# Aquifer Systems in the Great Basin Region of Nevada, Utah, and Adjacent States:

# A STUDY PLAN

By James R. Harrill, Alan H. Welch, David E. Prudic, James M. Thomas,
Rita L. Carman, Russell W. Plume, Joseph S. Gates, and James L. Mason

---

U.S. GEOLOGICAL SURVEY

Open-File Report 82-445

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Carson City, Nevada

1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

---

For additional information
write to:

U.S. Geological Survey
Room 229, Federal Building
705 North Plaza Street
Carson City, NV 89701

Copies of this report may be
purchased from:

Open-File Services Section
U.S. Geological Survey
Box 25425, Federal Center
Denver, CO 80225

Call (303) 234-5888 for
ordering information

## CONTENTS

## ILLUSTRATIONS

## CONVERSION FACTORS AND ABBREVIATIONS

"Inch-pound" units of measure used in this report may be converted to International System (metric) units by using the following factors:

| *Multiply* | *By* | *To obtain* |
|---|---|---|
| Acres | 0.4047 | Square hectometers ($hm^2$) |
| Acre-feet (acre-ft) | 0.001233 | Cubic hectometers ($hm^3$) |
| Acre-feet per year (acre-ft/yr) | 0.001233 | Cubic hectometers per year ($hm^3/yr$) |
| Feet (ft) | 0.3048 | Meters (m) |
| Inches (in.) | 25.40 | Millimeters (mm) |
| Miles (mi) | 1.609 | Kilometers (km) |
| Square miles ($mi^2$) | 2.590 | Square kilometers ($km^2$) |

## ALTITUDE DATUM

The term "National Geodetic Vertical Datum of 1929" (abbreviation, NGVD of 1929) replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The NGVD of 1929 is derived from a general adjustment of the first-order leveling networks of both the United States and Canada. For convenience in this report, the datum also is referred to as "sea level."

# AQUIFER SYSTEMS IN THE GREAT BASIN REGION OF NEVADA, UTAH, AND ADJACENT STATES:

## A STUDY PLAN

By

James R. Harrill, Alan H. Welch,
David E. Prudic, James M. Thomas,
Rita L. Carman, Russell W. Plume,
Joseph S. Gates, and James L. Mason

## ABSTRACT

The Great Basin Regional Aquifer Study includes about 140,000 square miles in parts of Nevada, Utah, California, Idaho, Oregon, and Arizona. Within that area, 240 hydrographic areas occupy structural depressions formed primarily by basin-and-range faulting. The principal aquifers are in basin-fill deposits; however, permeable carbonate rocks underlie valleys in much of eastern Nevada and western Utah and are significant regional aquifers. Anticipated future water needs require a better understanding of the resource so that wise management will be possible. In October 1980, the U.S Geological Survey started a 4-year study to (1) describe the ground-water systems as they existed under natural conditions and as they exist today, (2) analyze the changes that have led to the systems' present condition, (3) tie the results of this and previous studies together in a regional analysis, and (4) provide means by which effects of future ground-water development can be estimated.

A plan of work is presented that describes the general approach to be taken in this study. It defines (1) the major task necessary to meet objectives and (2) constraints on the scope of work. The approach has been strongly influenced by the diverse nature of ground-water flow systems and the large number of basins. A detailed appraisal of 240 individual areas would require more resources than are available. Consequently, the general approach is to study selected "typical" areas and key hydrologic processes. Effort during the first 3 years will be directed toward describing the regional hydrology, conducting detailed studies of "type" areas, and studying selected hydrologic processes. Effort during the final year will be directed toward developing a regional analyses of results.

Special studies that will address hydrologic processes, key components of the ground-water system, and improved use of technology include evaluations of regional geochemistry, regional hydrogeology, recharge, ground-water discharge, and the use of remote sensing. Areas selected for study using ground-water flow models include the regional carbonate-rock province in eastern Nevada and western Utah, six valleys--Las Vegas, Carson, Paradise, Dixie, Smith Creek, and Stagecoach--in Nevada, plus Jordan Valley, the Milford area, and Tule Valley in Utah.

# INTRODUCTION

## Background and Objectives

In 1977, the United States House of Representatives introduced a national program of regional aquifer analyses and stated that the U.S. Geological Survey was to implement the program (Committee Report 95-392). The resulting RASA (Regional Aquifer-System Analysis) program represents a systematic effort to study a number of regional ground-water systems that together underlie much of the United States and compose a major part of the Nation's water supply. Twenty-five systems have been identified for study. The Great Basin RASA study, which started in fiscal year 1981, is the tenth in the program.

For the purposes of the RASA program, a regional aquifer system has been defined in general terms as "an areally extensive set of aquifers which are linked in some way." This link may be a hydraulic interconnection between aquifers (for example, aquifers linked by a river); an economic or water-use connection, where a group of aquifers is a water source to a common element of the economy; or a combination of characteristics shared by a group of aquifers that cause them to be the group most efficiently studied as a single exercise.

The general objectives for all RASA studies are to:

1. Describe, both hydraulically and geochemically, the present ground-water system and the original ground-water system as it existed prior to development.

2. Analyze the changes that have led to the present condition of the system.

3. Tie together, in a regional analysis, the results of this and earlier studies dealing with individual segments of the system.

4. Provide capabilities through which the effects of further ground-water development can be estimated.

In addition to the general RASA objectives, the following are specific goals for the Great Basin study:

1. Assist in developing a data base comprehensive enough to support mathematical modeling of basins throughout the region as the need develops. The data base would be capable of providing planners and managers with much of the factual information needed to support sound management decisions.

2. Delineate and quantitatively describe ground-water flow systems. Flow systems will be grouped into general categories representative of the main types present.

3. Develop a better understanding of the various processes that result in ground-water recharge and, within the limits of this study, develop and apply approved techniques to make quantitative estimates of recharge and discharge.

4. Develop mathematical models of flow systems considered representative of the region ("type areas").

5. Use experience gained in detailed model studies to design and document generalized models that can be readily applied to similar systems throughout the region.

6. Evaluate the relative hydrologic impacts of selected development alternatives on the various types of flow systems in the region. Development alternatives will be evaluated using models constructed for the "type areas."

The purpose of this report is to present a plan of work that will:

1. Describe the general approach to be taken in this study.

2. Define the major tasks necessary to meet the objectives and defines constraints on the scope of work.

3. Outline the general scheduling of work and allocation of resources to coordinate the work so that the results will be brought together at the end of the study.

4. Outline the general methods that will be used to develop a regional analysis of results.

## Study Area

The study area is characterized by a series of generally north-trending mountain ranges separated by alluviated valleys. Most mountain ranges are 5 to 15 miles wide and rise 1,000 to 5,000 feet above adjoining valleys, which in turn are about as wide as the mountain ranges. They are typically elongate and many extend in a northeast or north direction for more than 50 miles. The area has had a complex geologic history that includes major episodes of sedimentation, igneous activity, orogenic deformation, and continental rifting. A major tectonic change occurred about 17 million years ago with the onset of extensional faulting that has formed the major basins and ranges which characterize the present-day physiography. This period of structural deformation is still continuing.

The Great Basin contains a regional aquifer in the sense that most individual basins share a number of common characteristics. Included are basins that have continuity through permeable sedimentary deposits or bedrock, thereby forming multibasin ground-water flow systems, basins that are linked by river systems, and basins that function as isolated hydrologic systems. These basins occupy structural depressions that have been filled or partly filled with sedimentary deposits derived from the adjacent mountains. They generally have arid to semi-arid climates and their water supply is generated from precipitation that falls on the adjacent mountains. Annual ground-water recharge is generally small in relation to the large volumes of water stored in the basin-fill reservoirs.

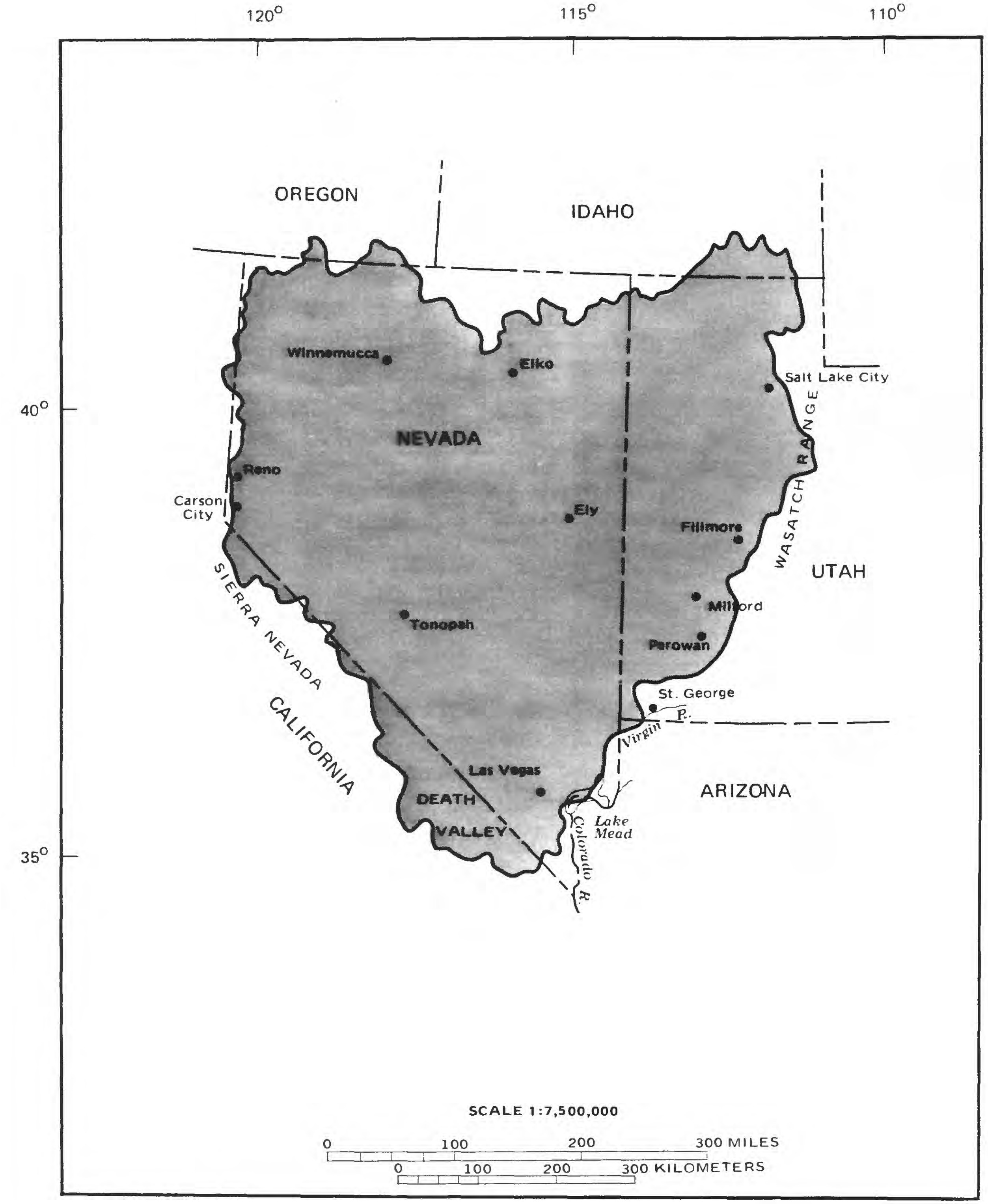


Figure 1.--Location of study area.

Boundaries of the Great Basin RASA study area, which includes about 140,000 square miles in Nevada, Utah, California, Oregon, Idaho, and Arizona, are shown in figure 1. The study area has been expanded slightly from that described by Eakin and others (1976) to include discharge areas of several large multibasin flow systems. Parts of the headwater areas of some of the principal drainages and some small valleys in the Wasatch Range (Utah) and the Sierra Nevada (California) have been excluded because they do not contain large basin-fill reservoirs. A total of 240 hydrographic areas are recognized within the study area (plate 1). These are usually the basic units used by State and local agencies for planning and management of water resources. Most contain a basin-fill reservoir and include the drainage areas of the adjacent mountains.

## Need for This Study

A prerequisite to wise ground-water management is an adequate understanding of how the ground-water system operates. The RASA program is an effort to improve this understanding on a regional scale. In the Great Basin, the need for this understanding is even more pressing locally. Population centers along the Wasatch front in Utah and the east flank of the Sierra Nevada in Nevada are experiencing rapid growth and increased demands for water. Initially, water supplies for these areas were developed by simple exploitation of readily available water sources. Demand in many areas has now increased to the extent that this is no longer possible, and careful management of all available water resources is necessary to meet anticipated future needs.

Much of the region is sparsely populated and is characterized by remoteness and open space. In recent years, these attributes have become a resource. Consequently, much of the area was considered for use by the MX missile system, large coal-fired powerplants are being constructed at several locations, nuclear power plants are being considered, and other areas are being evaluated as potential sites for waste disposal. Large amounts of Colorado River water are currently pumped by the Southern Nevada Water Project and similar pumpage by the Central Utah Water Project is planned. Development of these and similar projects will probably greatly affect the ground-water resources in much of the region within the next several decades.

Impacts from existing and anticipated future ground-water developments will be on regional and local scales. This study will provide a basis for evaluating the effects of development in the Great Basin region.

## Approach

The approach taken to meet the objectives of this study has been strongly influenced by the diverse nature of ground-water flow systems and the large number of basins in the area. Some hydrologic characteristics can be described regionally. However, a detailed appraisal of 240 individual areas would require more resources than are available. Consequently, the general approach is to identify key components and critical parameters that are present in many ground-water flow systems throughout the region. These will be studied in selected areas that have conditions representative of the region. Information developed during these "type area" evaluations should have considerable transfer value to other similar areas.

The final year of this project will be directed toward developing a regional analysis of results and the transfer of as much information as possible throughout the study area. Success of this approach is dependent on: (1) Adequate delineation of ground-water flow systems, (2) identification of the main hydrologic components of these systems, and (3) development of a better understanding of hydrologic processes and improved techniques for collecting and processing data.

## Flow Systems

Several investigators have attempted to delineate regional ground-water flow systems in the Great Basin. The most extensive work has been in southern Nevada (Winograd, 1962; Winograd and Eakin, 1965; Blankennagel and Weir, 1973; and Winograd and Thordarson, 1975). Eakin (1966) described the White River flow system using ground-water budget techniques and hydraulic gradients. Mifflin (1968) evaluated flow systems throughout Nevada. He identified 136 systems and separated them into two groups on the basis of the presence or absence of interbasin flow. Mifflin's work was augmented by Rush and others (1971), who prepared a map summarizing information on water resources and interbasin flows for 232 hydrographic areas in Nevada. Winograd and Friedman (1972) demonstrated that ratios of the chemical isotopes deuterium and hydrogen were useful tools for tracing regional ground-water flow in the Great Basin. Gates and Kruer (1980) described areas thought to be associated with regional ground-water flow in western Utah. These references do not include all work pertaining to interbasin movement of ground water in the study area; however, they summarize most information currently available and are the sources most used to prepare this report.

Most previous work has involved evaluating interbasin flow in comparatively local areas and then aggregating the results to delineate interbasin flow systems. The resulting assemblage of flow systems by itself does not provide a great deal of information about regional hydrologic processes. Consequently, the following approach is to be used to delineate flow systems in the hope that results will provide an improved regional perspective.

A basic premise is that each flow system terminates in a sink. Consequently, if all of the sinks are identified, the task of delineating flow systems is reduced to identifying areas that contribute water to a particular sink. For local systems consisting of only one basin and for smaller regional systems consisting of a sink and one or more adjacent tributary basins, the task is simple. However, some of the larger regional systems extend for more than 100 miles and have flow paths that traverse as many as seven basins. In most instances, some water is discharged at intermediate points along flow paths; consequently, only part of the water flows all the way to the regional sink. In the simplest case, the intermediate discharge represents a circulation cell in the shallower part of a regional system. In many systems, however, the intermediate discharge represents flow derived from a group of areas that constitutes a regional-scale multibasin subsystem. This situation is dealt with by assuming that a large regional flow system has one principal sink area and that all flow in the system is generally toward this sink. The general hierarchical scheme used to represent a multibasin system is shown in figure 2.

