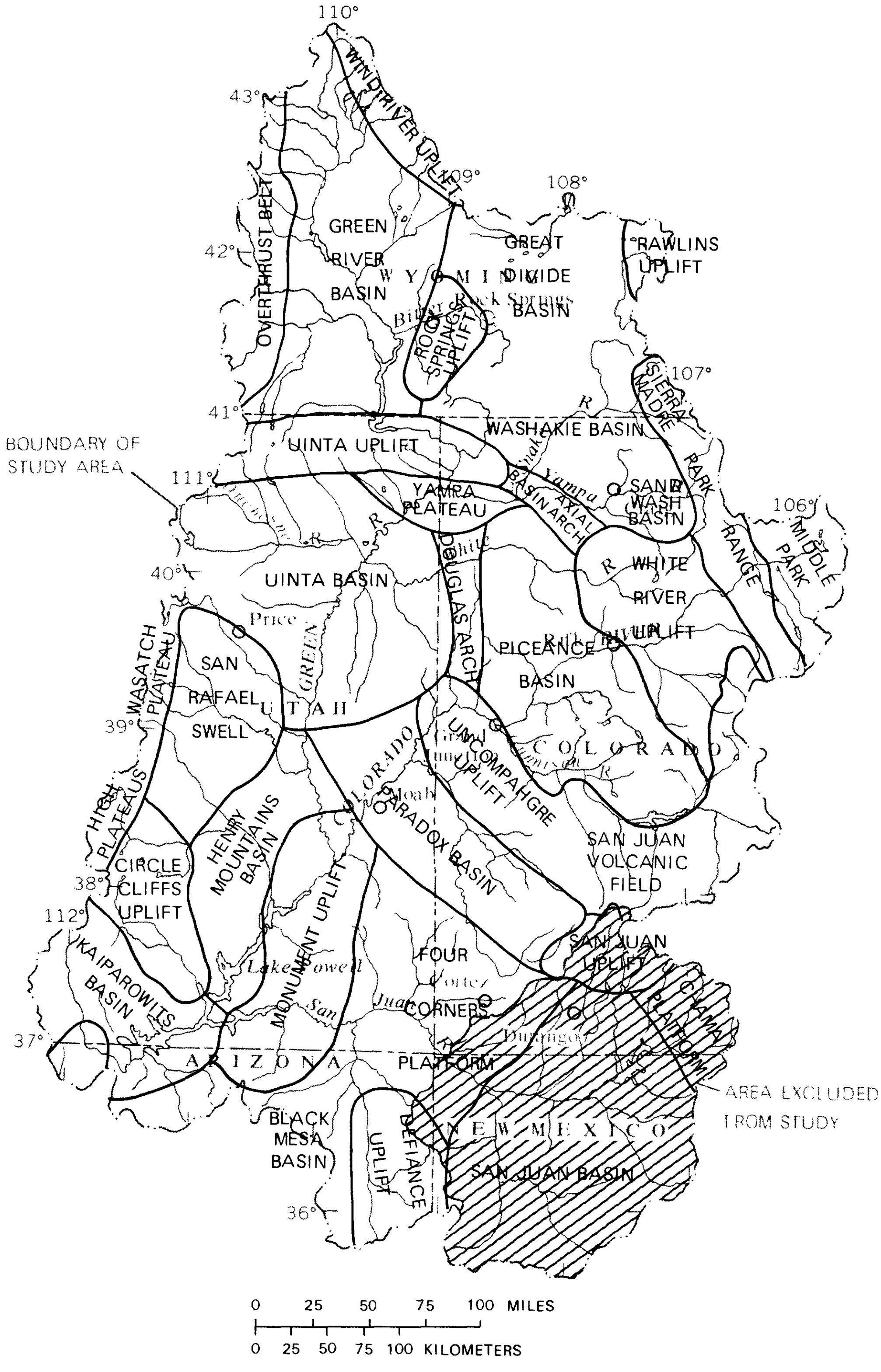

Figure 3.--Principal tectonic features of the Upper Colorado River Basin.

