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GROUNDWATER SALINITY IN THE COLORADO RIVER BASIN

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IWMI INTERNATIONAL WATER MANAGEMENT INSTITUTE

ACIAR Australian Centre for International Agricultural Research

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FOREWORD

Socioeconomic development and poverty alleviation in many developing countries depend on water. Governments and Development Agencies recognized this issue and, invested heavily on water resources development projects during the Twentieth Century. Presently, opportunities for further water resources development are limited, either due to the absence of water or due to lack of financial resources. The demand for food is continuously increasing due to a steady rise in population. Irrigated agriculture, which consumes 69% of all freshwater resources, and produces 40% of all food, will require additional 17% water to meet the demand for food. This water is not available from primary sources (rain, snow melt, groundwater). Further, freshwater consumption in irrigated agriculture decreased to meet increasing demand of freshwater for domestic and industrial requirements. Therefore, water from all primary as well as secondary sources (drainage, sewage) will be used conjunctively in agriculture. The conjunctive water use has its implications as evaporation and transpiration of water will concentrate salts and pollutants and threaten environmental sustainability of agricultural lands. Proper institutional and technical strategies must be in place to manage water conjunctively to minimize threat to the environment. This study aims to address this concern.

The broad goals of the study are to, 'Identify *combinations* of institutions and technical strategies to manage surface and groundwater at regional scale, to promote environmental sustainability and to maximize agricultural productivity of water ('crop per drop'), initially in the Rechna Doab in Pakistan and Murrumbidgee Region in Australia'.

The study is being carried out by IWMI in collaboration with Pakistan Council of Research Water Resources (PCRWR), and CSIRO Land and Water, Griffith, NSW, Australia.

This report reviews conjunctive water management issues in the Colorado River Basin.

The study is financially sponsored by the Australian Council of International Agriculture Research, Australia.

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PREFACE

This consultancy report is not a research report, but rather, a bibliographic search and summarization of valuable documents. This report consists of four sections, Section 1 has been only slightly modified from a journal paper written by the author and published in a booklet during 1982 that was also edited by the author regarding the Colorado River Basin.

The bibliographic search uncovered about 1,500 publications related to the Colorado River Basin. More than 100 documents were selected for review. Finally, 24 documents were photocopied and used in this case study, plus a number of maps (not copied). This material was used for preparing Section 2 on groundwater salinity in the Upper Colorado River Basin and Section 3 on groundwater salinity in the Lower Colorado River Basin. The author has attempted to adequately reference the sources of information. For some of the figures and tables, information has been combined and condensed, but most have been taken directly from these publications, which is also the case for the vast majority of the written material.

Section 4 was prepared by the author as a synthesis of the information in Sections 2 and 3. In addition, the importance of groundwater salinity in the future development of the Colorado River Basin has been given some interpretation.

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1. COLORADO RIVER BASIN DEVELOPMENT[1]

1.1. HISTORICAL SETTLEMENT

There is archeological evidence that some 2000 years ago irrigation canals were built and maintained by the ancient Hohokam Tribe (Hohokam is a Pima Indian word, which loosely translated, means the people who have gone away) in the Salt River Valley of the Lower Colorado River Basin (LCRB) near present-day Phoenix, Arizona. The Hohokams probably began settlement of the valley as early as 300 BC and abandoned it about AD 1400, possibly because irrigation raised the water table, which induced waterlogging and alkali problems. This would have rendered much of the land unfit for cultivation. Other Indians practiced irrigation in the vicinity before and during the period of exploration of this region of the southwest by white men. Exactly how many people were here is conjectural, but certainly several tens of thousands must have lived and worked in this economy. However, by the time Spanish explorers entered the region in the middle of the 16th Century, this prior civilization was gone and only small settlements of Indians remained, but the economic base was still agriculture. For example, the Navajos, who are situated in the Lower Basin, only arrived during the last 500 years.

The next irrigators of the Colorado River Basin were Jesuits who established themselves at the old missions of Cuevavi and San Xavier in Arizona in 1732. In the period of 1768-1822, considerable irrigation was practiced along the Santa Cruz River near the missions and the Spanish presidios of Tubac and Tucson.

By the treaty concluding the Mexican War in 1849, and by the Gadsden Purchase of 1853, the United States acquired the territories of New Mexico, Arizona and California. Discovery of gold in California in 1849 brought hordes of adventurers westward. They crossed the Colorado River near Yuma, Arizona, and at Needles, California. In 1857, Lieutenant J. C. Ives traveled 400 miles up the river by boat to the Black Canyon, present site of Hoover Dam. He reported the region to be valueless.