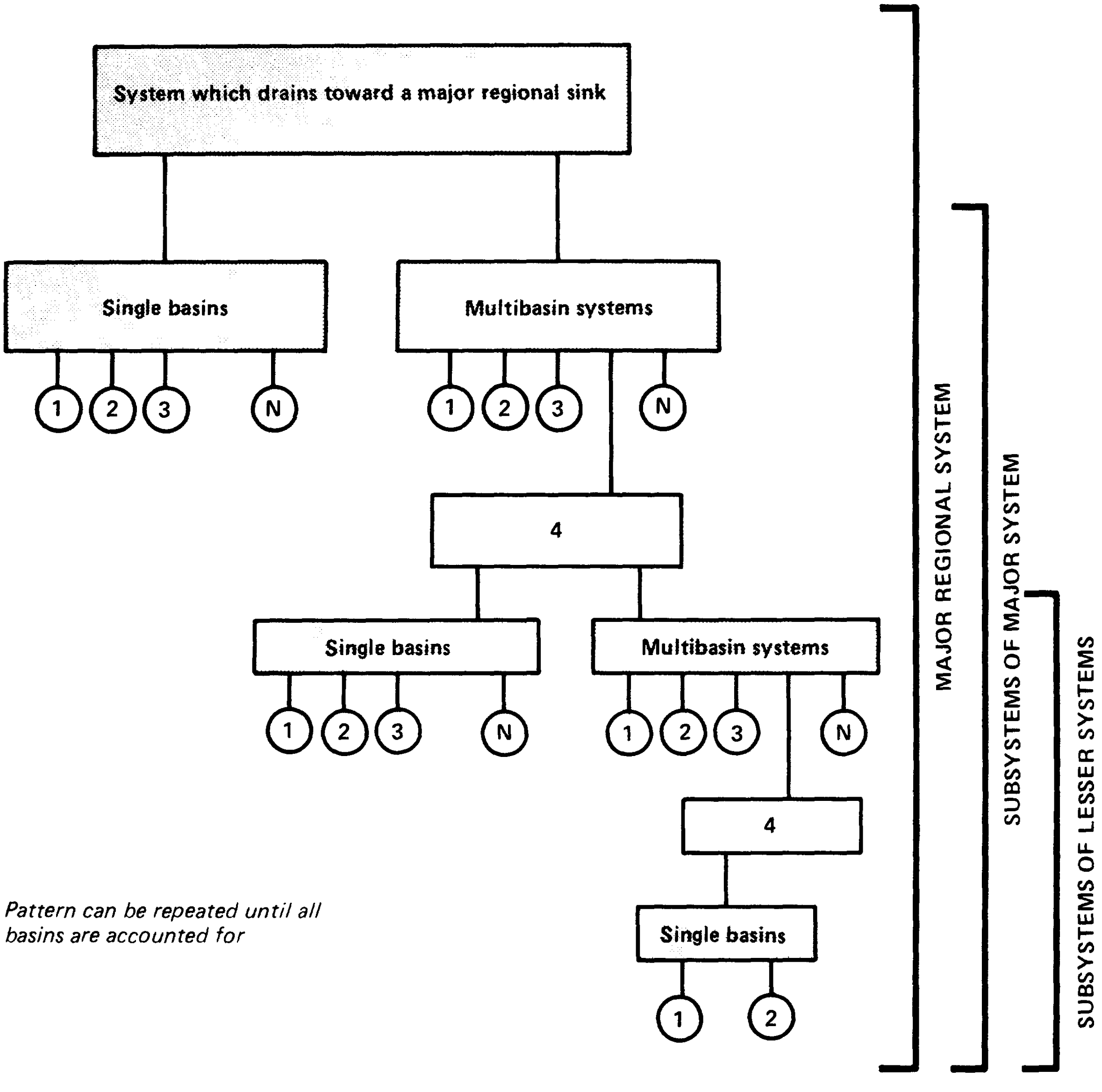


Figure 2.--Hierarchical scheme used to delineate multibasin flow systems.

An initial delineation of the major flow systems was made using information currently available and the general procedures outlined in the preceding paragraphs. The flow systems are shown in figure 3. Of the 39 systems shown, 14 are single-basin flow systems and the others are multibasin systems. The major flow systems delineated during the planning stages of this study will be evaluated in more detail and subsystems delineated during the course of this study.

## Flow-System Components

Many basins in the Great Basin are geologically and hydrologically similar and the first inclination in planning this study was to evaluate "type" basins and then attempt to transfer the resulting information to similar basins. Although similar, each basin is unique because of its size, geometry, location, and relative significance of the various flow-system components present. For maximum transferability of information, emphasis will be placed on the recognition and understanding of flow-system components.

To adequately utilize information on key flow-system components, the systems must first be understood well enough to subdivide them into distinct components that have valid hydrologic significance in terms of physical processes, geology, geomorphology, or other factors. Basins where key flow-system components are similar will be grouped to form sets of basins for which information has a high degree of transferability.

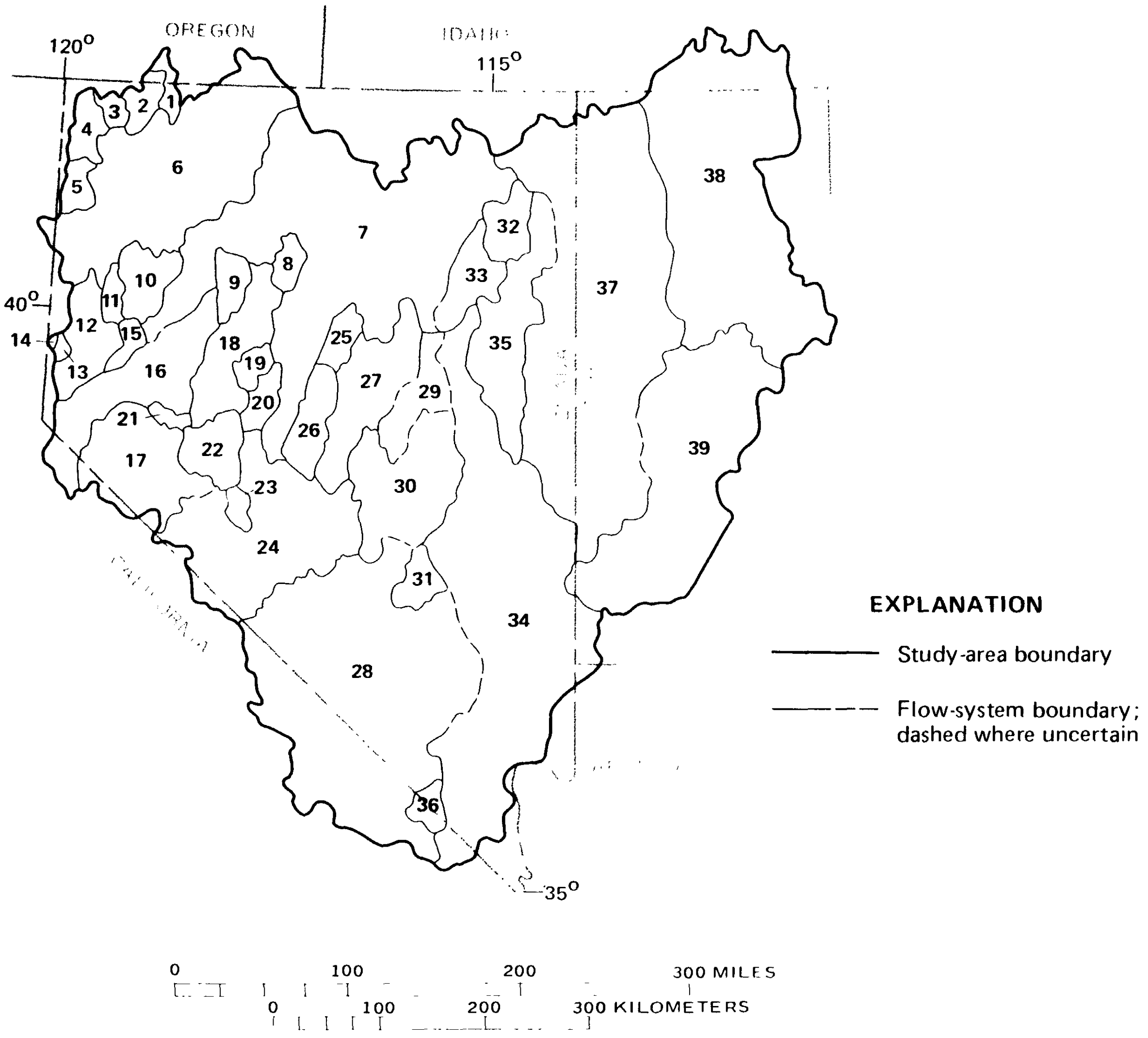
Recognition of flow-system components is necessary to develop a ground-water flow model. Consequently, considerable information is available from work done on existing models that can be applied directly to this study. A review of available information for the Great Basin Region indicates that a number of components have already been analyzed and some have been expressed mathematically. They can be grouped into three general types: flux-related, boundary-related, and property-related components. A brief description and examples follow for each type.

*Flux-related components*: Involve processes related to recharge, discharge, or movement within the system. Examples are recharge to consolidated rock within the mountains, recharge on alluvial fans, spring discharge, seepage areas, surface-water/ground-water interactions, and evapotranspiration.

*Boundary-related components*: Generally geologic features related to external and internal boundaries of the flow system. Examples are poorly permeable consolidated rock, faults, regional structures, and size.

*Property-related components*: Generally features that affect the hydraulic properties of aquifers and confining beds. Examples are depositional facies, depositional environments, composition of source-area materials, and post-depositional alteration. Areas that have had similar geologic histories probably will have similar property-related components.

The above constitutes an initial list. Additional components may be added and some now listed may be subdivided to specifically identify features observed in the field.



FLOW SYSTEMS

| | |
|---|---|
| 1 | Continental Lake system |
| 2 | Virgin Valley |
| 3 | Swan Lake Valley |
| 4 | Long Valley |
| 5 | Duck Lake Valley |
| 6 | Black Rock Desert system |
| 7 | Humboldt system |
| 8 | Buffalo Valley |
| 9 | Buena Vista Valley |
| 10 | Granite Springs system |
| 11 | Winnemucca Lake Valley |
| 12 | Truckee system |
| 13 | Lemmon Valley* |
| 14 | Cold Spring Valley |
| 15 | Fernley Sink system |
| 16 | Carson system |
| 17 | Walker system |
| 18 | Dixie Valley system |
| 19 | Edwards Creek Valley |
| 20 | Smith Creek Valley |
| 21 | Rawhide Flats |
| 22 | Gabbs Valley |
| 23 | Monte Cristo Valley |
| 24 | South Central Marshes |
| 25 | Grass Valley |
| 26 | Northern Big Smoky Valley |
| 27 | Diamond Valley system |
| 28 | Death Valley system |
| 29 | Newark Valley system |
| 30 | Railroad Valley system |
| 31 | Penoyer Valley |
| 32 | Independence Valley system |
| 33 | Ruby Valley system |
| 34 | Colorado system |
| 35 | Goshute Valley system |
| 36 | Mesquite Valley |
| 37 | Great Salt Lake Desert system |
| 38 | Great Salt Lake system |
| 39 | Sevier Lake system |

*Part of multibasin system. Not known whether subsurface drainage is to the northwest (out of study area) or to the Truckee system.

Figure 3.--Delineation of major flow systems.

## Information Deficiencies

Initial planning included listing information deficiencies and hydrologic problems common throughout the region. A single study usually cannot address all deficiencies or problems; however, work can be directed toward the more critical deficiencies to obtain the greatest return for time and funds invested. Determination of the most critical deficiencies is subjective; but, during initial planning, input was solicited from many individuals and, on the basis of this input and the evaluation of the project staff, three general areas were identified where a special effort is needed: (1) Obtaining an improved understanding of the processes of ground-water recharge, (2) developing improved quantitative estimates of rates of natural ground-water discharge by evapotranspiration, and (3) applying remote-sensing technology to develop and maintain an improved inventory of ground-water withdrawals. These three areas will be the topics of special studies that should generate results having application throughout the study area. Many of the other deficiencies will be addressed to some extent by work done to support the description of the regional systems.

## Organization of Study

This study is part of a nationwide program conducted in accordance with guidelines and technical control furnished by the Ground-Water Branch of the Water Resources Division, U.S. Geological Survey. The Great Basin Study group is headquartered in Carson City, Nev., and work will be done as a part of the Water Resources Division's Nevada District operations. A support project has been organized in Utah and selected elements of work will be performed as part of the Utah District program.

During the first year of the study, the Desert Research Institute, University of Nevada, will begin an evaluation of ground-water recharge processes in the Great Basin Region. Additional work will be contracted out as appropriate during the subsequent years of the project.

# PLAN OF WORK

The major work elements of this project include support and coordination functions and specific subprojects. The cumulative results of all of these efforts should meet the objectives outlined for this study. Work elements are grouped into five general categories: Support functions, regional characterization, special studies, model studies, and regional analysis of results. Work during the first year of study will be directed toward inventorying and analyzing available information, describing the ground-water hydrology regionally, defining the most critical elements of work, and starting work on these elements. During the second and third years of study, effort will be directed toward the execution of special investigations related to critical elements of work. A continuing effort to analyze and describe the hydrology will be made throughout the study. Reports summarizing these studies will be prepared as results become available. Effort during the fourth year will be directed toward (1) producing a regional analysis that adequately summarizes results and (2) preparing a summary report. Figure 4 lists the major work elements and shows their planned timing. Following is a description of the problems to be addressed by each work element, the approach to be followed, the manner in which each element is related to the overall project, and the planned report products.

## Support Functions

Certain tasks contribute to many of the work elements and are considered general support functions. The major support functions are project administration and data collection, compilation, and management. In addition, the Nevada and Utah Districts will provide support in logistics, manuscript typing, preparation of illustrations, report processing, and computer operations. Data collection, compilation, and management is the only support function for which further discussion is warranted.

Much information on the hydrology of the Great Basin has been collected during previous studies. These data are not consistent in quality and format, and need to be screened and processed to support regional-scale analysis. One effort of this study will be to evaluate these data and, if found suitable, to format them for use. Additional field data will be collected to support special studies and reduce major deficiencies in existing data.

During the first year, emphasis will be placed on screening and formatting data. Essential field work, which includes the taking advantage of one-time opportunities such as the collection samples from deep drill holes and the collection of essential background data also will be done. During the second and third years, emphasis will be placed on the collection of field data in support of the special studies.

Data accumulated during this study must be efficiently processed, stored, retrieved, and formatted to accommodate many different needs. Time-sharing computer terminals will be used to store and manage data on one or more large host computers. Computer equipment available for project use has graphic display capabilities that will be developed as fully as possible.

For efficiency, existing management systems and other computer software will be used to reduce programming demands on the project staff. Site-specific data will be stored in the Geological Survey's WATSTORE (National Water Data Storage and Retrieval System) data files where appropriate. Special-purpose data files will be created to accommodate information that cannot be placed in the WATSTORE system. Technical advice and assistance will be provided by the Nevada District computer operations section.

Summaries of screened and collected data will be released as appropriate. Data for Utah may be published as one or more of a series of Utah District Basic Data Reports. Data collected in other parts of the study area will be summarized in one or more U.S. Geological Survey open-file reports.

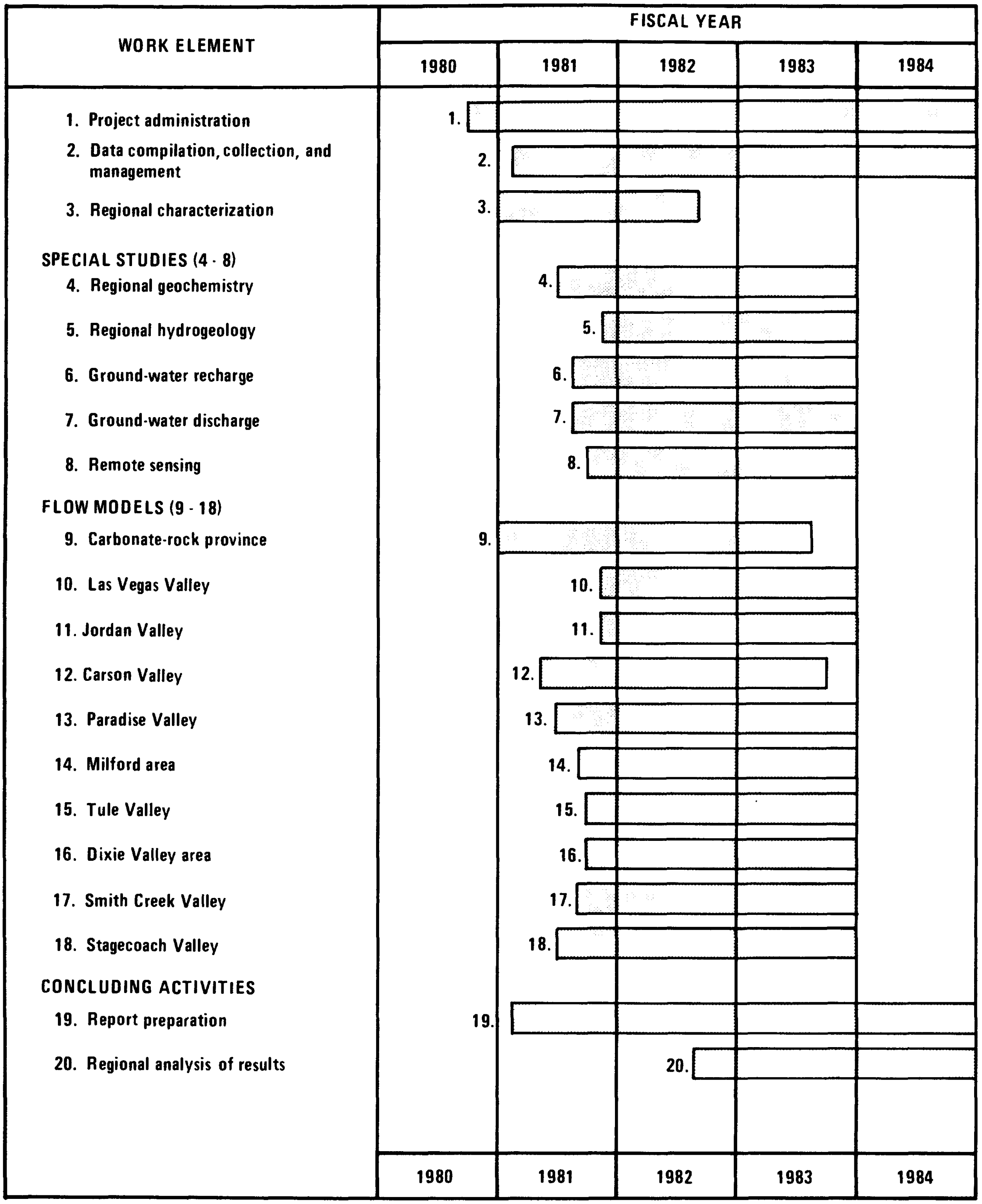


Figure 4.--Major work elements.