Both the limestone and sandstone units variously contain fresh or slightly saline to briny water, depending on locality, depth of burial, and rate of ground-water flow. In the Paradox basin, the Hermosa Formation of Pennsylvanian age is not important as an aquifer; however, the formation contains a thick saline series consisting mainly of halite (common salt) which locally contributes to the degradation of water quality in adjacent aquifers and some streams.

Although possible aquifers of Paleozoic age in Wyoming aggregate a thickness of more than 4,000 ft, they are deeply buried or absent under most of the Green River basin. Therefore, these aquifers may be of interest as sources of water only around the periphery of the Green River basin, commonly in hydrologically isolated fault blocks. Few wells tap these rocks, but springs yielding as much as 4,000 gal/min indicate the hydrologic potential of the aquifers.

Mesozoic Aquifers

The aquifers of Mesozoic age occur throughout the project area in Colorado, except in parts of the Uinta, White River, and San Juan uplifts where they have been removed by erosion. These aquifers in Colorado are part of the stratigraphic sequence of Mesozoic rocks that has a total thickness of more than 8,000 ft.

The principal aquifers of Mesozoic age in Utah are sandstones in the Glen Canyon Group (Wingate Sandstone, Kayenta Formation, and Navajo Sandstone) and the Entrada Sandstone of the San Rafael Group. The sandstones of Mesozoic age are the most areally extensive and the thickest bedrock aquifers in the Upper Colorado River Basin. They also are the most likely to contain water of a chemical quality useful for most purposes; over a broad area, they are the shallowest of the bedrock aquifers.

These sandstones are missing in about one-fourth of the region because of uplift (sometimes by igneous rock) and subsequent erosion or because of lack of original deposition. The Mesozoic sandstones have been studied in parts of Utah and Arizona, generally as part of the overall ground-water system. Data from part of the area are sufficient to provide control required for predictive modeling; however, the data available in most areas are not sufficient. For example, the potentiometric surface is known or can be inferred in only a part of the region.

The Mesozoic section in the Wyoming part of the Upper Colorado Region may be divided hydrologically by the relatively impermeable shale barrier that consists of the Hilliard, Baxter, Steele, and Mancos Shales. Below this barrier, the Nugget Sandstone (deepest), the sandstone of the Dakota or Cloverly Formations, and deposits of the Frontier Formation (shallowest) probably are aquifers. Above the shale barrier, sandstone beds in the Mesaverde Group are the principal Mesozoic aquifers. These sandstone beds crop out around the Rock Springs uplift and the Rawlins uplift, but are buried or absent in much of the Green River basin. The Mesaverde Group is as much as 5,000 ft thick, but facies changes in the coal-bearing, continental beds result in variable aquifer characteristics.

Cenozoic Aquifers

The emphasis of the study of Cenozoic aquifers is Tertiary aquifers, because Quaternary aquifers are not important regionally. Aquifers of Tertiary age in Colorado occur in the Piceance basin and in the region north of the White River. In the Piceance basin the Uinta and Green River Formations are aquifers because they contain fractures, solution channels, and sandstone beds. North of the White River the potential aquifers include the North Park, Browns Park, Uinta, Green River, Wasatch, and Fort Union Formations. The total maximum thickness of formations of Tertiary age exceeds 14,000 ft.

Sedimentary rocks of Tertiary age in Utah range in age from the Paleocene to the Pliocene, and crop out in part of the highlands of the Uinta uplift and along their flanks, in the High Plateaus of Utah, and in the Uinta basin. The fringe of the Green River basin in Wyoming laps up on the Uinta uplift at the Utah-Wyoming border. Most of the Tertiary rocks in the highlands, such as the Browns Park Formation in the Uinta uplift, are limited in extent or are discontinuous in occurrence.

The most important Tertiary aquifers in Utah are in the Uinta basin where the strata range in age from the Paleocene to the Oligocene and include the Wasatch, Green River, Uinta, and Duchesne River Formations. The Duchesne River Formation is the most important of these Tertiary aquifers because of its higher permeability and present (1982) utilization, but it is restricted in area to the south flank of the Uinta uplift and the Uinta basin north of the Duchesne and the White Rivers.