In 1869, Major John Wesley Powell explored 500 miles of the Colorado River system from Green River, Wyoming, to the mouth of the Virgin River within the present area of Lake Mead. Powell's studies and recommendations were the first and for many years the most significant in shaping policy and legislation for adapting the arid lands of the West to agriculture.

One of the first permanent settlements in the Upper Colorado River Basin (UCRB) was the fort built by Antoine Robidou in 1832 near the confluence of the Uinta and Duchesne Rivers. John Robertson established a trading post on Blacks Fork about 1834 and induced Jim Bridger to settle nearby along the Immigrant Trail to Oregon and later to California. Fort Bridger became an important resupply point for the Mormon pioneers in 1847 and succeeding years and for California-bound travelers following the gold discovery of 1849.

Breckenridge, Colorado, on the basin's eastern rim, was settled in 1859 by miners and prospectors pushing over the mountains from older mining districts on the eastern slope of the Continental Divide. Within the next decade, other mining camps were established nearby. Unsuccessful miners turned to farming and supplied agricultural products to the mining communities. Settlements grew downward from the mountains to the valleys, the advance being slowed somewhat by conflicts with the Indians who occupied the territory. Grand Junction, Colorado, now the largest community in the UCRB, was not settled until 1882. The greater part of the Uinta Basin in northeastern Utah was

[1] Taken from Skogerboe (1982).

established as an Indian reservation in 1881, and lands unoccupied by Indians were not open to settlement until 1905.

1.2. Indian Water Rights

During the last half of the 19th Century, the Indian conflicts had been settled in the basin and Indians were placed on reservations. Through the years, there has been considerable litigation regarding the rights of Indians under the various treaties that established these reservations.

A very famous court case was *Winters vs U.S.*, in which the court decreed:

> The Indians had command of the lands and the waters, command of all their beneficial use, whether kept for hunting, and grazing roving herds of stock, or turned to agriculture and the arts of civilization.

The Winters case, which is often referred to as the Winters Doctrine or Reservation Doctrine, is the basic law of entitlement for Indian peoples. An important consequence is that Indian water rights, to all intents and purposes, were made paramount over non-Indian water rights by this Doctrine, because nearly all Indian reservations were created prior to the diversion of waters from the rivers of the western U.S.A. by non-Indian interests.

Conceivably, the Indian reservations located in the Colorado River Basin could lay claim to a majority, if not all, of the waters in the basin. In fact, this has not been the case. However, there is litigation presently underway to provide more water for some reservations than is presently being used. More importantly, there is a real legal basis for Indians to claim much more water than they are presently utilizing.

1.3. Economic Growth

The early history of the basin has its roots in the mining industry. As has already been mentioned, the discovery of gold and other precious metals led to an influx of prospectors and miners and the establishment of numerous early settlements. Mining activity and commercial requirements of the booming populations associated with the industry attracted the early railroad development. Even the construction of the Union Pacific was partially based on the influences of gold and silver discoveries in California and Nevada in the mid-1800s. Similar discoveries in the Colorado Rockies and the desperate need for transportation to the mining camps led to the construction of a great network of railroads, mostly narrow gauge to cope with the mountain conditions. These in turn produced a demand for wood for railroad ties and bridge timbers and for fuel. Coal replaced wood as a domestic and industrial fuel source and led to the coal mining industries of Colorado, Utah and Wyoming.

In the late 1800s and early 1900s the growing populations, both within the region and in the adjacent metropolitan areas, provided an expanding coal market for heating and industrial uses. For a time coal production was of major economic importance. After World War II the substitution of gas for coal as a fuel and the adoption of diesel power on the railroads caused a major decline in coal mining. The decline in coal production was precipitous and many mines, even whole camps, and towns, were closed and abandoned. The trend has been reversed in recent years as demands increase for coal for the generation of thermoelectric power. Soaring demands for electric power have recently led to the development of strip-mining techniques and the construction of mine-mouth powerplants. These have resulted in increased coal production, but with only little recovery of coal mining employment.

Mining of molybdenum in western Colorado was started during World War I. Production grew rapidly and now about half of the free world's production is obtained from the area.