## Regional Characterization

Early in the project, available data will be compiled and summarized to provide an initial regional characterization of the study area. The characterization will include information on:

1. Generalized rock types,
2. Major geologic structures and lineaments,
3. Hydraulic properties of materials,
4. Thickness of basin fill,
5. Water-level contours in the basin-fill deposits,
6. Water-level data for consolidated-rock aquifers,
7. Depth to ground water in basin-fill deposits,
8. Natural ground-water discharge,
9. Ground-water withdrawals,
10. Ground-water quality, and
11. Delineation of flow systems.

This information will be summarized in a series of maps and tables that will provide an initial overview of the regional system.

## Special Studies

Some of the tasks that contribute to the progress of the overall investigation are extensive and complex enough to be treated as subprojects. These tasks address specific problems and, when completed, each should contribute to an improved understanding of ground-water hydrology of the Great Basin. The following sections briefly describe the special studies planned for this project in terms of the problems that they address, the general approach that will be taken, the anticipated products, and their transferability and relationship to the regional hydrology.

### Regional Geochemistry

To describe the geochemistry of the ground-water system, a substantial early effort will be made to obtain existing data on water chemistry from other agencies, researchers, and libraries, and to transform them into a usable format. These data will be entered into files compatible with the WATSTORE water-quality file, which will permit the use of existing applications programs and reduce the need to develop computer software.

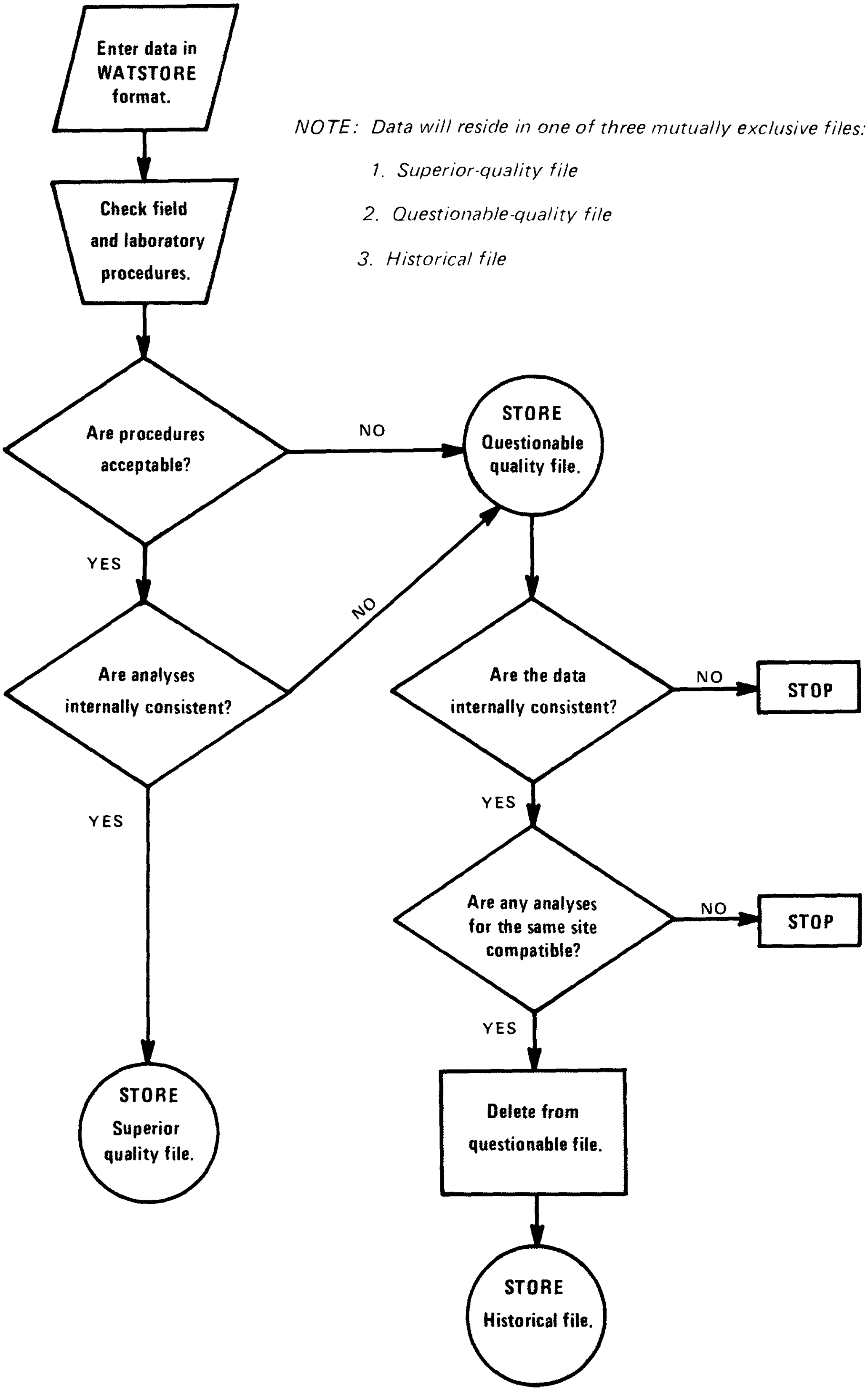
Data analysis will begin by evaluating the quality of the data (see figure 5), which in turn will include a review of field and laboratory procedures used by the various investigators. Analyses of samples that have been collected and processed using proper field and laboratory procedures will be examined further for anion and cation balance and other factors relating to the internal consistency of analytical results. Analyses that are internally consistent and have been properly collected and processed will be placed in a "superior-quality" data file. This file will be used for thermodynamic calculations and considered as standard of reference. Those analyses that are internally consistent but may not have been collected and processed according to current field or laboratory procedures will be placed in a "historical-data" file. Most samples collected and processed in the field prior to about 1970 probably would not be acceptable by today's standards. Presently used field procedures of acidification, filtering, and analysis of unstable constituents were not generally used before about 1970. As a result, the quality of older (historical) data is not as high as that of data in the superior-quality file. In spite of this limitation, the historical data are valuable in documenting spatial and temporal water-quality changes.

Analyses not suitable for storage in either the superior-quality file or the historical-data file will remain in a "questionable-data" file. The primary purpose of this file will be to provide an inventory of all data canvassed. The problem with each analysis will also be recorded and should provide valuable information to individuals involved in future data searches. If questions regarding this information can be resolved, then the data can be transferred readily to one of the other data files.

Regional ground-water quality will be portrayed initially on a map showing total dissolved solids. This map will be based on data from the historical- and superior-quality files. It may be supplemented by maps showing other aspects of the regional geochemistry, if the data base is of sufficient size and quality. The resulting maps may assist in the identification of inter-valley flow and sources of recharge. This type of analysis probably will be most applicable to sedimentary basin fill due to the small amount of data available for the flow systems in the underlying and surrounding consolidated rock.

An effort will be made to better define flow through carbonate rocks, using geochemical models similar to those presented by Plummer and Back (1980). The age of water in the carbonate rocks may be determined using carbon-14 isotope dating techniques. In addition, both hydrologic and geochemical data from the upper part of the carbonate system in the Spring Mountains, near Las Vegas, will be analyzed in an attempt to relate geochemical processes to ground-water flow.

The geochemistry of ground water in sedimentary basin fill will be studied in a similar manner. If sufficient data can be obtained, the mass-balance approach will be used to examine several geochemical models. Geochemical data also may provide information on flow directions and mixing, and possibly on flow rates.



*NOTE: Data will reside in one of three mutually exclusive files:*

1. *Superior-quality file*
2. *Questionable-quality file*
3. *Historical file*

Figure 5.--Handling process for water-quality data.

Geochemical data collected in "type study areas" will be categorized and examined in relation to the hydrogeologic environment. This procedure should result in an objective method for characterizing the geochemistry of the ground water in the Great Basin. If clear associations with known hydrogeologic environments can be discerned, water quality may be estimatable on that basis alone.

Stable hydrogen- and oxygen-isotope data have been used to indicate sources of recharge and flow directions in the Great Basin (Winograd and Friedman, 1972). The use of this technique is presently limited by a lack of data. Collection and analysis of ground-water samples for stable isotopes throughout the study may aid the definition of sources of recharge and directions of flow.

In summary, the geochemical studies will consist of (1) statistically characterizing the regional geochemistry, and (2) collecting and analyzing water-quality data to assist in determining sources of recharge, directions of ground-water flow, and possibly rates of ground-water flow. Unique geochemical models may not be definable for all flow paths; however, where unique models, or a limited model suite, prove feasible, an estimation of probable water quality may be possible in hydrogeologically similar areas. This would be helpful in attempting to characterize water quality in basins where data are limited or nonexistent.

## Regional Hydrogeology

Structural processes that have formed the many basins characteristic of this region, and depositional processes associated with basin-fill deposits, will be evaluated in terms of the way they affect the occurrence, movement, and availability of ground water.

A special effort will be made to evaluate the carbonate-rock province in western Utah and and eastern Nevada. This province includes 30,000 to 40,000 feet of marine sedimentary rocks of Precambrian and Paleozoic age (Hess and Mifflin, 1978, page 9). Hess and Mifflin note that: (1) The deposits generally are dominated by carbonate rocks, with minor amounts of clastic rocks; (2) the hydrogeologic framework of the carbonate-rock province is complicated by marked facies changes and structural displacements that include Mesozoic thrust faulting and Cenozoic block faulting; and (3) nearly all geologic investigations in the area to data have failed to describe hydrogeologic characteristics of the rocks.

Movement of ground water through the carbonate-rock province is generally believed to be toward the Great Salt Lake Desert and the Great Salt Lake, the Colorado River, and Death Valley; however, the actual path or paths of flow are undoubtedly complicated by faults that act as barriers or, locally, as conduits. The initial working hypothesis is that when water is recharged, mostly in and adjacent to the mountains, it then moves primarily within downfaulted blocks beneath basins. Eventually, this water encounters barriers that result in changes in flow direction; in some places, such a change may result in discharge by spring flow. Therefore, structural controls are probably as important as lithologic controls. Cambrian and Devonian carbonate rocks are considered significant water-bearing units because they are susceptible to solution along fractures and other openings (Hess and Mifflin, 1978, pages 26-32).

The approach used to evaluate the carbonate-rock province will include analysis of stratigraphic sections, geologic and geophysical logs of oil test holes, and structural features. Existing literature will be reviewed to learn what hydrogeologic information can be gained from previous investigations. Geologic and geophysical logs of oil test wells will be useful for identifying lithologic units and permeable zones. Borehole resistivity and porosity logs have been useful in analysis of regional flow patterns and water quality in carbonate aquifers of the Great Plains (MacCary, 1981). The usefulness of such data in the Great Basin will depend on the number of logs available and the presence of significant areal variations in dissolved-solids concentration of water within the system. Comparison of lithology, permeable zones, and structural features mapped in previous investigations should help to define the hydrogeologic framework of the carbonate province and better delineate flow systems.

The Great Basin is typified by numerous basins and basin-fill reservoirs that store large amounts of ground water. The number of basins in the study area is so large that only a few can be studied in detail. What is learned from a few, however, may have general application throughout the region. In simplest terms, a basin can be described as follows: (1) It commonly occupies a bedrock depression that is a few thousand to more than 10,000 feet deep, filled with clastic deposits; (2) the depression usually is structural, and is bordered by faults; (3) the clastic deposits commonly consist of fluvial, lacustrine, and volcanic materials of Miocene and Pliocene age, overlain by deposits of late Pliocene and Quaternary age. On basin margins, the younger deposits consist of coarse, poorly sorted alluvial-fan materials. Toward the center of the basin, the deposits include playa and lacustrine materials of Pleistocene and Holocene age.

The approach employed in individual "type-basin" studies will include the use of surface geophysics to define the shape and size of the bedrock basin, analysis of geophysical and drillers' logs and surface geophysics to determine the general lithology of basin-fill deposits, and study of surface geologic and geomorphic features. Gravity and seismic techniques will be used to estimate depths to bedrock for selected valleys. Seismic refraction will be used to confirm the gravity data. Electrical-resistivity and seismic-refraction data will be used to estimate basin-fill lithology.

Well driller's logs will be used to determine lateral and vertical variations in particle size within the valley fill. Surface-geomorphic features may be useful in evaluating the distribution of aquifers especially in valleys having few wells. Bredehoeft and Farvolden (1963) and Hawley and Wilson (1965) have shown relationships between geomorphic features, aquifer distribution, and productivity in valleys of northern Nevada.

Geologic mapping will be useful in two ways. Bedrock structure and lithology may indicate areas where interbasin flow is possible, and Tertiary and Quaternary deposits along valley margins may indicate the water-yielding character of subsurface deposits.

## Ground-Water Recharge

The overall objective of this phase of the study is to gain an improved understanding of the mechanics and distribution of ground-water recharge in the Great Basin. Work will be divided into two main parts: (1) Reconnaissance and moderately detailed studies to evaluate the processes of recharge and to quantify, to the extent possible, the amount of recharge, and (2) identification of precipitation-related characteristics that have high correlations with natural ground-water recharge.

The approach used to evaluate recharge processes will be to select several hydrologic environments that include variations in climate, geomorphology, geology, runoff, and other factors representative of the range of conditions found in the Great Basin. All areas will first be evaluated on a reconnaissance basis, and if possible, the quantity and chemical quality of precipitation, soil moisture, ground water, and runoff will be measured. Emphasis will be placed on identifying and understanding the processes by which recharge occurs at each area. Attempts will be made to define water budgets for selected areas and to quantify the recharge. Precipitation-related parameters will be evaluated in an effort to identify those that might produce improved estimates of recharge. Initial effort will be directed to assembling precipitation data from exisiting long- and short-term sites and storing them in forms suitable for statistical analysis. An analysis will be made to determine the value of short-term data from high-altitude sites. Subsequent effort will be directed toward determining the relation of precipitation data to ground-water recharge.

The purpose of the study of ground-water recharge is to help refine water budgets for the regional aquifers. If the developed recharge data correlate with geology, geopmorphology, precipitation, runoff, or some combination of those features, better budget estimates may be possible. If correlations are poor, this work will help to provide a better understanding of the mechanics of recharge and the environments in which it occurs.

Because of personnel limitations, most of this work will be done through contracting. Initial work will be done by the Desert Research Institute. It is intended that the results will be summarized in a series of reports.

## Ground-Water Discharge

Evapotranspiration accounts for most ground-water discharge in the Great Basin. Consequently, the accuracy with which this discharge can be determined directly affects the validity of water budgets prepared throughout the Region. Most past studies of phreatophyte transpiration generally involved use of lysimeters in which the depth to water was very shallow, thereby limiting their applicability to many field conditions. The main goal of this phase of the study is to develop improved methods for determining transpiration by phreatophytes, because that type of discharge is complex and widespread. However, evaporation from bare soil and free-water surfaces will be briefly evaluated.

The approach will be to measure the transpiration in phreatophyte communities as they occur naturally in the Great Basin. A technique has been developed by E. P. Weeks (U.S. Geological Survey, Denver, Colo.) to make eddy-correlation measurements of evapotranspiration under natural field conditions. The technique involves the rapid, repetitive measurement of vertical wind flux, air temperature, net radiation, and vapor density at a station situated about 6 feet above the vegetation canopy. These data are processed statistically and the results are used to compute evapotranspiration rates. The technique will be further developed for use in the current study.

Initial plans are to select two sites and instrument both with Penman-type weather stations to obtain enough data to calculate a nearly continual record of potential evapotranspiration. The eddy-correlation equipment will be set up on each site at regularly scheduled intervals and run for several days to obtain measurements of actual evapotranspiration. Calculated potential evapotranspiration and other climatic data, such as precipitation, will be used to extend short-term measurements of actual evapotranspiration to obtain estimates for the entire growing season. Several methods may be used to determine evapotranspiration supplied by soil moisture and direct precipitation. The initial technique used will be to simply subtract measured local precipitation from estimated total evapotranspiration and assume that the difference is supplied by either ground water or soil moisture. Measurements of soil moisture from land surface just above the water table will be made at the beginning and end of the evaluation period to determine changes. Analysis of water-level fluctuations in wells, and possibly some small-scale ground-water flow modeling, will be used as a means of checking the evapotranspiration measurements. This will be the first time that such an approach is used in a non-research application. It should improve measurements of evapotranspiration and existing estimates of ground-water discharge. Additional sites may be established during the second and third years of the study if resources permit.

Additional effort is needed to refine techniques for developing areal estimates of evapotranspiration from point determinations. Emphasis will be placed on determining characteristics that (1) have a high correlation with, or affect, evapotranspiration (such as depth to water, water quality, plant type, and volume of foliage per acre) and (2) can be mapped or sensed adequately to allow areal determination throughout the region. Attempts will be made to use remote-sensing techniques for determining the areal distribution of evapotranspiration. Landsat (Land satellite) images will be examined to determine if their resolution and the type of information content are adequate. Landsat does not have thermal-sensing capabilities, but the newer temperature data from the Heat-Capacity Mapping Mission satellite may be investigated to determine whether evapotranspiration correlates with sensed temperature.

The principal results anticipated from this phase of the study are (1) an operational technique to measure evapotranspiration under natural field conditions and (2) improved procedures for estimating the distribution of evapotranspiration over large areas. Both of these results would have wide applicability throughout the Great Basin study area.

## Remote Sensing

Substantial population growth and accompanying development in the Region are anticipated for at least the next 10-20 years. Up-to-date information on water use and other stresses on the hydrologic system are needed for wise water-resource management. The need for this information comes at a time when its acquisition has become extremely expensive. Consequently, as part of this study, efforts will be made to develop new techniques that will allow inventories to be made using newest technology. Techniques that utilize remote sensing hold the most promise. During the study of the High Plains aquifer system, several techniques were tested to determine the acreage of irrigated cropland. Of the methods tested, only Landsat imagery proved to be cost effective for an area as large as the High Plains (Heimes and Luckey, 1980, page 1).