The occurrence of water in the remaining part of the Tertiary section in Utah generally is similar to that in the Green River basin in Wyoming and the Piceance basin in Colorado. The hydrology of the oil-shale-bearing zones in the southeastern part of the Uinta basin is being assessed currently. According to W. F. Holmes (U.S. Geological Survey, personal commun., 1982), data from this quadrant of the basin might be extrapolated to the remaining parts of the basin for highly generalized modeling.

Tertiary aquifers are the most widespread and the most commonly tapped in the Wyoming part of the Upper Colorado Region. They include the Fort Union Formation, the Wasatch Formation and its several tongues, the Battle Springs Formation (a coarse-grained, arkosic formation that is equivalent to the Wasatch), the Laney Shale Member of the Green River Formation, and the Bridger or Washakie Formation.

Because of their occurrence over more than 80 percent of the Green River basin, the aquifers of Tertiary age are preeminent as sources of ground water in the basin. Their actual potential productivity differs from place to place because of differences in aquifer thickness; rock characteristics including grain size, degree of sorting, and fracturing; and available recharge. Some aquifers of Tertiary age, notably the members of the Green River Formation, contain water with considerable amounts of evaporite salts. This saline ground water may be discharged into streams, contributing to salinity problems of the Green River, the principal tributary of the Colorado River.

Igneous and metamorphic rocks may be aquifers in parts of the project area. Major volcanic regions are the San Juan volcanic field of southwestern Colorado and the south-central part of the physiographic subdivision, High Plateaus of Utah (fig. 3). These regions may include aquifers of various types, including fractured and jointed intrusive and extrusive rock such as basalt, volcanic tuff and ash breccia, and sedimentary rocks included in volcanic sequences. Minor volcanic regions include the basalt deposits east of Grand Junction, Colo., which are potential aquifers because of joints and fractures. Igneous and metamorphic rocks underlie the entire region but locally are relatively shallow, especially in mountainous areas. These rocks probably do not include areally extensive aquifers but may be permeable locally where jointed or fractured.

Recharge to aquifers in the Upper Colorado River Basin ultimately is derived from precipitation over the basin, whether that recharge is from rain or snow falling directly on the outcrop of the aquifers, by movement from other aquifers that have been recharged at the surface, or by water from streams that obtain their flow from areas of greater precipitation. Minor recharge to aquifers can occur even where precipitation is small, but rates of recharge significant in relation to potential withdrawals occur only in an estimated 10 to 20 percent of the basin--the mountain and high plateau areas along the eastern and western borders of the basin. Aquifers in the basin may contain large volumes of recoverable water in storage, and if the rate of natural recharge is small, most of the water for large potential withdrawals must come from storage.

Presumably these aquifers discharge naturally to streams and affect surface-water supplies. These supplies in the Colorado River basin have been allocated among several States by compact. Claims for appropriation of the flow in most areas equal or exceed the available flow. Thus, any decrease of surface flow due to ground-water development intercepts supplies that have been allocated.

The chemical quality of water in aquifers rarely is uniform, partly because some formations include significant deposits of soluble evaporite minerals such as halite and gypsum. The Entrada Sandstone, for example, contains both fresh and saline water in the Upper Colorado River Basin. The overlying Curtis Formation locally contains water much more saline than that in the Entrada. In most of the basin, the distribution of ground water of various chemical qualities is the result of a natural regimen in equilibrium.

PLAN OF STUDY

Planning and Staffing

The work schedule for the study is shown in figure 4. Some preliminary planning and staffing of the project was done in the last part of fiscal year 1981, and was continued during fiscal year 1982. The active phase of the project will last 4 years from fiscal year 1982 through fiscal year 1985.