Uranium-vanadium deposits have been mined sporadically since about the turn of the century. Exploration and mining boomed during and following World War II with the development of atomic fission and the demands for atomic energy. At that time, the Government was essentially the only customer, and exploration and production were slowed when supplies exceeded the demands. Radioactive mineral deposits in the region are among the greatest known in the world today.

Production of oil and gas in the region dates from the early 1900s. Petroleum booms came with the discovery of the Rangely field in western Colorado in the 1940s and the Greater Aneth field in southeastern Utah in the late 1950s. Activity in exploration has tapered off in recent years with the drilling of many unsuccessful wildcat wells.

Timber harvesting began with the early settlers who produced lumber for home and business construction, rail ties, mine props, fuel wood and poles. During the period 1868-1905, several million railroad ties were cut for the Union Pacific Railroad. The accessibility and abundance of this forest product were major factors in the completion of the transcontinental railroad and its subsequent expansion to the early settlements of the region. In recent years, with new methods of utilization and processing, uses for the local timber resources have been greatly expanded and timber has become of major importance to the local economy. The wood is now used in the manufacture of a variety of products such as plywood, mouldings, specialty paneling, treated posts and poles, excelsior, boxes, pulp chips and matches.

Impetus to hydroelectric power generation was given by the mineral industry. The first hydroelectric development was at Aspen, Colorado, in 1885, the Ames Plant, located in the upper portion of the Dolores drainage in Colorado, was among the first hydroelectric plants to transmit alternating current at high voltage. As the region became settled and the need for electricity grew, several small hydroelectric plants were built. It was not until the 1950s that steam-electric power production had significant growth.

During World War II, a very diversified and expanding economy began to evolve in the lower Basin. Hoover Dam's power plant provided a source of plentiful electricity for industry. The yearlong climate was favorable to military training activities and the advent of air conditioning tempered the harshness of the hot summer months. Las Vegas, Nevada, with its flamboyant entertainment industry; Lake Mead, Lake Havasu and Lake Mohave on the Colorado River; and the lakes formed behind the dams on the Salt, Verde and Gila Rivers in central Arizona invited recreationists, hunters and fishermen. The affluent economy that developed during the war started a tourist influx to the arid southwest to escape the cold winter months occurring elsewhere. Light industry followed to capture a labor pool and to utilize the yearlong working environment.

Agriculture and forestry provide less than 10 per cent of the total economic output in the Colorado River Basin. Manufacturing provides less than 10 percent of the economic output in the UCRB, but more than 20 percent in the LCRB. In contrast, mining is very important in the UCRB (one-third of economic output), but only provides 10 per cent of the economic output in the LCRB. Noncommodity-producing industries, which include outdoor recreation and tourism, provide more than half of the gross economic output in the Basin.

Tremendous growth in noncommodity-producing industries is expected in the decades ahead throughout the basin. Mining activities are expected to show rapid growth in the UCRB, while manufacturing activities are expected to show significant growth in the years ahead in the LCRB.

1.4. WATER DEVELOPMENT

In the early 1900s, a series of actions were instituted, which led to interstate compacts and international treaties, State and Congressional legislation, and Supreme Court decisions, which today in aggregate constitutes the "Law of the River."

The first action comprising the Law of the River began in 1922 with the approval of the Colorado River Compact by representatives of the Colorado River Basin States. The compact appropriated the waters of the Colorado River System between the Upper and Lower Basins but did not divide the water among the States. The Boulder Canyon Project Act of 1928 approved the compact and authorized the construction of Hoover Dam and the All-American Canal System.

The Mexican Treaty of 1944 obligated the United States to deliver 1,500,000 acre-feet of Colorado River water annually to the Republic of Mexico. The Upper Colorado River Compact of 1948 divided the Upper Basin Colorado River Compact apportionments of the Colorado River for beneficial consumptive use among the Upper Basin States. This, in turn, led to the Colorado River Storage Project Act of 1956, which established an Upper Basin Development Fund and authorized the initial phase of the comprehensive Upper Basin plan of development. The hydrologic divisions used in planning is shown in Figure 1.

Today, the waters of the Colorado River are highly controlled. Major reservoir facilities have a combined storage of 65 million acre-feet (maf), which is more than four times the mean annual flow of less than 15 maf.

1.5. INTERNATIONAL RELATIONS

Before the Colorado River was controlled by Hoover Dam, its annual fluctuations from snowmelt torrents to meager later summer flows limited Mexico's ability to use Colorado River water to a maximum of about 750,000 af per year. Following completion of Hoover Dam in 1935 with regulated releases and reduction of floods, Mexico began to greatly expand its usage of Colorado River water, reaching a reported use of 1,800,000 af in 1943. A treaty was negotiated wherein the Republic of Mexico was guaranteed an annual delivery of 1,500,000 af.