Landsat imagery will be used throughout the Great Basin study area to assist in developing inventories of irrigated land and some types of phreatophytic vegetation. These inventories then can be used to extend a small sample of actual pumpage data throughout the area.

The use of Landsat imagery in the present study will depend upon both funding and coordination with other programs, such as the National Water Use Program and those of other interested State and Federal agencies. If future funding is reduced below anticipated levels or the coordination of activities is not successful, remote-sensing efforts will be limited largely to areas selected for model studies. Pumpage in these areas will be inventoried carefully using techniques similar to those outlined by Heimes and Luckey (1980, pages 7-16). Some additional effort will be directed toward developing techniques to estimate how much of the total water applied to crops in conjunctive-use areas is supplied by pumped ground water. Landsat images will be obtained and computer-compatible tapes of the images processed to classify the major groupings of crop types associated with various levels of water use. This information will be aggregated according to hydrologic areas and subareas, and will provide direct input to the ground-water flow model. Efforts will be made to identify and inventory major phreatophytes (to the extent that the resolution of the Landsat data permits) and possibly certain soil types associated with ground-water discharge areas.

## Model Studies

### Numerical Models

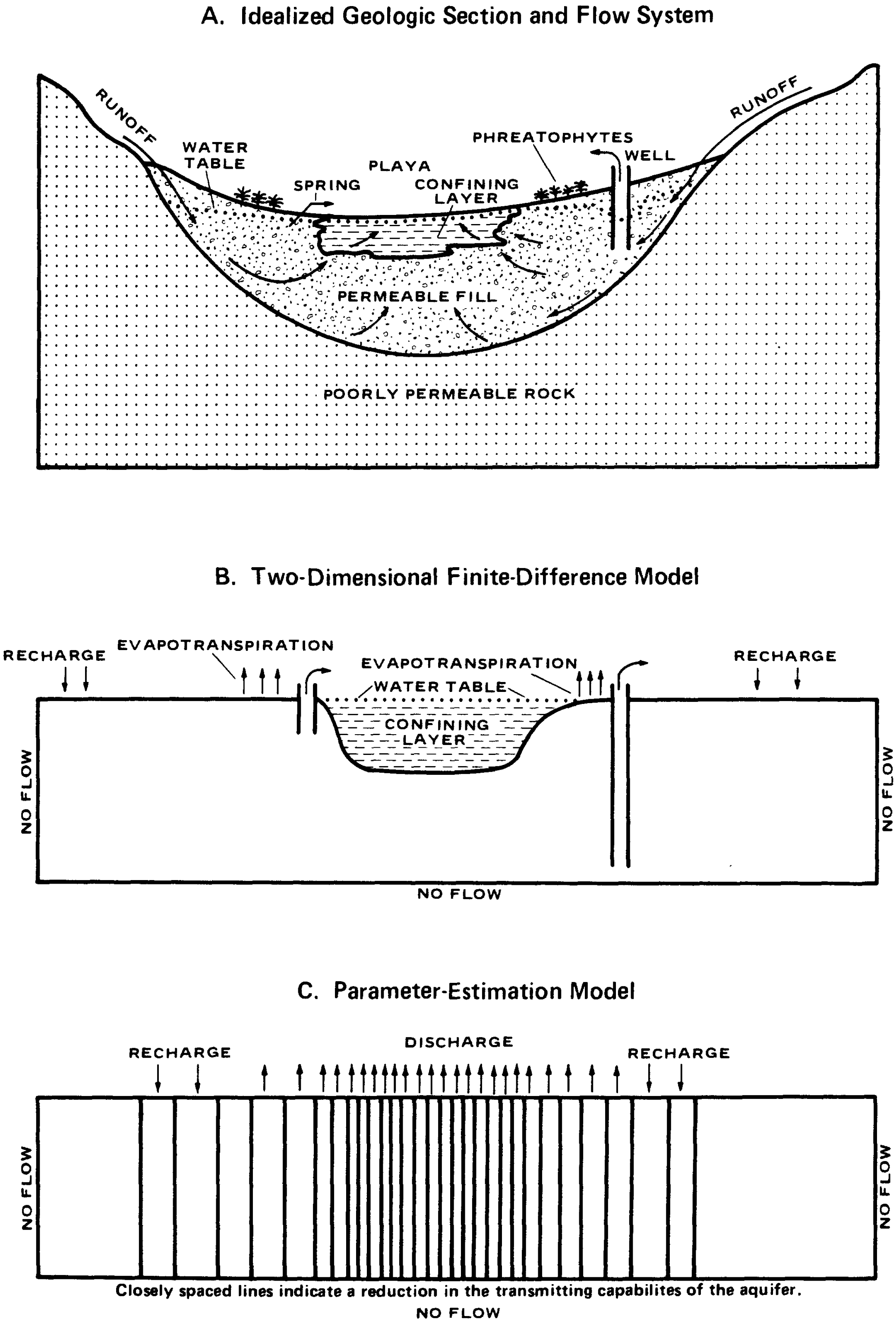
One of the principal techniques to better define ground-water flow systems within the Great Basin will be the use of computerized numerical models, which are simply a set of numbers that represent aquifer properties and a set of instructions to the computer to use those numbers in solving equations in one, two, or three dimensions and with respect to time. Discussions of the use of numerical flow models are presented by Pinder and Bredehoeft (1968), Remson and others (1971), Prickett and Lonnquist (1971), Trescott (1975), Trescott and others (1976), Cooley (1977), and Frind and Verge (1978).

Several different computer programs will probably be used depending on the geologic and hydrologic variability within the Great Basin. In closed basins where few geohydrologic data are available, either a two-dimensional, finite-difference model (Trescott and others, 1976) or a parameter-estimation model (Cooley, 1977) may be used to determine reasonable values of aquifer properties. Representation of a generalized basin-fill reservoir using these models is shown in figure 6. A parameter-estimation model was used with reasonable success in a similar basin in southern Idaho (Nichols, 1979).

In basins where detailed models may not be warranted because of cost and time constraints, lumped-parameter models or quasi-lumped-parameter models (Birtles and Reeves, 1977) may adequately answer management questions. Possible applications of the lumped-parameter models would be to estimate the effect of pumping on perennial streams, or the long-term effect of pumping on spring discharge in a valley.

Results of related Geological Survey studies, either completed (Harrill, 1982) or ongoing, will be used in this study. At least two studies (those of Pahrump and Las Vegas Valleys) have used or are using a modified version of a three-dimensional finite-difference model (Trescott, 1975) to simulate ground-water flow. Representation of a ground-water flow system using this model is shown in figure 7. Where sufficient data exist, the results from these studies may be transferred to similar basins.

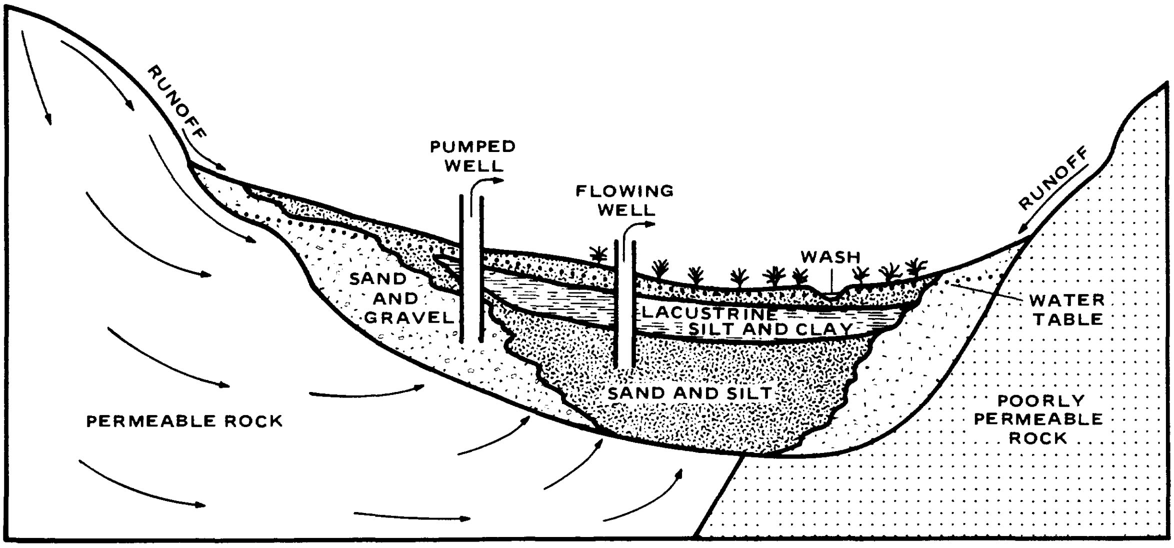
On a more regional scale, the three-dimensional finite-difference model will also be used to aid in the conceptualization of general ground-water flow directions in the widespread carbonate aquifer that underlies most of west-central Utah and eastern Nevada.



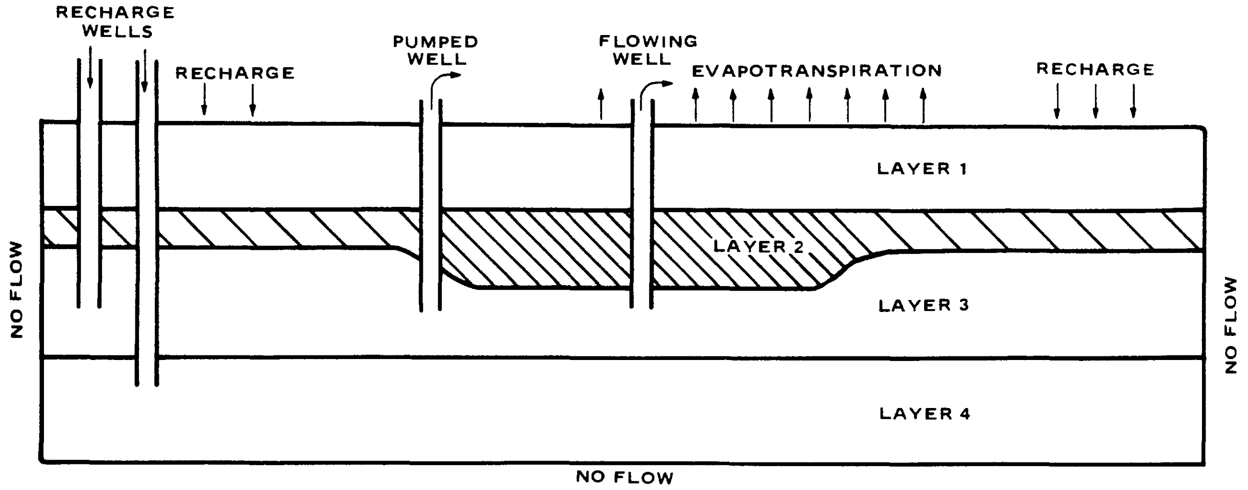
Closely spaced lines indicate a reduction in the transmitting capabilites of the aquifer.

Figure 6.--Simulation of a basin-fill aquifer using a two-dimensional finite-difference model and a parameter-estimation model.

A. Idealized Geologic Section and Flow System



B. Simulated Model of Geologic Section and Flow System



| | |
|---|---|
| LAYER 1 | SHALLOW UNCONFINED ZONE.<br>Model simulates thickness, capacity to store and transmit water, recharge, and evapotranspiration. |
| LAYER 2 | CONFINING LAYER.<br>Model simulates thickness and capacity to store and transmit water. Closely spaced lines represent a reduction in the transmitting capacity of the layer. |
| LAYER 3 | CONFINED AQUIFER.<br>Model simulates capacity to store and transmit water. Inflow from permeable rock is simulated by recharging wells. Pumpage and discharge from flowing wells are simulated by discharging wells. |
| LAYER 4 | LOWER AQUIFER.<br>Poorly defined. Layer may include permeable rock. Model simulates capacity to store and transmit water, and lateral recharge. Recharge is simulated by recharging wells. |

Figure 7.--Simulation of a basin-fill aquifer using a three-dimensional finite-difference model.

## Study Areas

One regional area and nine basins have been selected for model studies, as shown in figure 8. The regional study will evaluate aspects of the various flow systems in the carbonate-rock province. The nine other areas constitute (within the scope of this study) a representative sampling of hydrologic conditions most common in ground-water flow systems in the Great Basin. The areas range from well-watered to arid basins and from basins where bedrock underlying the basin fill is generally impermeable to basins where most of the ground-water flux presumably moves through permeable bedrock. The areas also range from large to small and from highly developed to essentially undeveloped. Three of these areas are currently under study or are scheduled for study in the near future as cooperative District projects. Results from these studies can be adapted to meet the needs of this project with only moderate additional effort.

In the following sections, each area is briefly described in terms of general hydrology and the natural and man-induced conditions that will be simulated.

### Carbonate-Rock Province

The carbonate-rock province within the Great Basin is dominated by limestone and dolomite of Paleozoic age. Faulting, which began in the Cenozoic, has produced north-trending mountain blocks with intervening down-faulted blocks that commonly are overlain by several thousand feet of Tertiary and Quaternary sediments. The province is bounded by the Wasatch Range on the east and the Roberts overthrust belt on the west, and extends northward from Lake Mead and the Virgin River to the divide between the Great Basin and the Snake River drainage basin (figure 8). Hess and Mifflin (1978, page 2) delineated the carbonate province as the area where 80 percent of the measured rock sections were composed of more than 50 percent carbonates (figure 8).

As in most carbonate aquifers, ground water in those of the Great Basin flows predominantly along secondary openings, such as solution-widened fractures, joints, and bedding planes. However, unlike most other carbonate aquifers, those in the Great Basin have undergone considerable deformation since the rocks were deposited. This undoubtedly affects ground-water flow.

Several large springs discharge within the province. Many investigators (Eakin, 1966; Mifflin, 1968; Winograd and Thordarson, 1975; Bolke and Sumison, 1978; and Gates and Kruer, 1980) have concluded that these large springs are the result of interbasin ground-water flow through the carbonates. Interbasin flow can also account for the very deep water levels in valleys upgradient from these springs where at least some natural discharge of ground water by evapotranspiration would be expected if interbasin flow were not present.

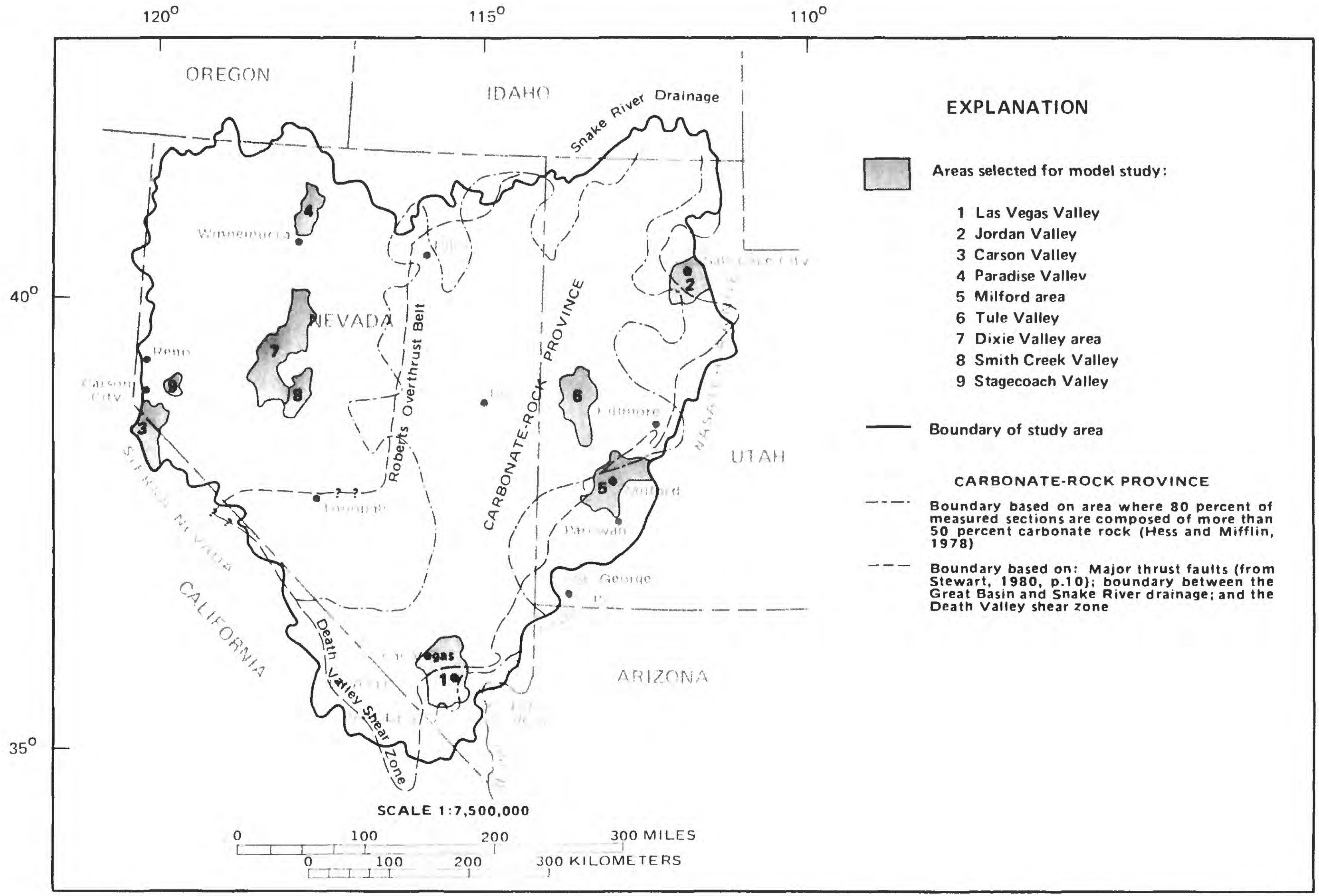


Figure 8.--Location and general extent of the carbonate-rock province and areas selected for model studies.