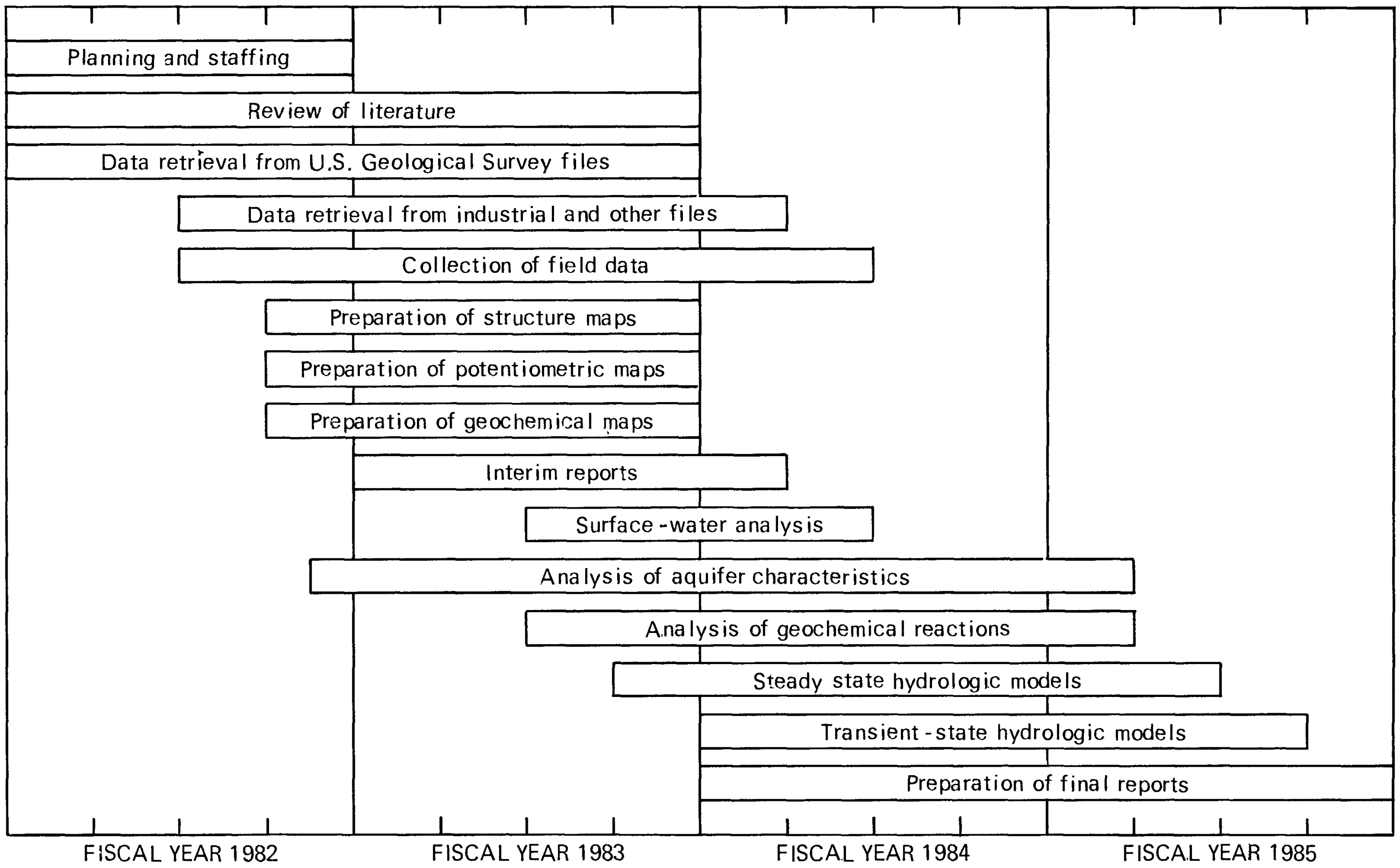

Figure 4.--Work schedule for RASA project for the Upper Colorado River Basin.

The planning and staffing phase required 1 year because of the time needed to identify the diverse sources of information for the project and the time needed to obtain the various types of personnel required during the active phase. The overall project will be divided among the Colorado, Utah, and Wyoming Districts. The personnel needed are:

- One Project Coordinator for overall project management (also serves as project chief for Colorado District studies);
- Eight hydrologists for data compilation, analysis, and simulation studies (includes project chiefs for Utah and Wyoming District Offices);
- Four hydrologic technicians for data collection; and
- Part-time personnel, as needed.