Between 1945 and 1961 there were no major problems with respect to the river, as the salinity of the water delivered to Mexico at the Northerly International Boundary was generally within 100 parts per million (ppm) of the water at Imperial Dam, the last major diversion for users in the United States. In 1947, the Welton-Mohawk Project in Arizona was authorized by Congress, with construction being completed in 1952 by the U.S. Bureau of Reclamation. The project lands soon became waterlogged and a pumped drainage program was implemented to lower the water table under project lands. The wells, pumps and drainage canals were completed and began operations in 1961. The drainage water was discharged into the Colorado River below the last United States diversion, but above the Mexican diversion at Morelos Dam. It included a substantial proportion of highly saline groundwater that had been concentrated through reuse during the previous half-century. Initially, it had a salinity of around 6,000 ppm. A sharp reduction in river flows to Mexico occurred. Around the same time, due to the combined impact of the Welton-Mohawk drainage water and reduction of dilution water there was a sharp increase in the salinity of the water delivered to Mexico, (from an average of 800 ppm in 1960 to more than 1,500 ppm in 1962). Mexico raised strenuous objections to receiving the drainage waters.

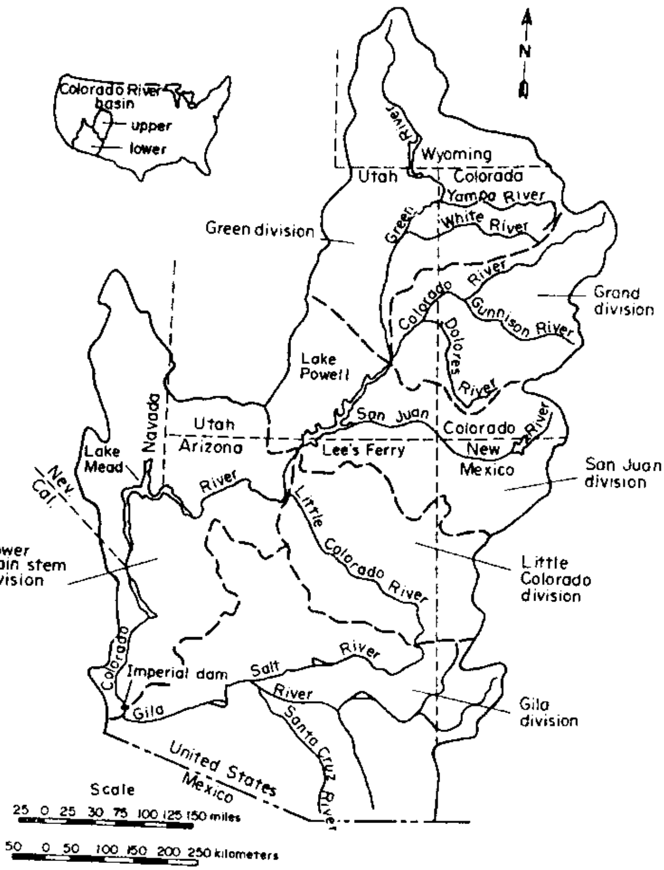


Figure 1. Hydrologic Divisions in the Colorado River Basin.

This international problem precipitated action on the part of the U.S. Government, which resulted in the passage by Congress on 24 June 1974 of the Colorado River Basin Salinity Control Act, Public Law 93-320 (PL 93-320). This act not only provides measures for alleviating the salinity problem in Mexicali Valley, but also contains numerous measures for salinity control throughout the basin in order to allow for full development of the water entitlements to each state.

1.6. Salinity Control

The water supplies of the Colorado River are the most fully utilized of any major river basin in the U.S.A. During this century, the salinity concentrations in the Lower Main Stem have been steadily increasing (Figure 2). Although the salinity problems in the Republic of Mexico (Mexicali Valley) brought international attention, salinity control measures would still be required without the international problem. In fact, the political attention focused upon solving the problems of international relations actually facilitated salinity control measures that will allow for full development of each state in the Upper Basin to their entitlement, while protecting the utility of the water supplies in the Lower Basin. However, future water development will have to be done under the constraints of salinity control.