Precipitation within the province falls mainly on the mountains; thus, most recharge to the system occurs either in the mountains or from streams discharging onto adjacent alluvial fans. Water recharged into the mountains, particularly composed of carbonate rocks, moves downward to the zone of saturation and then laterally toward points of discharge. The conceptualized flow paths within the carbonates and overlying sediment-filled basins are sketched in figure 9.

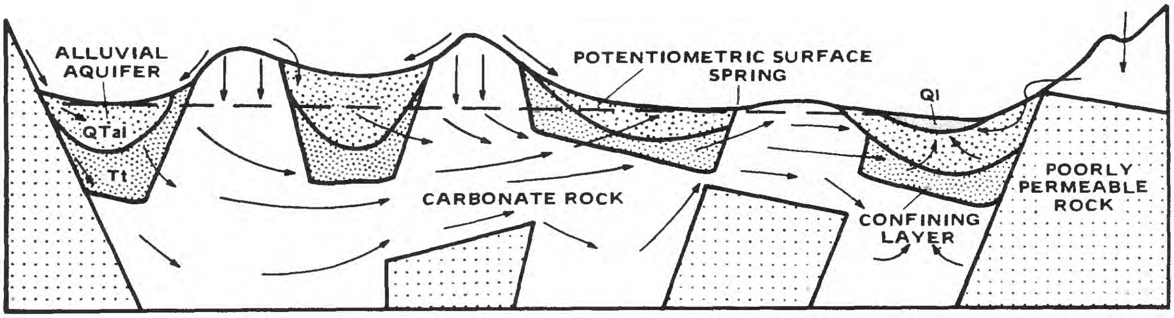
The initial modeling approach will be to assume a two-layer system as shown in figure 9. Within each model cell, aquifer properties will be assumed to be isotropic. Modeling of flow through individual fractures and faults will not be attempted because, at the small scale of the model, the carbonate aquifer can be assumed to behave as if it were homogeneous. However, model transmissivity of cells that include known faults will be increased or decreased depending upon how ground-water flow is affected. Clastic Cambrian and Precambrian rock beneath the carbonates are assumed to be impermeable.

Initial simulations will use values of recharge and discharge obtained from reconnaissance reports of most of the basins within the carbonate-rock province. These values may be adjusted in later simulations. Discharge from the lower layer will be simulated springflow, and discharge from the upper layer will be simulated in model cells that correspond to valleys.

Model boundaries corresponding to the Great Salt Lake Desert, Utah Lake, the Virgin River, Lake Mead, and Death Valley will be simulated as constant-head boundaries. Remaining boundaries will be no-flow boundaries inasmuch as the consolidated rocks outside the carbonate-rock province generally are less permeable than the carbonates and probably act as barriers to ground-water flow.

The initial model of the carbonate province will be highly generalized because data as to the thickness of the carbonate and overlying basin-fill aquifers and their interconnection are scarce. Also, little information is available on the hydraulic properties of these aquifers. However, best approximations of transmissivity, properties of confining beds, and recharge rates will be selected and a sensitivity analysis performed to determine types of information most needed for further refinement of the model. Other data, such as better geologic definition, rates of flow as estimated by carbon-14 isotope age dating (discussed previously in the section "Regional Geochemistry"), mixing of water from different recharge areas as indicated by changes in water quality, and an evaluation of heat flow, may aid in model refinement.

## A. Generalized Geologic Section and Flow System



Ql Quaternary lake deposits (clay and silt)

QTal Quaternary and Tertiary deposits

Tt Tertiary tuff, ash flow and some interbedded sediments

——→ Arrows indicate general direction of ground-water flow

## B. Simulated Model of Geologic Section and Flow System

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| LOW | MEDIUM | HIGH | MEDIUM | HIGH | LAYER 2<br>MEDIUM | HIGH | MEDIUM | HIGH |
| ▨ | | ▨ | | ▨ | CONFINING LAYER | ▨ | | ▨ |
| LOW | HIGH | HIGH | HIGH | MEDIUM | LAYER 1<br>HIGH | LOW | HIGH | LOW |

**LAYER 1 and LAYER 2**

LOW
MEDIUM } Indicates transmissivity
HIGH

**CONFINING LAYER**

☐ Low vertical hydraulic conductivity

▨ High vertical hydraulic conductivity which does not greatly impede vertical movement of water

Figure 9.--Conceptualization of an aquifer system in the carbonate-rock province for use with a digital model.

## Las Vegas Valley, Nev.

The drainage area of Las Vegas Valley encompasses about 1,500 square miles in Clark County, southern Nevada. The principal ground-water reservoir has an area of about 550 square miles and is composed of unconsolidated and semiconsolidated deposits that partly fill the structural depression underlying the valley (figure 10). Most of the naturally occurring ground-water recharge is generated in the Spring Mountains. The valley is surficially drained by Las Vegas Wash, which was an ephemeral stream prior to urbanization of the area. Ground water generally flows from the west side to east side of the valley, where most is discharged by evapotranspiration or seepage into Las Vegas Wash. A small amount of ground water leaves the area as subsurface flow beneath Frenchman Mountain. Parts of the Spring Mountains, the Sheep Range, and the Las Vegas Range are composed predominantly of carbonate rocks that may readily transmit water. In these areas, much of the natural recharge of about 30,000 acre-feet per year apparently originates in the mountains and enters the basin-fill ground-water reservoir as flow across the bedrock-alluvium contact (Harrill, 1976, page 64).

Population of Las Vegas Valley has grown from several hundred in the early 1900's to about 500,000 in 1980. Much of this growth was supported by ground water, and a basin-wide overdraft has existed since about 1948. Colorado River water has been imported to the basin since the 1950's to augment ground-water supplies; however, it was not until the Southern Nevada Water Project was initiated in the 1970's that enough water was brought into the area to supply all the new growth and allow ground-water pumpage to stabilize (at least temporarily) at a level of 70,000 to 75,000 acre-feet per year.

Water levels in some parts of the valley have declined more than 250 feet below pre-pumping levels, and in some places the land surface has subsided 2 to 4 feet. These water-level declines are still continuing along the west side of the valley. In the central part of the valley, large amounts of imported and pumped water have been used to irrigate lawns; a portion of this water has recharged the upper part of the basin-fill reservoir, and the water table has risen to within a few feet of land surface. Some formerly ephemeral streams are now perennial and new growths of phreatophytes have developed locally.

The sustained overdraft and consequent water-level declines and associated land subsidence have been of long-standing concern. Importation of large quantities of Colorado River water are alleviating the overdraft on a basin-wide basis, but where pumping is concentrated in the most productive aquifers, localized overdraft continues. Downward movement of poor-quality water to the principal aquifers and the effect of poor-quality ground water that returns to the Colorado River are both of concern. The problems are complex, and the Nevada District is currently working on a ground-water flow model that will assist local agencies in evaluating impacts of various development alternatives. In addition, a more localized investigation to evaluate water resources in the Kyle and Lee Canyon areas in the Spring Mountains is underway. This study will provide valuable information about seasonal variations in ground-water conditions in one of the principal recharge areas for the Las Vegas ground-water basin.

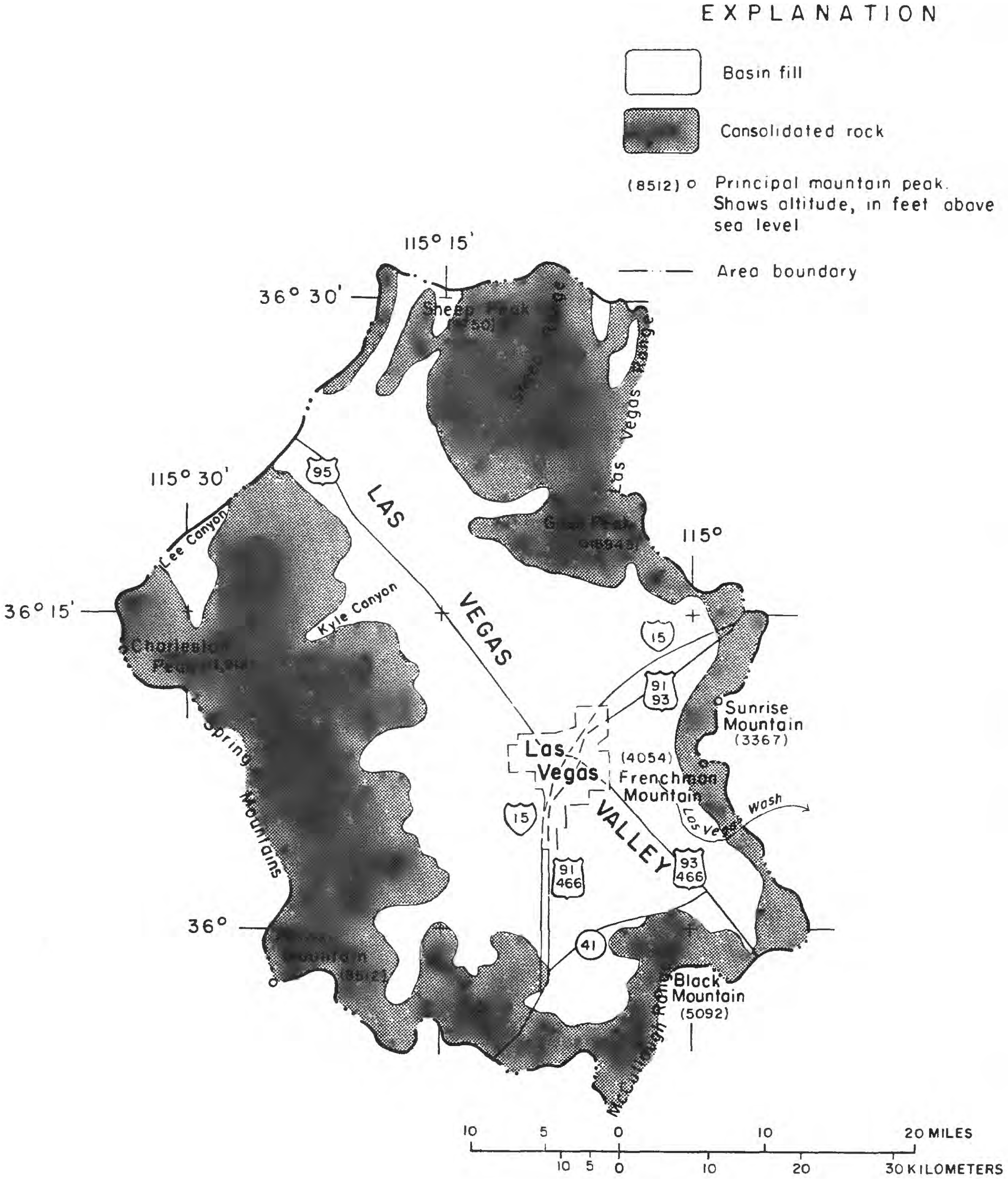


Figure 10.--General features of the Las Vegas Valley study area, Clark County, Nevada.

Las Vegas is the most heavily overdrafted basin in the entire study area. Understanding how the flow system has responded to sustained pumping prior to importation of Colorado River water and how the system is currently responding to the imported water would have transfer value to other areas in the Great Basin. Consequently, Las Vegas Valley was selected as an area for model study. The ongoing District study will be supplemented by this project and the results generalized to apply to other areas in the region having similar conditions.

## Jordan Valley, Utah

Jordan Valley and its drainage basin include about 800 square miles on the eastern edge of the Great Basin in northern Utah and virtually coincide with the area of Salt Lake County. The valley floor includes about 500 square miles and is bounded on the east by the Wasatch Range, on the west by the Oquirrh Mountains, on the south by the Traverse Mountains, and on the northwest by Great Salt Lake (figure 11). Altitude ranges from about 4,200 feet above sea level at the shore of Great Salt Lake to more than 11,300 feet in the Wasatch Range and more than 9,300 feet in the Oquirrhs.

Several studies of the hydrogeology of Jordan Valley have been made, including those by Richardson (1906), Taylor and Leggette (1949), Marine and Price (1964), and a study that included an analog-model analysis of the valley's ground-water reservoir was made by Hely and others (1971).

The Jordan Valley forms the lower one-fifth of the Jordan River drainage basin. The Jordan River flows into the valley from Utah Lake through the Traverse Mountains, and then along the axis of the valley to Great Salt Lake. Several perennial streams from the Wasatch Range are tributary to the Jordan River. Average annual discharge of the river as it enters the valley is about 270,000 acre-feet. During the 1964-68 water years, about 284,000 acre-feet per year entered Jordan Valley in the river and in canals and aqueducts. Streamflow originating in the valley's drainage during the same period was 179,000 acre-feet per year, for a total of more than 460,000 acre-feet per year.

The Jordan River is almost entirely diverted into irrigation canals, just below where it enters the valley. Most of the river's flow below the diversions during the irrigation season consists of ground-water inflow. Average annual gain in flow attributed to ground-water inflow is about 150,000 acre-feet.

The main source of ground water in the Jordan Valley is the unconsolidated basin fill. Much of the ground water in the northern part of the valley and along its axis is confined. Along the margins of the valley, ground water occurs under water-table conditions in coarse-grained basin fill deposited as alluvial fans and lakeshore or delta features. The Jordan Valley was classified by Eakin and others (1976, plate 1B) as a topographically open, partly drained basin with a perennial stream.

Ground water has been used in the Jordan Valley since the 1850's, but estimates of withdrawals are available only since 1931. As of 1980, a total of more than 12,000 wells had been constructed in the valley; most are small-diameter domestic and stock wells. During 1931-79, annual discharge from wells increased from about 39,000 to 136,000 acre-feet. Almost half the withdrawals in 1979 were for municipal use.

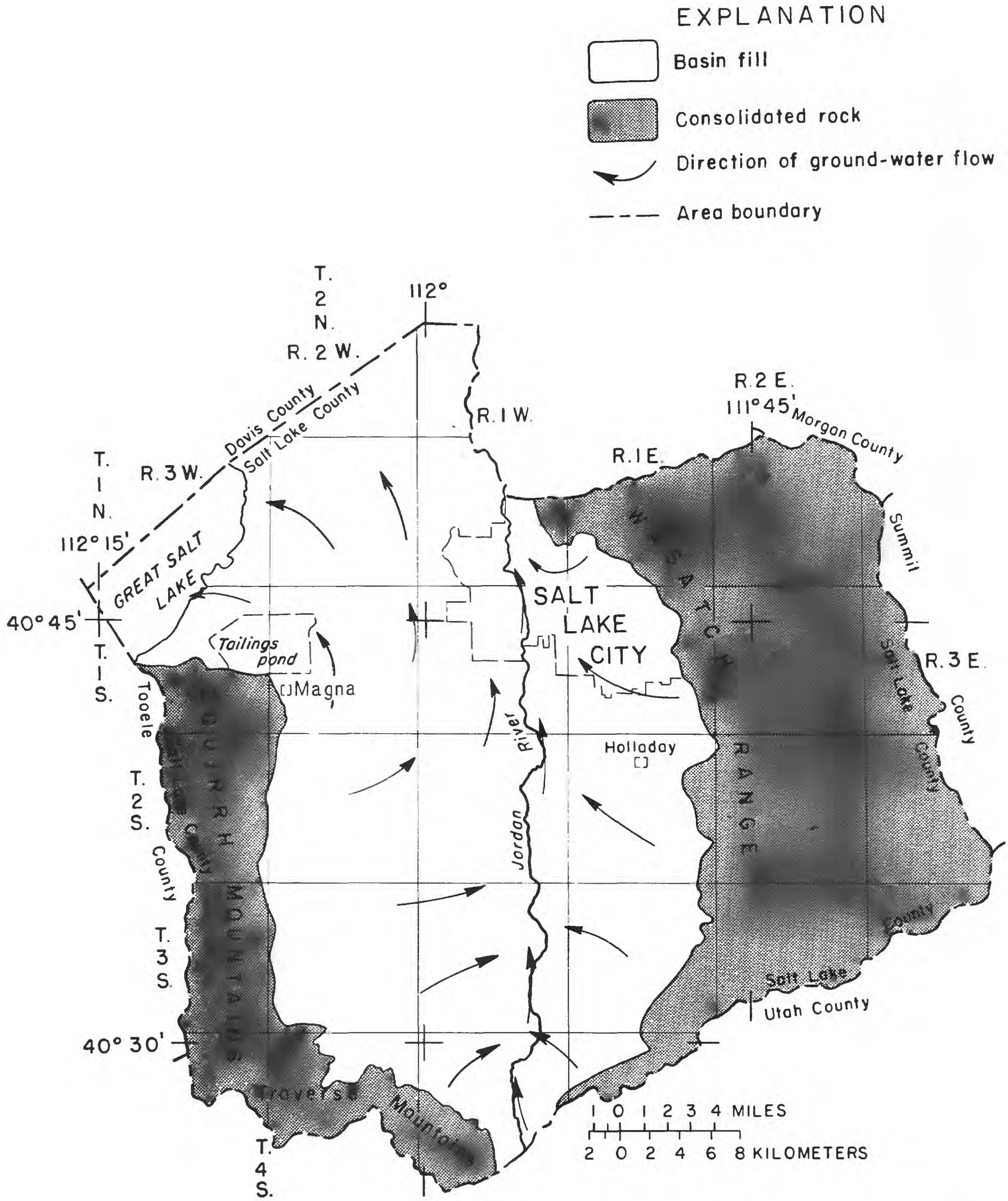


Figure 11.--General features of the Jordan Valley study area, Salt Lake County, Utah.