After review of the literature is completed, an extensive data compilation, collection, and analysis program will be used to assemble and interpret the geologic, hydrologic, and geochemical data for publication in a series of intermediate reports in the form of hydrologic atlases. The distributed hydrologic and geochemical characteristics of various aquifer systems will be analyzed and regional simulation models will be prepared where adequate data are available. Models will be used to simulate various types of steady-state and transient ground-water flow conditions, including the effects of withdrawals from, or injection through, hypothetical well fields.

Each District office will be assigned to study specific aquifers. The Colorado District will analyze the aquifers of Paleozoic age within the entire project area and the aquifers of Tertiary and Quaternary age in Colorado. The Utah District will analyze the aquifers of Mesozoic age in the entire project area and provide a general assessment of the aquifers of Tertiary and Quaternary age in Utah. In addition, the Utah District will incorporate published hydrologic data from northeastern Arizona into the overall study. The Wyoming District will analyze aquifers of Tertiary and Quaternary age in Wyoming.

The final reports for the project will be published in a series of professional paper chapters. Each chapter will address a major topic within the project framework and will describe the data analysis, conceptual hydrologic or geochemical system, results of simulation analyses and a synthesis of the overall study.

Review of Literature

Most reports on water resources in the Upper Colorado River Basin are on small areas widely scattered across several States (see section on previous investigations). These reports are designed to meet the needs of the State and Federal agencies who funded the studies. Regional evaluations were made by LaRue (1916) and Iorns and others (1965). These two reports are principally on surface-water supplies, although Iorns and others (1965) include a ground-water summary and hydrogeologic maps by D. A. Phoenix. Subsequently, the Upper Colorado Region State-Federal Interagency Group (1971) issued a report having 16 appendixes that provide detailed summaries of the then-available data on land and water use, mineral resources, climate, and the several other factors relating to development of the basin, with alternative programs for resources and conservation to the years 1980, 2000, and 2020.

Price and Waddell (1973) prepared maps showing selected ground-water data for the basin, and Price and Arnow (1974) described the basin in a report that is part of a nationwide series of ground-water appraisals. The citations given above are examples of reports and sources of geologic and hydrologic data that are readily available. A thorough search will be made for all references pertinent to the RASA project in the Upper Colorado River Basin.

Data Retrieval from U.S. Geological Survey, Industrial, and Other Files

First, the National Water Data Storage and Retrieval System known as WATSTORE (Hutchinson, 1975) and the Rock Analysis Storage System known as RASS of the U.S. Geological Survey will be searched for available data. Additional data will be obtained from the following sources:

(1) Geologic information in published reports and maps, drillers' logs, and geophysical logs.
(2) Ground-water data in records of exploratory, industrial, municipal, or individually owned test holes or wells. In addition, a limited field inventory of water wells will be conducted.
(3) Surface-water data, required to estimate recharge to or discharge from ground-water reservoirs, from stream-discharge measurements, channel-geometry studies or chemical-loading studies; and
(4) Water-quality data in State reports, oil company files, drill stem tests, and university collections. The number of water-quality samples that are needed to adequately describe an area will be evaluated using statistical tests (Miesch, 1976b; Nelson and Ward, 1981).

The data that are in the U.S. Geological Survey files and the data that will be acquired from other sources must be evaluated for both internal consistency and adequacy. The analysis of the data, although aided by statistical packages available on the Survey computer (SAS Institute, Inc.,[1] 1979), will require a major part of the project time.

Collection of Data

Detailed field investigation of the entire project area is not possible because time, manpower, and funds are limited. However, data collection will be done in representative parts of the project area to complement the geologic and hydrologic data obtained from computer files. Areas lacking sufficient data for the preparation of geochemical maps will require additional geochemical sampling. Samples will be collected for the analysis of major ions, trace elements, and isotopes of carbon, oxygen, and hydrogen. Once a data base is established, interpretation of the data will begin.