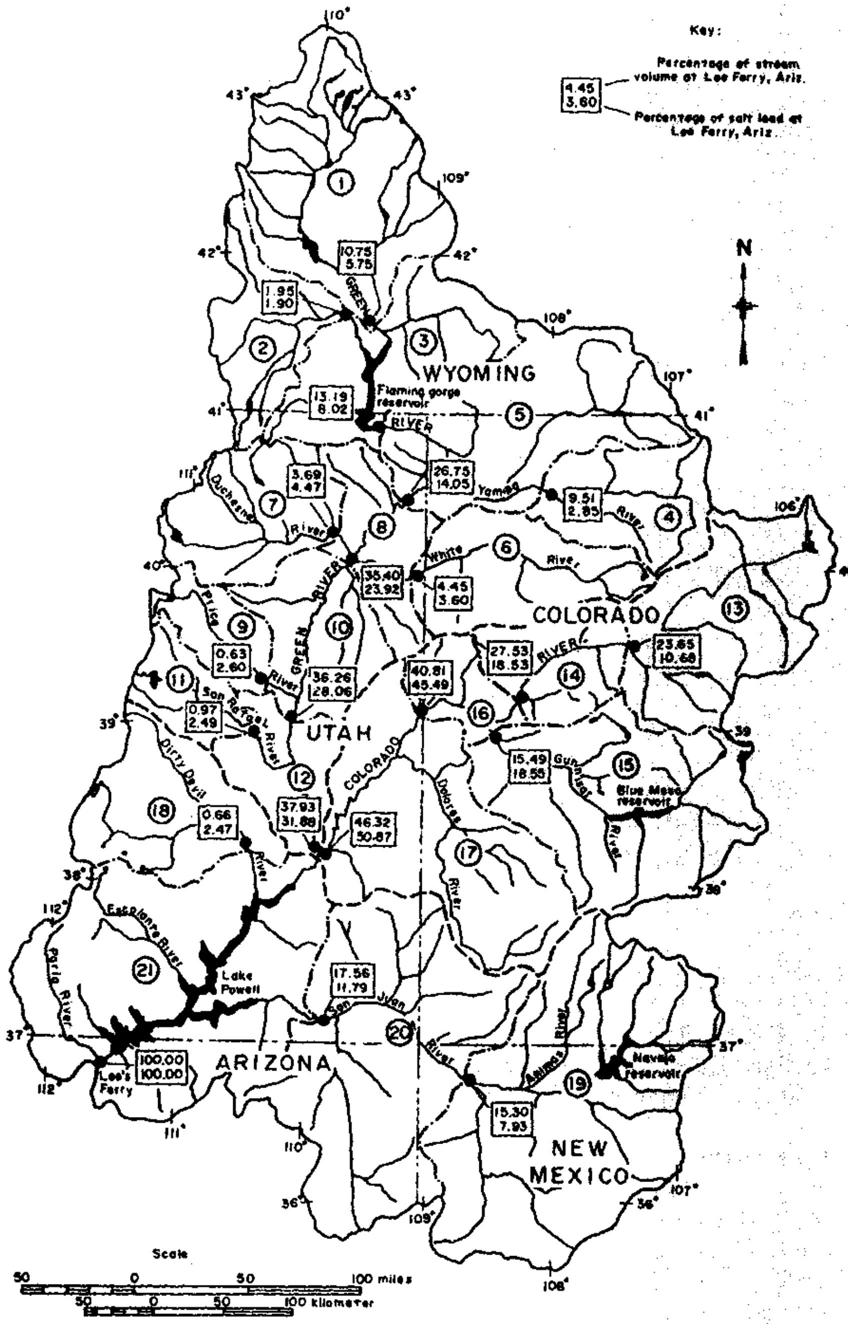


Figure 2. Map Showing the Percentage of Stream Volume and Percentage of Salt Load Passing Through the Downstream Node of Each Sub-basin as Referenced to Lee Ferry, Arizona.

Certain portions of the Upper Colorado River Basin are underlain at shallow depths by the marine-deposited Mancos Shale Formation (Figure 3), which contains considerable lenses of crystaline salts. Canal seepage and cropland deep percolation passing through the Mancos Shale will experience salt pickup. The Grand Valley in western Colorado has a salt pickup rate of 16-28 metric tons per hectare per year, which is higher than any other irrigated area in the U.S.A.