Although water levels have declined in areas where withdrawals for municipal and industrial use have been large, no long-term, basin-wide decline in water levels had occurred during 1931-80, and in some locations water levels had risen because of lawn and agricultural irrigation.

Average annual precipitation ranges from less than 12 inches in the southeastern part of the Jordan Valley to more than 60 inches in the Wasatch Range along the southern boundary of the basin. Annual recharge to the ground-water reservoir is estimated to average about 370,000 acre-feet. About 36 percent of the recharge occurs as seepage from consolidated rocks of the bounding mountain ranges.

Recharge along the margins of the valley consists of seepage (1) from consolidated rock to the basin fill, (2) from streams as they leave the mountains, and (3) from precipitation on the valley margins. Ground water moves toward the axis of the valley and northward, where it becomes confined under lenses of clay deposited on the bottom of Pleistocene lakes. The water then leaks upward to the shallow water-table zone where it (1) seeps to the Jordan River, (2) is discharged by evapotranspiration, or (3) seeps into Great Salt Lake.

Recharge from canals, irrigation, and the tailings pond near Magna is superimposed on the natural flow system in the northwestern part of the valley. Much of this recharge is to the shallow water-table zone overlying the confined aquifer. It discharges by flow to the river, by evapotranspiration, or by inflow to Great Salt Lake.

The Jordan Valley will be the subject of a 4-year study under the Federal-State cooperative program beginning in July 1981 and will include three-dimensional modeling of ground-water flow and modeling of solute transport. Work that will augment this study will be supported with RASA funds. Results of the flow model will be incorporated in the RASA study.

The Jordan Valley was selected for detailed study because of its economic importance, because much data are already available, and because it is considered representative of an area in the Great Basin having relatively large recharge. The final model will be used to test the effects of various ground-water development schemes.

### Carson Valley, Nev.-Calif.

Carson Valley is a productive agricultural area in Douglas County, Nev., and Alpine County, Calif., and encompasses a drainage area of about 530 square miles. The valley is a structural basin with an area of about 120 square miles, bordered on the west by granitic rocks that form the Carson Range of the Sierra Nevada and on the east by volcanic and metavolcanic rocks that form the Pine Nut Range. The axis of the valley is traversed by the Carson River, which flows northward (figure 12). Average surface water and ground water inflow is about 355,000 acre-feet per year and the average surface-water outflow is about 272,000 acre-feet per year. The difference of about 80,000 acre-feet per year represents evapotranspiration within the valley.

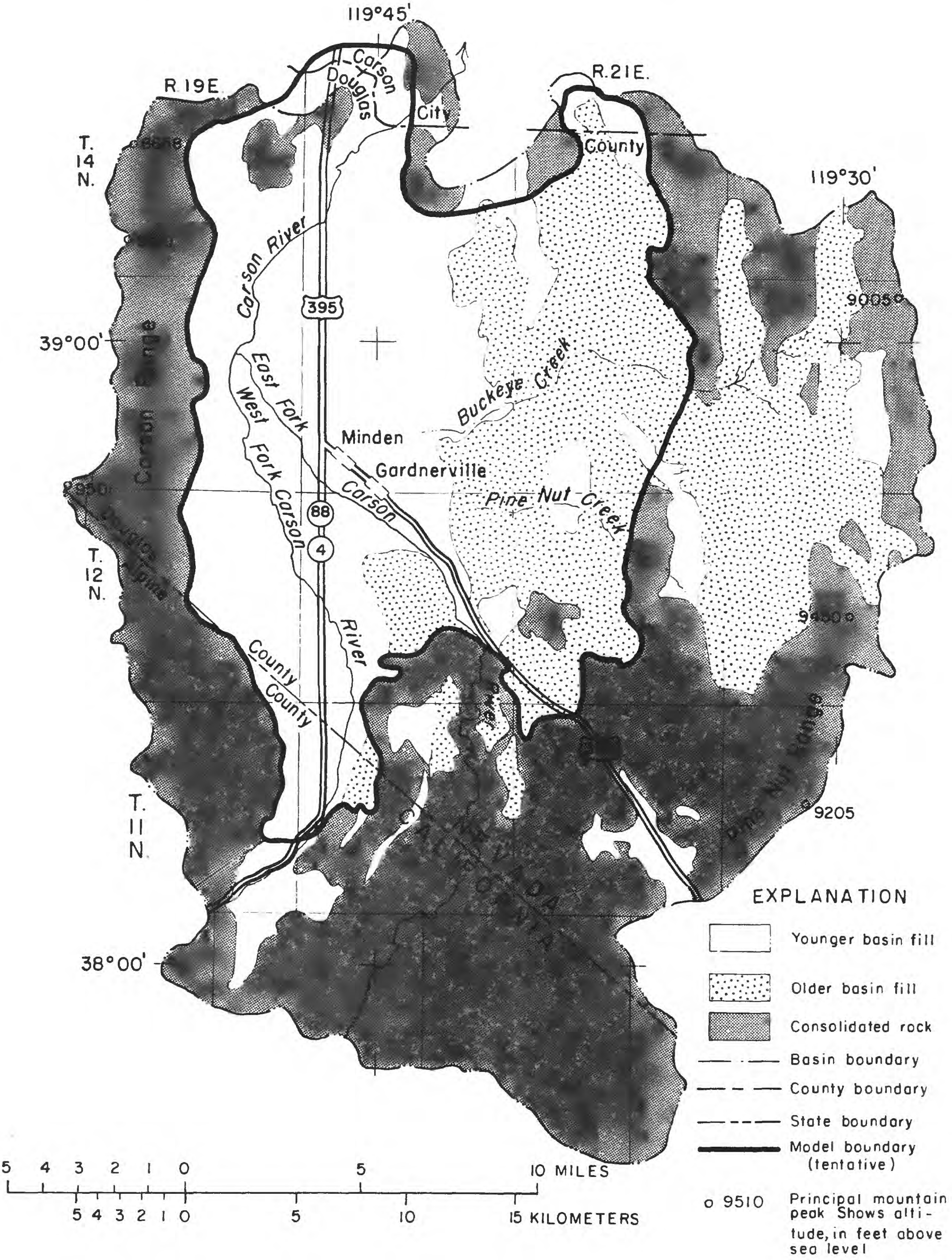


Figure 12.--General features of the Carson Valley study area, Douglas County and Carson City, Nevada, and Alpine County, California.

Carson Valley has recently experienced rapid urban growth, which is expected to continue. Pumpage for agricultural and public supply has increased greatly in the past several years. Concern is widespread that sustained heavy pumping will adversely affect surface-water rights. Ground water can be obtained (1) from storage, causing water levels to decline; (2) by capture of water that formerly supplied ground-water discharge; or (3) by inducing additional recharge to enter the system, with consequent depletion of surface-water supplies. The current understanding of the ground-water flow system is inadequate to allow reliable quantitative prediction of the probable effects of pumping stresses. The U.S. Geological Survey has begun a cooperative study that will use a ground-water flow model to evaluate the hydrology of the area and to make predictions of probable intermediate and long-term impacts of various development alternatives.

Work to augment this study will be supported by the RASA project because the techniques that will be used and the general results obtained will have a high transfer value to other areas where perennial streams traverse alluvial valleys. Techniques used to evaluate the various relationships and interactions between surface water and ground water will be of particular interest to the objectives of the Great Basin Regional Aquifer Study.

### Paradise Valley, Nev.

Paradise Valley occupies about 600 square miles of the Little Humboldt River drainage basin in Humboldt County, north-central Nevada. The area contains a basin-fill ground-water reservoir with a surface area of about 330 square miles. It is bounded on the west by the Santa Rosa Range, on the north by low-lying volcanic hills, on the east by the Hot Springs Range, and on the south by the floodplain of the Humboldt River (Harrill and Moore, 1970, plate 1). The valley floor is the floodplain of the Little Humboldt River. During most years, river flow is perennial only in the north (upstream) part of the valley (figure 13). Water from the river and other perennial streams infiltrates readily into the basin fill in the northern half of the valley, and the southern half is generally an arid basin where the hydrologic regimen is dominated by ground water. In occasional very wet years, flow of the Little Humboldt River reaches the southern end of the valley, where it ponds to form a temporary lake or breaks through sand dunes and drains to the Humboldt River.

The rocks that form the Santa Rosa Range, the Hot Springs Range, and those that underlie the basin at depth are relatively impermeable. The flow system can be generally conceptualized as a north-south-oriented alluvial trough that is recharged in the northern half by streamflow and then drains to the south by subsurface flow.

Initially, all irrigation was by diverted streamflow. Virtually all land irrigable by streamflow--about 39,000 acres--has been farmed or used as pasture for many years. Until the early 1970's, most ground-water pumpage was to augment surface-water supplies. Pumpage increased slowly from about 600 acre-feet per year in 1950 to about 7,800 acre-feet per year in 1968. Water use changed sharply in the early 1970's when conditions in the southern part of the valley were determined to be well suited for growing potatoes.

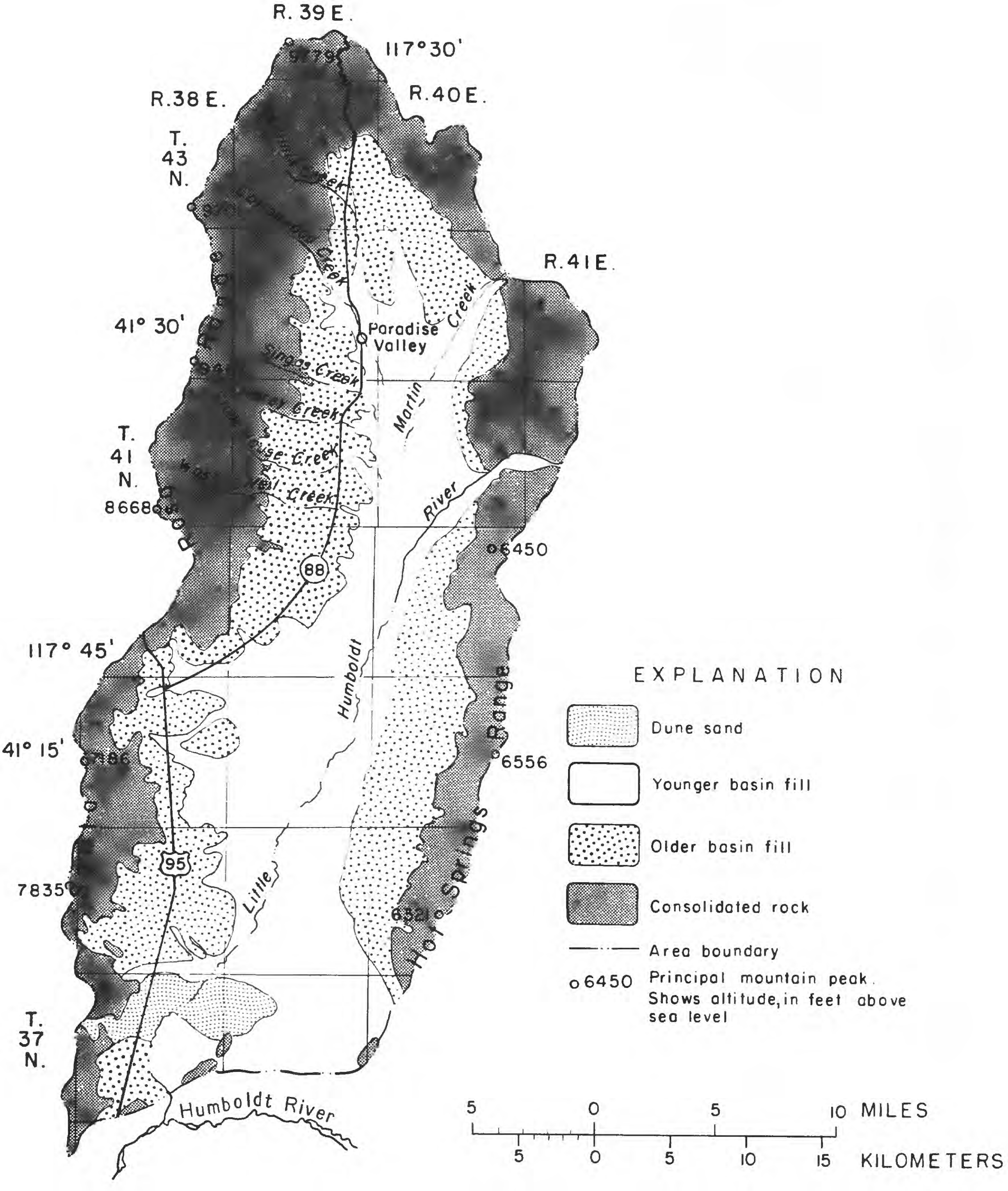


Figure 13.--General features of the Paradise Valley study area, Humboldt County, Nevada.

Large tracts of land were put into production and irrigated by pumped ground water. Pumpage has increased rapidly; in 1980, more than 50,000 acre-feet was withdrawn, primarily to irrigate potatoes and alfalfa.

The Paradise Valley area was chosen for model studies because of the wide range of hydrologic conditions present. Conditions vary from a surface-water-dominated flow regimen at the north end of the valley to an arid ground-water-dominated regimen at the south end. Knowledge gained from this simulation will be generally applicable to similar areas throughout the region.

### Milford Area, Utah

The Milford area occupies 1,160 square miles in parts of Millard, Beaver, and Iron Counties in southwestern Utah, of which about 450 square miles is underlain by basin-fill deposits (figure 14). The north-south alluvial valley is bounded by mountains on the east, west, and south. Eakin and others (1976, plate 1) have classified the area as a topographically open sink--that is, the valley receives surface and subsurface inflow from upgradient valleys, and is not drained by either stream or ground-water outflow. Roosevelt Hot Springs, a KGRA (Known Geothermal Resource Area), is at the base of the Mineral Mountains, northeast of the town of Milford. The Beaver River, the only perennial stream, enters the area from the southeast. It is regulated by a dam at Rocky Ford Reservoir, upstream from the area and east of Minersville in Beaver Valley. Most of the water entering the valley is diverted for irrigation. In very wet years water flows north and infiltrates the basin-fill deposits. In the spring of 1979, the streamflow extended to within 5 miles of Milford.

The consolidated rocks that underlie the basin fill and crop out in the surrounding mountains are relatively impermeable except in areas of open joints. The hydrogeologic units used by Mower and Cordova (1974, page 5), consist of sedimentary and metasedimentary rocks of Precambrian through Tertiary age, volcanic rocks of Tertiary age, and basalt, rhyolite, and granite of Tertiary and Quaternary age.

Water needs in the area are supplied by the Beaver River and wells in the unconsolidated basin fill. Mower and Cordova (1974, page 1) report an average annual inflow from the Beaver River of 27,600 acre-feet. Pumpage from irrigation wells has increased from 60 acre-feet in 1918 to a maximum of 70,200 acre-feet in 1974. A large increase in pumping since 1950, together with below-average precipitation, resulted in reported water-level declines of as much as 30 feet from 1950 to 1970. The downward trend has continued through 1980, but at a slower rate.

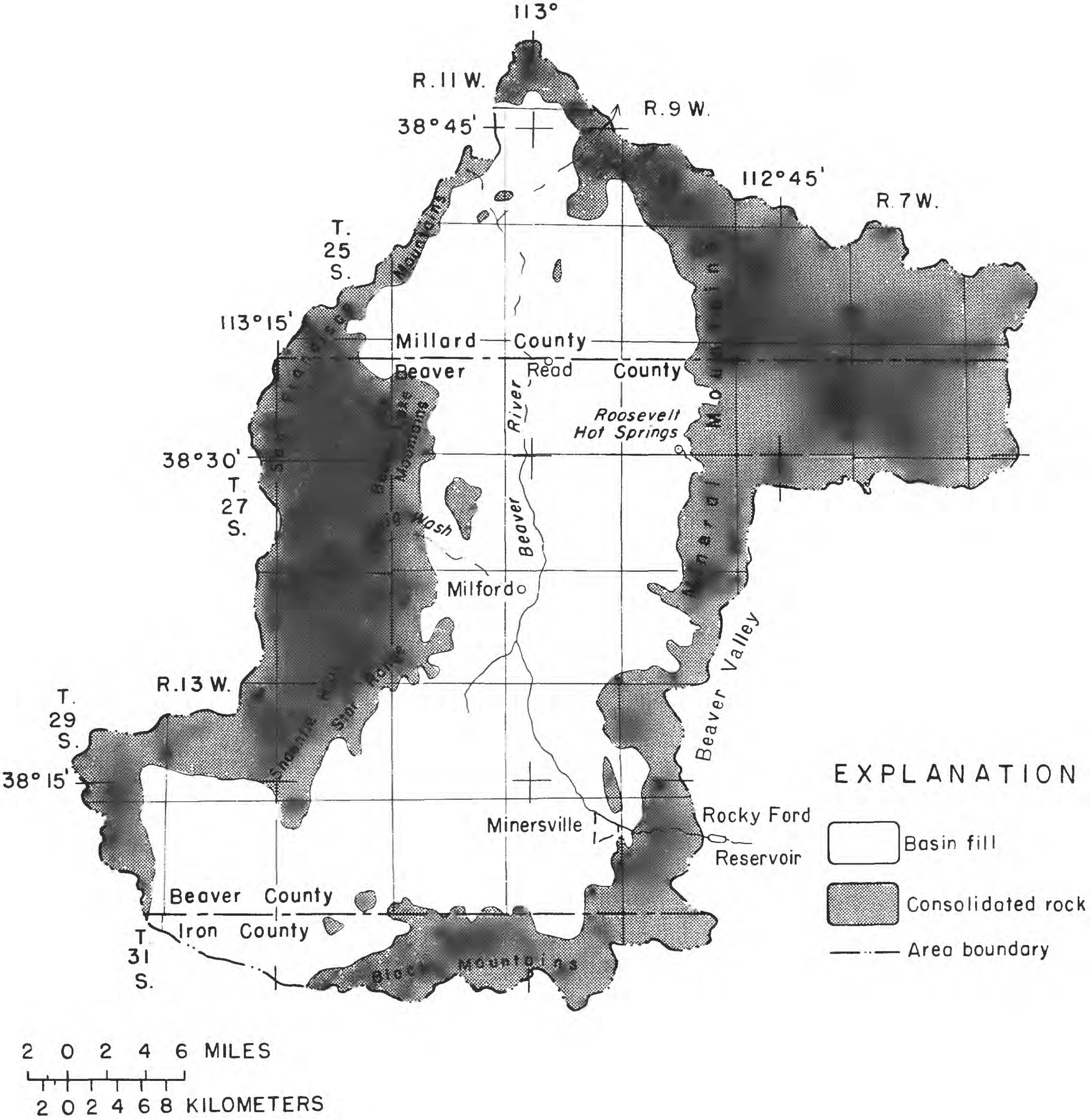


Figure 14.--General features of the Milford area, Millard, Beaver, and Iron Counties, Utah.