[1]The use of a brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Preparation of Structure Maps

Data obtained from published reports, files, and field investigations will be used to prepare structure-contour maps that describe the areal and vertical position of aquifer systems. Thickness maps of the aquifers and overburden are planned also. These maps will help to ensure that data are identified with the correct aquifer, will help define the regional flow systems, and will help in the preparation of simulation models.

Preparation of Potentiometric Maps

Water-level data for wells will be obtained from published data, data files, and field measurements. These data will be used to prepare potentiometric maps for selected aquifer systems. The resulting areal or cross-sectional potentiometric maps will be compared with regional geochemical maps and used to interpret patterns of natural recharge, movement, and discharge. Potentiometric maps also will be compared with maps showing the altitude of the top of the aquifer and aquifer thickness to identify regions where the aquifers are confined or unconfined. The potentiometric maps will be used to help prepare simulation models that are described in the sections on "Steady-State Hydrologic Models" and "Transient-State Hydrologic and Solute-Transport Models."

Preparation of Geochemical Maps

Geochemical data from published reports, data files, and field measurements will be compiled on regional maps for selected aquifer systems. In addition, rock samples will be studied using a petrographic microscope, scanning electron microscope, and x-ray diffraction to determine diagenetic changes that have occurred in the aquifer materials in selected local areas. These studies will provide information on possible increase or decrease of porosity and permeability. The geochemical and hydrologic data will be used to interpret the water-rock interactions that are responsible for the regional geochemical trends.

Regional patterns of water quality often can indicate complexities in the hydrologic system that might otherwise be overlooked during construction of a ground-water model. The preparation of geochemical maps depicting regional trends in water quality will contribute to the development of conceptual and simulation models and their interpretation. A preliminary analysis of regional trends will be made with the data that are presently available in the files of the U.S. Geological Survey. This analysis will be limited to those aquifers with a sufficient number of samples and areal coverage on a basinwide scale. Miesch (1976a; 1976b) has described methods for the regional analysis of geochemical patterns. The analysis also will help in designing subsequent sampling programs and in the preparation of geochemical maps.

Interim Reports

A series of hydrologic atlases will be prepared by the first quarter of fiscal year 1984. These reports will present the following information on those aquifers for which adequate geologic and hydrologic data are available: Areal extent, general stratigraphic columns, structure-contour maps, overburden-thickness maps, potentiometric maps, and dissolved-solids concentration maps.

Surface-Water Analysis

The flow-system analysis is likely to indicate that certain aquifers discharge to, or are recharged by, streams in certain reaches. For those reaches, a surface-water analysis will be conducted. The analysis will attempt to determine the rate of discharge or recharge for use in preparing hydrologic budgets and simulation models. The period of record for the streamflow-gaging station, the effects of stream regulation, and losses related to evapotranspiration will be considered. The surface-water analysis will include:

Stream-hydrograph analysis during low-flow conditions for selected stations to determine stream gain in reaches affected by discharge from aquifers.

Low-flow determinations, using historical stream-discharge records to calculate average minimum flows and streamflow gains.

Gain-and-loss studies in selected reaches of streams.

Measurements of changes in quality related to changes in dissolved material carried by a stream to indicate aquifer discharge.

Analysis of Aquifer Characteristics

Aquifer characteristics will be estimated using several techniques. Geologic and geophysical logs will be reviewed to locate and correlate permeable zones. Data from drill-stem tests in exploratory holes will be analyzed to estimate the hydraulic conductivity of the tested intervals (Bredehoeft, 1965). Core-hole samples of Mesozoic sandstone aquifer materials will be collected for laboratory analysis of hydraulic conductivity. Estimation of the storage characteristics of aquifers will be attempted using geophysical logs. Aquifer tests using existing wells may be possible where suitable wells are available for testing. The theoretical distribution of aquifer characteristics will be determined using a technique described by Weiss (1982) in which these characteristics are related to overburden and aquifer thickness, ground-water temperature and dissolved-solids concentration. The resulting estimates of aquifer characteristics from each technique will be compared with geologic and potentiometric maps, as well as with regional trends in water quality. Preliminary distributions of the aquifer characteristics will be selected, based on the integration of all available data and the analytical techniques mentioned above.