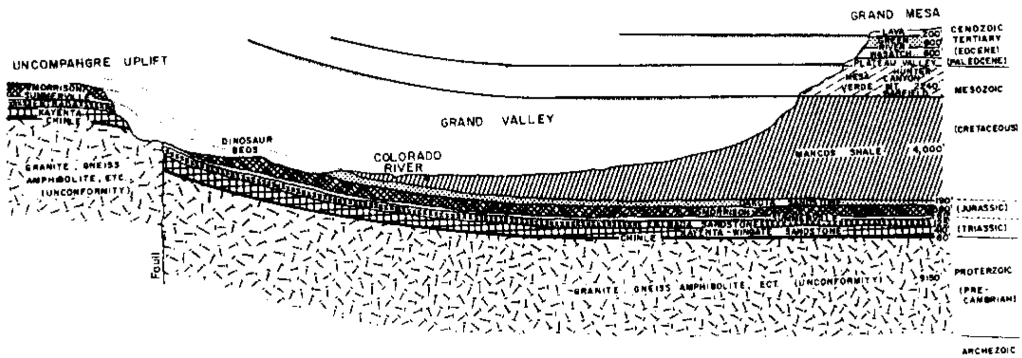


Figure 3. Geologic Cross-section of the Grand Valley.

1.7. ENERGY DEVELOPMENT

The Colorado River Basin contains a vast supply of energy resources (Figure 4.) In particular, potential energy sources consist of oil shale, coal, uranium, oil, gas, hydropower and geothermal resources. Eventual development of these resources depends upon the economics of processing each particular resource deposit. In addition, resource extraction and conversion must be compatible with environmental restraints. The actual resources ultimately developed will depend upon a complex interchange of available energy resources, water resources, economics, environmental safeguards, political intervention and private resource ownership.

The resources to be considered for large-scale commercial development with significant impact upon the water resources of the Colorado River Basin are oil shale, coal and uranium. Known reserves of both, oil and natural gas will be tapped as each field becomes economically productive. The increasing value of these resources, along with new technological developments for increasing reservoir yields, will permit recovery from deeper wells. All in all, the oil and gas fields are not expected to be a major contributor to the total energy output of the basin.

The water resources of the Colorado River Basin are already heavily utilized, so continued development of any remaining water may well demonstrate the problems of over-allocating a vital resource. Future energy developments within the Upper Basin will require large amounts of water (perhaps 1 billion m^3 by the year 2000) in addition to significantly altering the chemical quality of any remaining downstream water supplies. Several legal compacts and treaties, which regulate the flow of the Colorado River, stipulate water deliveries that the Upper Basin must make to the Lower Basin, as well as compulsory deliveries to the Republic of Mexico. A growing awareness for environmental protection will also play a significant role in determining future resource developments.