Mower and Cordova (1974, page 1) have estimated that the total annual recharge averaged 58,000 acre-feet for the period 1970-71; infiltration from irrigated farmland accounts for 22,700 acre-feet and subsurface inflow from bedrock in the surrounding mountains supplied 16,000 acre-feet. Other sources of recharge include subsurface inflow from Big Wash and the two tributary valleys (Beaver Valley and Beryl-Enterprise area), losses from streams and major canals, and infiltration from precipitation on the valley floor. Total annual discharge was estimated to average 81,000 acre-feet for 1970-71. Discharge from wells accounted for 56,900 acre-feet per year, of which 56,000 acre-feet was from irrigation wells. Evapotranspiration was estimated to be 24,000 acre-feet annually. Estimated outflow to the north into the Black Rock Desert was insignificant at less than 10 acre-feet per year.

The Milford area was chosen for ground-water modeling because of the varied hydrologic conditions present and because it is representative of basins where discharge generally is greater than recharge. The primary emphasis of the modeling study will be to examine the effects of continued withdrawal from irrigation wells in the central part of the area. Continued water-level decline, change in natural discharge of ground water, and variability in recharge-withdrawal relationships and other effects also will be studied. Recharge-withdrawal relationships would be treated as a variable rather than a constant parameter. As a consequence of the modeling efforts, a revised estimate for subsurface inflow from mountain bedrock may be made.

### Tule Valley, Utah

Tule Valley, an undeveloped basin in the western desert of Utah, was the subject of a hydrologic reconnaissance in 1973-74 (Stephens, 1977). The drainage basin includes about 940 square miles, of which about 370 are underlain by valley-fill deposits, as shown in figure 15. The valley is topographically closed and is bounded by the House Range on the east, the Confusion Range on the west and southwest, and by low hills and the Fish Springs Range on the north and northeast. Several low passes lead to Wah Wah Valley on the south, Snake Valley on the west and northwest, the Great Salt Lake Desert on the north, and Fish Springs Flat on the northeast. The basin has no permanent inhabitants and is mostly federally and State owned.

Altitudes range from about 4,470 feet at the valley's playa to over 9,600 feet in the House Range. The basin has no perennial streams, and total surface water runoff to the playa is estimated to be about 4,000 acre-feet per year.

Total annual precipitation over the basin is estimated to average 400,000 acre-feet and annual recharge from precipitation is estimated at 7,600 acre-feet. Ground-water discharge was estimated by Stephens (1977, page 21) to be about 40,000 acre-feet per year, almost all by evapotranspiration of water discharged by springs at the margins of the playa and by upward leakage to the playa. Gates and Kruer (1980, page 78) revised this figure to about 32,000 acre-feet per year. The imbalance between recharge and discharge is attributed to inflow through consolidated rock from outside the basin. Stephens (1977, page 16) postulated that some water moves northeast through Tule Valley on its way to Fish Springs Flat.

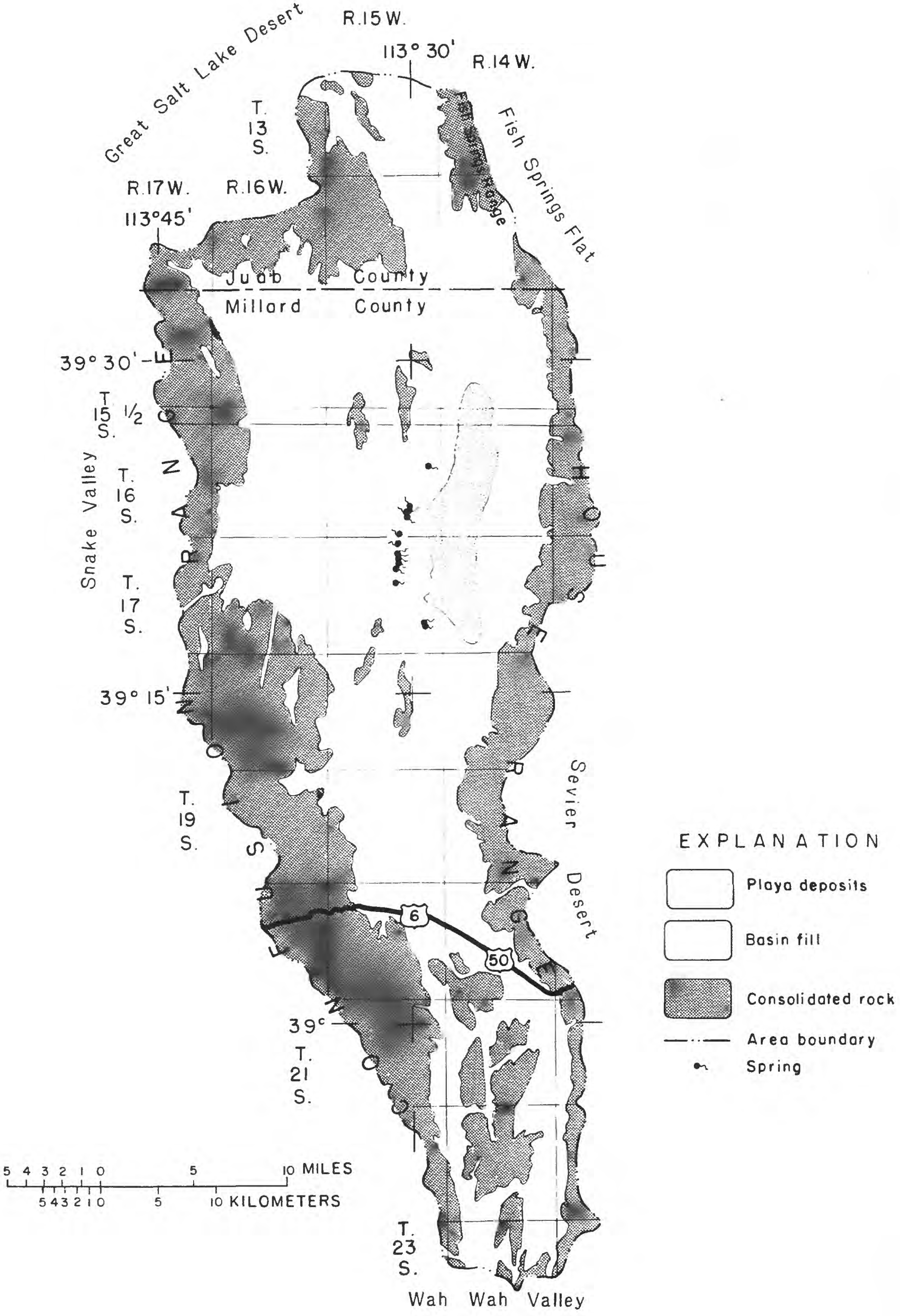


Figure 15.--General features of the Tule Valley study area, Millard and Juab Counties, Utah.

The current understanding of the ground-water flow system in Tule Valley is that local recharge moves toward the playa, where it is discharged. Additional water moves into the basin from Snake Valley, with smaller amounts possibly entering from Pine and Wah Wah Valleys, and discharges from springs on the playa's western edge. Some of this water may also move through (or beneath) Tule Valley on its way to Fish Springs Flat instead of discharging in Tule Valley. The basin has been classified by Eakin and others (1976, plate 1) as a topographically closed, partly drained basin.

Tule Valley was selected for detailed study and modeling because it is an undeveloped basin in the arid part of the Great Basin in Utah. The valley also is part of an interbasin flow system in carbonate rock in western Utah and eastern Nevada. Ground water is its principal water resource.

The tentative plan of study is to do comprehensive surface-geophysical surveys (possibly including gravity, aeromagnetic, airborne-electromagnetic, seismic-refraction, and resistivity techniques) in an attempt to obtain enough data to construct a simplified digital model of the valley. An evaluation of the results will help to determine whether geophysical data can compensate for a lack of hydrologic data in a relatively short-term evaluation of an undeveloped basin. An attempt will be made to develop techniques for estimating model parameters from geophysical data.

### Dixie Valley Area, Nev.

Dixie Valley, in west-central Nevada, is the terminus of both surface- and ground-water flow from six smaller valleys (Fairview, Stingaree, Cowkick, Eastgate, Jersey, and Pleasant), and from the surrounding mountain blocks. Dixie Valley and the six smaller tributary valleys comprise the Dixie Valley area of this study (figure 16). The Dixie Valley area is bounded on the west by the Sand Springs, Stillwater, and East Ranges; on the north by Grass and Buffalo Valleys; on the east by the Desatoya, Clan Alpine, and Fish Creek Mountains; and on the south by Gabbs Valley. The area encompasses about 2,360 square miles and includes about 1,000 square miles underlain by basin-fill deposits.

The block-faulted mountains that generally encompass the perimeter of the area are composed of igneous, metamorphic, and sedimentary rocks. These rocks are complexly folded, thrust faulted, and deeply dissected. Except for minor amounts of water that move through joints or fractures, these rocks are considerably less permeable than the unconsolidated deposits in the valleys and probably prevent a ground-water flow into or out of the drainage area (Cohen and Everett, 1963, page 12).

Most of the available ground water is stored in basin-fill deposits that underlie the valley floors. In the center of Dixie and Fairview Valleys, coarse-grained deposits are overlain by fine-grained lake deposits. The precise thickness of unconsolidated deposits is not known, but estimates from gravity data suggest a thickness in excess of 5,000 feet beneath much of the valley floor (Donald H. Schaefer, U.S. Geological Survey, written commun., 1981).

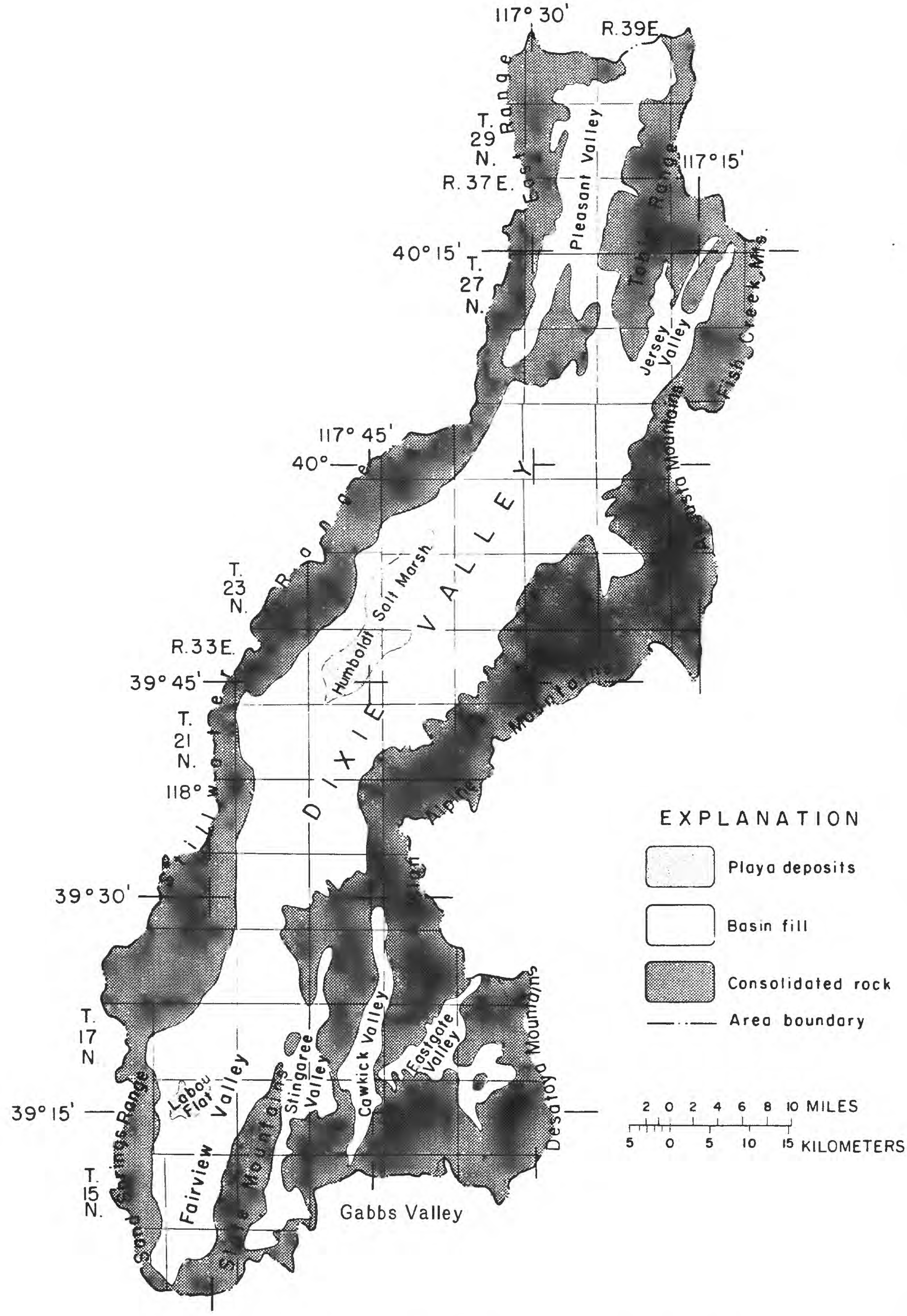


Figure 16.--General features of Dixie Valley study area, Churchill, Lander, Pershing, and Mineral Counties, Nevada.

Precipitation within the drainage basin is the sole source of water to the unconsolidated aquifers. Most of the precipitation falls in the higher mountains, usually in the form of snow during the winter months. Because the rocks forming the mountains are poorly permeable, most of the excess water runs off as streamflow onto adjacent alluvial fans, where the surface water infiltrates to recharge the unconsolidated aquifers. Periodically, surface water flows to playas in either Fairview Valley or Dixie Valley and is then evaporated.

Natural discharge is by evapotranspiration. The primary discharge area is in Dixie Valley surrounding and including the Humdoldt Salt Marsh.

The Dixie Valley drainage area was chosen for more detailed study because the basin is typical of several other basins where surface water and ground water flow into them from other valleys. It is also an area where active structural deformation is associated with movement along normal faults. Two severe earthquakes in the basin, on December 16, 1954, altered the hydraulic continuity between Dixie Valley and the smaller valleys to the southeast.

Attempts will be made to better define the hydrologic system in the Dixie Valley area with either a two- or three-dimensional model that has been modified to include recharge by ephemeral streams. Hopefully, the effects of the two earthquakes in 1954 can be simulated; however, the model will not be able to incorporate the uncertain effects of future earthquakes on the system, other than by means of hypothetical simulations.

### Smith Creek Valley, Nev.

Smith Creek Valley is a north-trending basin in west-central Nevada. It is bounded on the west by the Desatoya Mountains, on the north by the New Pass Range, on the east by the Shoshone Mountains, and on the south by Ione Valley (figure 17). The total drainage area, about 560 square miles, includes about 300 square miles underlain by basin-fill deposits. The valley is both topographically and hydrologically closed. Block-faulted mountains composed primarily of Tertiary volcanic rocks enclose the valley on the east, north, and west. A ground-water divide in the south end of the valley consists of peaks of Tertiary volcanic rock protruding through a thin layer of alluvium. The basin fill ranges from Tertiary to Quaternary in age and is comprised of clay, silt, sand, and gravel that has been eroded from the surrounding mountains. Fine-grained lacustrine deposits of Pleistocene age form a playa in the central valley (Everett and Rush, 1964).

Precipitation, the sole source of recharge, originates mostly from snow melt or rainfall above the 7,000-foot level. The small amount of precipitation that falls on the valley floor contributes little to recharge, because of the high evapotransporation rate that dissipates most of the water before it reaches the saturated zone. A major part of the recharge on the alluvial fans is downward percolation from ephemeral streams produced by spring snow melt and rain. Recharge in the mountains is derived from snow melt that infiltrates joints, fractures, and other openings in the consolidated rock.