Analysis of Geochemical Reactions

To understand the effects of future ground-water withdrawals or other changes to the flow system on water quality, the chemical reactions that account for that quality must be understood. A chemical-equilibrium approach will be used with data from selected local areas where adequate data are available to aid in the interpretation of controls on water composition. This will be done using computerized chemical-equilibrium models such as WATEQ2 (Ball and others, 1979). An equilibrium model can show which minerals might control concentrations of solutes in the water. When the minerals that control water quality are identified, chemical reactions involving solutes and the mineral phases can be written. These reactions can be evaluated quantitatively by mass-balance and reaction-path calculations. Modeling may include isotope data to help to identify appropriate chemical reactions. These calculations will be evaluated with the information from the mineralogic study to describe the trends in water quality. This work will be used to help to interpret causes of the regional changes in water quality, where possible. This, in turn, will help describe regional flow systems.

Steady-State Hydrologic Models

Simulation techniques will be used to analyze selected flow systems in several ways. An inverse simulation model (Cooley, 1977) will be used to derive the theoretical distribution of hydrologic characteristics of aquifer systems for comparison with related hydrologic data. This model will be used to improve estimates of the distribution of hydraulic conductivity by analyzing the shape of the potentiometric surface in conjunction with a water budget. Other models will be employed to simulate the steady-state hydrologic characteristics of the flow systems and to determine the plausibility of conceptual models.

Model calibration will be effected by comparing (1) the measured and simulated potentiometric heads and (2) the measured and simulated natural discharge from major aquifers. Measured potentiometric heads will be obtained from drill-stem tests and measured discharge values will be obtained from low-flow measurements of the appropriate reaches of streams. The model parameters will be adjusted until the measured and simulated characteristics of the flow system are similar.

Transient-State Hydrologic and Solute-Transport Models

If the flow systems can be reasonably well defined by models, additional simulation analysis will be tried for predictive purposes. For example, simulation of the hypothetical effects of withdrawal and injection on aquifer systems will be attempted, if reasonably accurate estimates are obtained for the vertical and horizontal permeabilities and storage characteristics of aquifers and confining layers. A three-dimensional model is available for analyzing layered systems having anisotropic characteristics.

Models of solute transport may be prepared for the Navajo Sandstone and the limestones of Mississippian age in local areas that have sufficient hydrologic and geochemical data. Such models usually evaluate the effects of ground-water withdrawal or injection on the water quality of an aquifer, and the development and evolution of the observed water quality. For the RASA study, however, the models would help evaluate proposed water-rock interactions and the effects of mixing water from different aquifers. The ability to prepare and operate a solute-transport model depends to a large degree on the observations and interpretations made in the previous steps of the geochemical study. Most solute-transport models treat chemical species as conservative solutes, unaffected by chemical reactions. They treat only the advection and diffusion of the solutes and, at best, include an assumed first-order reaction to account for changes in concentration. At the present time several workers are developing solute-transport models that will account for the nonconservative transport of major solutes. Hopefully, an adequate model will be available for use in evaluating solute transport during the life of this project. Even if there is no nonconservative transport model available, the results and conclusions of other geochemical models will be valuable to both water users and those involved in hydrologic modeling of the aquifers.

Preparation of Final Reports

The final reports for the RASA project will consist of chapters in a professional paper. The chapters will describe major study topics within the project area for all aquifers. The chapters and major topics proposed are:

A. Hydrologic characteristics of selected regional aquifers
   - Hydraulic conductivity
   - Transmissivity
   - Storage characteristics

B. Geochemistry of regional aquifers
   - Chemical variability of ground water
   - Controls on chemical composition
   - Reaction models for selected aquifers

C. Mathematical models of selected regional aquifers
   - Characteristics of flow system
   - Descriptions of models
   - Model results

D. Synthesis of ground-water resources
   - Geohydrologic setting
   - Aquifer characteristics
   - Water quality
   - Effects of hypothetical development

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