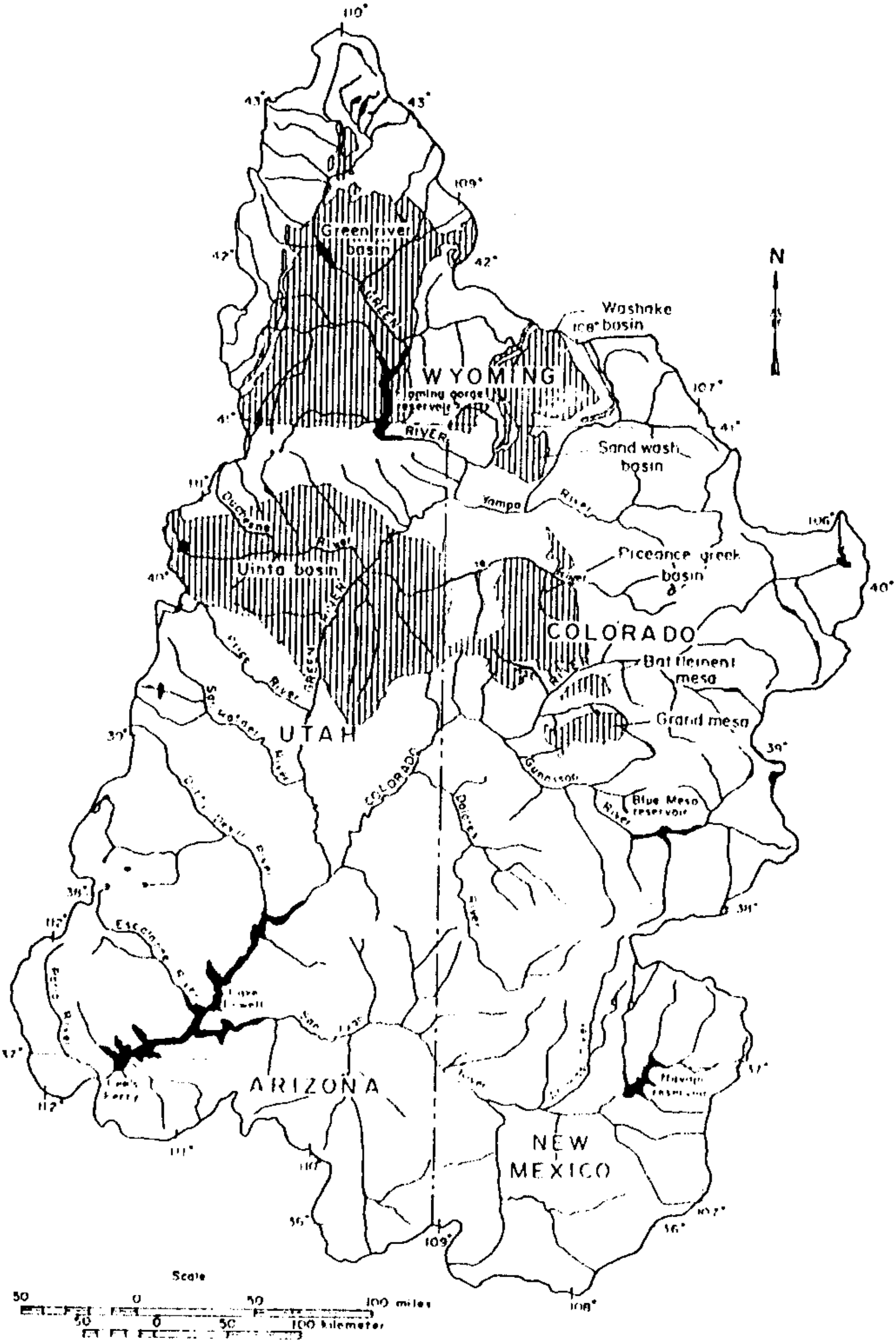


Figure 4. Energy Deposits in the Colorado River Basin.

As water availability becomes limiting for the desired level of energy output, a general shift in development from coal towards oil shale can be expected. This resource substitution tends to offset the water deficiency since shale conversion exhibits reduced water needs. Such a resource shift also implies a transfer of energy development emphasis from Wyoming and New Mexico coal fields to increased activity in the oil shale deposits of Colorado and Utah.

In the overall economic analysis of synthetic fuel developments, the cost of water supplies and water -related facilities represents a small part of the total energy cost. However, the demand for water at increased energy production levels creates a marginal value of water to the energy industry to the order of $40,000 per million liters. This value is three orders of magnitude greater than the value of irrigation water in the Upper Colorado River Basin, indicating that additional energy-related water supplies might be purchased from agricultural water supplies.

1.8. Population Projections

The present population in the UCRB is more than 400,000, but the population is projected at only 700,000 by the year 2020. In contrast, the population in the LCRB is presently about 3,000,000, which is projected to reach 7,000,000 by the year 2020. The present population in Mexicali Valley is more than 500,000, and although projections are not available, this population will likely increase to more than 1,000,000 by the year 2020.

A significant portion of the Colorado River waters are exported to southern California via the Colorado River Aqueduct to serve various municipalities, including Los Angeles and San Diego. The population of this service area is more than 9,000,000. However, if the population of southern California does increase, this will not impact the Colorado River because their water entitlement is legally fixed. Consequently, southern California is faced with having to import additional water supplies from northern California.

The population projections disclose that meeting future domestic water requirements will be particularly crucial in the LCRB, particularly the metropolitan areas of Phoenix and Tucson in Arizona and Mixicali in the Republic of Mexico. The Phoenix and Tucson areas are already seriously mining the surrounding groundwater reservoirs. Unfortunately, the construction of the multi-billion dollar Central Arizona Project, which began operating in the late 1980s, will only alleviate a portion of the present water supply problems.

1.9. Water Availability

The large reservoir capacity in the system (more than 65 maf), in comparison with the mean annual, flow provides long-term storage that allows the collection of flood flows and minimizes the impacts of drought years. The long-term estimate of mean annual virgin flow at Lee Ferry, Arizona (the dividing point on the Colorado River that separates the Upper Basin and Lower Basin) varies from 13.1 to 14.7 maf, with 13.8 maf frequently used in planning studies.