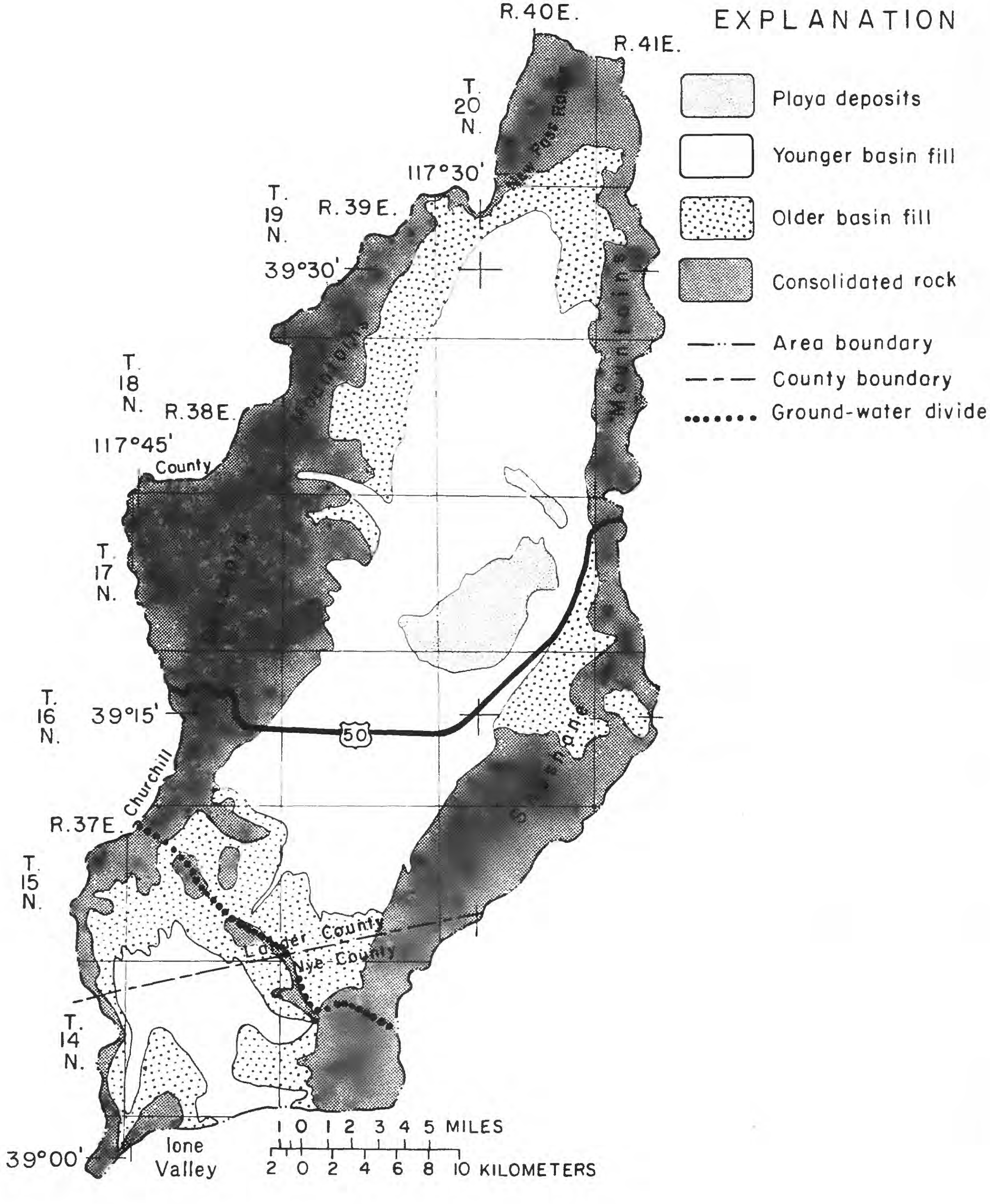


Figure 17.--General features of the Smith Creek Valley study area, Lander and Nye Counties, Nevada.

Discharge in the valley is by evapotranspiration, mainly on and adjacent to the playa areas. Phreatophytes account for most of the discharge; however, a significant amount is dissipated from the bare playa by evaporation.

Large quantities of water are stored within the basin fill. The quantity depends on the thickness and specific yield of the basin fill. Estimated maximum thickness is about 4,000 feet, as determined by gravity and seismic-refraction data. There is little stress on the hydrologic system, as only four irrigation wells and a few stock wells are present within the basin.

Smith Creek Valley was chosen for more detailed study because it is typical of a hydrologically closed basin with relatively impermeable volcanic rocks surrounding and underlying the basin fill. Studies undertaken in Smith Creek Valley hopefully will have transfer value to other hydrologically similar valleys within the Great Basin.

### Stagecoach Valley, Nev.

Stagecoach Valley is the smallest area picked for detailed study. Its total drainage area is only 78 square miles, of which 33 square miles is underlain by basin-fill sediments. The valley is in western Nevada about 20 miles east of Carson City and is part of the Dayton Valley hydrographic area, which in turn is part of the Carson River drainage basin (Glancy and Katzer, 1975). Stagecoach Valley is bounded by the Flowery Range to the north, by Churchill Butte and an alluvial divide separating Stagecoach and Churchill Valleys to the east, by the north end of the Pine Nut Mountains to the west, and by the Carson River to the south (figure 18).

Approximately 45 square miles of the valley consist of volcanic, metasedimentary, and intrusive rocks, which are considered poorly permeable compared to the valley-fill aquifer and probably provide a barrier to ground-water flow into and out of the basin. The sedimentary deposits in the valley consist of Tertiary and Quaternary detritus--clay, silt, sand, and gravel. The thickness and lithologic variation of the basin-fill deposits throughout the valley are not known. One well near the north-central part of the valley penetrated mainly sand and gravel and encountered consolidated rock at a depth of 234 feet, whereas another well near the west side of the valley penetrated 820 feet of interlayered clay and sand with minor amounts of gravel and did not encounter consolidated rock. The thickness of sediments may exceed 1,000 feet locally; however, the average thickness may be closer to 500 feet (Glancy and Katzer, 1975, page 13).

Geophysical techniques and perhaps some test drilling will be used to better define the thickness and character of the sediments. These investigations also may answer the question of whether sediments in Stagecoach Valley are hydraulically connected to the alluvium of the Carson River or whether, as postulated by Glancy and Katzer (1975, page 15), the valley is separated from the river by consolidated rocks that are covered by only a veneer of sediments.

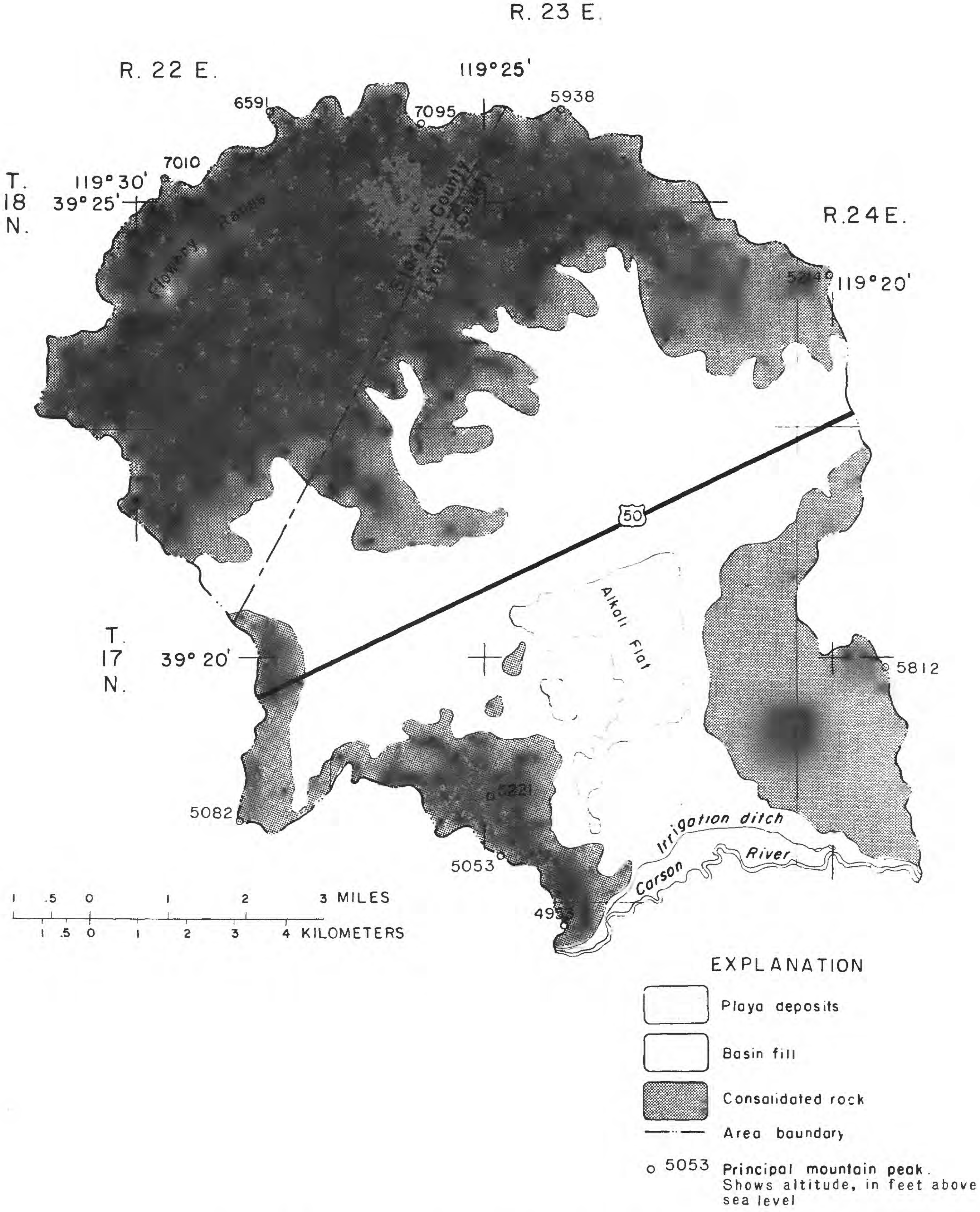


Figure 18.--General features of the Stagecoach Valley study area, Storey and Lyon Counties, Nevada.

The valley was chosen for further studies because it is a small basin where boundary effects and interference between pumped wells are more noticeable than in larger valleys, and because water levels in several wells were monitored prior to increased pumping for irrigation. Computer modeling of the area will hopefully determine whether ground water in Stagecoach Valley is interconnected with the Carson River and whether increased pumping in the valley could cause water to move from the river toward the heavily pumped wells.

## Regional Analysis of Results

During the last year of the project, efforts will be concentrated on summarizing and drawing together results of the descriptive work and special studies. The objective will be to produce information that portrays the ground-water resources of the area from a regional perspective.

Information that portrays the character and magnitude of the ground-water resource will be summarized graphically. Results of the various model studies will be regionalized in two ways: First, the individual models will be analyzed in terms of how they, or parts of them, could be applied to other areas throughout the region. The results of this analysis will be helpful in setting up other models throughout the region as the need arises. Second, a set of generalized management alternatives will be defined that reflect the choices most commonly considered by planners and managers, and the models then will be stressed according to the manner prescribed for each alternative. The results will be compared and differences analyzed in terms of the ways in which various types of flow systems will respond to typical patterns of development. Finally, a summary report that deals with the overall results of the entire study will be prepared during this phase of the work.

## REFERENCES CITED

Birtles, A. B., and Reeves, M. J., 1977, A simple, effective method for the computer simulation of ground-water storage and its application in the design of water resource systems: Journal of Hydrology, v. 34, p. 77-96.

Blankennagel, R. K., and Weir, J. E., 1973, Geohydrology of the eastern part of Pahute Mesa, Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Professional Paper 712-B, 35 p.

Bolke, E. L., and Sumison, C. T., 1978, Hydrologic reconnaissance of the Fish Springs Flat Area, Tooele, Juab, and Millard Counties, Utah: Utah Department of Natural Resources Technical Publication 64, 30 p.

Bredehoeft, J. D., and Farvolden, R. N., 1963, Disposition of aquifers in intermontane basins of northern Nevada: International Association of Scientific Hydrology, Commission of Subterranean Waters Publication 64, p. 197-212.

Cohen, Philip, and Everett, D. E., 1963, A brief appraisal of the ground-water hydrology of the Dixie-Fairview Valley area, Nevada: Nevada Department of Conservation and Natural Resources, Ground-Water Resources - Reconnaissance Report 23, 40 p.

Cooley, R. L., 1977, A method of estimating parameters and assessing reliability for models of steady state groundwater flow. 1. Theory and numerical properties: Water Resources Research, v. 13, no. 2, p. 318-324.

Eakin, T. E., 1966, A regional interbasin ground-water system in the White River area, southeastern Nevada: Water Resources Research, v. 2, no. 2, p. 251-271.

Eakin, T. E., Price, Don, and Harrill, J. R., 1976, Summary appraisals of the Nation's ground-water resources--Great Basin Region: U.S. Geological Survey Professional Paper 813-G, 37 p.

Everett, D. E., and Rush, F. E., 1964, Ground-water appraisal of Smith Creek and Ione Valleys, Lander and Nye Counties, Nevada: Nevada Department of Conservation and Natural Resources, Ground-Water Resources - Reconnaissance Report 28, 21 p.

Frind, E. O., and Verge, M. J., 1978, Three-dimensional modeling of ground-water flow systems: Water Resources Research, v. 14, no. 5, p. 844-856.

Gates, J. S., and Kruer, S. A., 1980, Hydrologic reconnaissance of the southern Great Salt Lake Desert and summary of the hydrology of west central Utah: Salt Lake City, Utah, U.S. Geological Survey Open-File Report 80-445, 85 p.

Glancy, P. A., and Katzer, T. L., 1975, Water-resources appraisal of the Carson River Basin, western Nevada: Nevada Division of Water Resources Reconnaissance Report 59, 126 p.

Harrill, J. R., 1976, Pumping and ground-water storage depletion in Las Vegas Valley, Nevada, 1955-74: Nevada Division of Water Resources Bulletin 44, 70 p.

----- 1982, Ground-water storage depletion in Pahrump Valley, Nevada-California, 1962-75: U.S. Geological Survey Open-File Report 81-635, 76 p.

Harrill, J. R., and Moore, D. O., 1970, Effects of ground-water development on the water regimen of Paradise Valley, Humboldt County, Nevada, 1948-68, and hydrologic reconnaissance of the tributary areas: Nevada Division of Water Resources Bulletin 39, 123 p.

Hawley, J. W., and Wilson, W. E., III, 1965, Quaternary geology of the Winnemucca area, Nevada: University of Nevada, Desert Research Institute Technical Report H-W 5, 66 p.

Heimes, F. J., and Luckey, R. R., 1980, Evaluating methods for determining water use in the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1979: Denver, Colo., U.S. Geological Survey Water-Resources Investigations 80-111, 118 p.

Hely, A. G., Mower, R. W., and Harr, C. A., 1971, Water resources of Salt Lake County, Utah: Utah Department of Natural Resources Technical Publication 31, 244 p.

Hess, J. W., and Mifflin, M. D., 1978, A feasibility study of water production from deep carbonate aquifers in Nevada: University of Nevada, Desert Research Institute Publication 41054, 125 p.

MacCary, L. M., 1981, Apparent water resistivity, porosity, and ground-water temperature of the Madison Limestone and underlying rocks: U.S. Geological Survey Open-File Report 81-629, 36 p.

Marine, I. W., and Price, Don, 1964, Geology and ground-water resources of Jordan Valley, Utah: Utah Geological and Mineralogical Survey Water Resources Bulletin 7, 68 p.

Mifflin, M. D., 1968, Delineation of ground-water flow systems in Nevada: University of Nevada, Desert Research Institute Technical Report H-W 4, 89 p.

Mower, R. W., and Cordova, R. M., 1974, Water resources of the Milford area, Utah, with emphasis on ground water: Utah Department of Natural Resources Technical Publication 43, 106 p.

Nichols, W. D., 1979, Simulation analysis of the unconfined aquifer, Raft River geothermal area, Idaho-Utah: U.S. Geological Survey Water-Supply Paper 2060, 46 p.

Pinder, G. F., and Bredehoeft, J. D., 1968, Application of a digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

Plummer, L. N., and Back, William, 1980, The mass balance approach: Application to interpreting the chemical evolution of hydrologic systems: American Journal of Science, v. 280, no. 2, pages 130-142.

Prickett, T. A., and Lonnquist, C. G., 1971, Selected digital computer techniques for ground-water resource evaluation: Illinois State Water Survey Bulletin 55, 62 p.

Remson, Irwin, Hanberger, G. M., and Molz, F. J., 1971, Numerical methods in subsurface hydrology: New York, John Wiley, 389 p.

Richardson, G. B., 1906, Underground water in the valleys of Utah Lake and Jordan River, Utah: U.S. Geological Survey Water-Supply Paper 157, 81 p.

Rush, F. E., Scott, B. R., Van Denburgh, A. S., and Vasey, B. J., compilers, 1971, State of Nevada water resources and inter-basin flows: Nevada Division of Water Resources map.

Stephens, J. C., 1977, Hydrologic reconnaissance of the Tule Valley basin, Juab and Millard Counties, Utah: Utah Department of Natural Resources Technical Publication 56, 37 p.

Stewart, J. H., 1980, Geology of Nevada, A discussion to accompany the geologic map of Nevada: Nevada Bureau of Mines and Geology Special Publication 4, 136 p.

Taylor, G. H., and Leggette, R. M., 1949, Ground water in the Jordan Valley, Utah: U.S. Geological Survey Water-Supply Paper 1029, 357 p.

Trescott, P. C., 1975, Documentation of finite difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 103 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water Resources Investigations Book 7, Chapter C1, 116 p.

Winograd, I. J., 1962, Interbasin movement of ground water at the Nevada Test Site, Nevada, *in* Geological Survey Research 1962, short papers in geology and hydrology, articles 60-119: U.S. Geological Survey Professional Paper 450-C, p. C108-C111.

Winograd, I. J., and Eakin, T. E., 1965, Interbasin movement of ground water in south-central Nevada - The evidence, *in* Abstracts for 1964: Geological Society of America Special Paper 82, p. 227.

Winograd, I. J., and Friedman, Irving, 1972, Deuterium as a tracer of regional ground-water flow, southern Great Basin, Nevada and California: Geological Society of America Bulletin, v. 83, no. 12, p. 3691-3708.

Winograd, I. J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada - California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.