With the completion of the Central Arizona Project during the 1980s, the Lower Basin is fully utilizing their entitlement to the Colorado River. The Republic of Mexico is already utilizing their full entitlement of 1.5 maf. In contrast, the Upper Basin is presently consuming 4 maf, but the question is their full entitlement, with estimates varying from 4.2 to 7.5 maf; however, there is not sufficient water supplies to exceed roughly 5.8 maf. There are still serious questions to be answered regarding the degree of water development that will be allowed in the Upper Basin.

The population projections for the Lower Basin show that domestic water demands will increase by 1.0 maf by the year 2020. Considering that groundwater depletions exceed recharge by 2.5 maf annually, and that the Lower Basin entitlement is already nearly fully utilized, the only viable alternative appears to be the conversion of irrigation water supplies to meet domestic demands in the future.

The greatest demands for new water supplies in the Upper Basin will be the result of energy development. Since the water supplies in the Upper Basin are not fully utilized, there is considerable capacity to accommodate new energy developments. In many cases, water transfers will be made from irrigated croplands to energy complexes. However, the Upper Basin States have in the past been exporting significant portions of their entitlements to meet growing water demands in the metropolitan areas of Salt Lake City, Denver and Albuquerque. These areas are still growing very rapidly, so there will be great demands upon the system to meet competing water demands.

Finally, many of the questions regarding Indian water rights are yet unresolved. Even very reasonable demands would create serious water allocation problems throughout the basin and adjoining basins.

2. GROUNDWATER SALINITY IN THE UPPER COLORADO RIVER BASIN

2.1. GENERAL ASSESSMENT[2]

The Upper Colorado Region covers about 113,500 square miles (293,965 km^2) in parts of Arizona, Colorado, New Mexico, Utah, and Wyoming. Drainage from about 97 percent of the region is to the Colorado River. About 60 percent of the land is owned or administered by the Federal Government, and another 15 percent is in Indian trust. The predominantly arid to semiarid region is sparsely populated (averaging about three persons per square mile, or about one and one-half persons per km^2) and is used chiefly for grazing, recreation, and mineral development.

The water supply for the region comes from precipitation within the region, which averages about 95 million acre-feet (117,182.5 hm^3) per year. Development of the region's water supply has been limited almost entirely to surface water. Only about 2 percent of the total estimated volume of water withdrawn (about 5.7 million acre ft, or 7,030.9hm^3) and consumed (about 3.6 million acre-ft, or 4,440.6 km^3) in the region in 1970 came directly from groundwater sources.

By the year 2020 consumptive use of water within the region and water exports to adjacent regions are expected to total more than 6.5 million acre-feet (8,017.8 hm^3) per year. Use of the groundwater resources of the Upper Colorado Region in water-resources management can help to meet these water needs.

A tremendous amount of water is stored in the rocks (groundwater reservoirs) of the Upper Colorado Region. Recoverable water in just the upper 100 feet (30.5 m) of saturated rocks is estimated to be as much as 115 million acre-feet (141,852.5 hm^3). That amount is nearly twice the total active storage capacity of all surface-water reservoirs in the Colorado River Basin. The average annual replenishable supply of the groundwater reservoir is about 4 million acre-feet (4,934 hm^3). This amount of water could irrigate about 1.3 million acres (526,110 ha) of crops having an annual water requirement of 3 feet per acre (0.9 m/ha), or it could provide about 3,600 million gallons (13,627,440 m^3) per day for industrial use.

Most of the groundwater is in consolidated rocks, which generally yield water to wells slowly. Much of the groundwater is saline and, in some places, occurs at great depths. Nevertheless, the groundwater is more uniformly distributed than is surface water, both areally and with time; therefore, it can be used advantageously in overall water resources management. Recent advancements in the field of demineralization and in evaluation and development of groundwater make this possible.

Options available for use of groundwater in water-resources management in the region include conjunctive use with surface water or development of groundwater as an independent supply. The latter option could be for a perennial supply or for a time-limited supply (mining groundwater), depending on the need and the existing groundwater conditions. All options can be carried out so as to meet the requirements of the Colorado River Compact. The options could be implemented to optimally develop the Upper Colorado River Basin's allocation of Colorado River water while meeting the Compact commitments to the Lower Basin.

[2] Taken from Price and Arnow (1974).

2.2. Upper Colorado River[3]

As part of the U.S. Geological Survey's National Water-Quality Assessment program, analysis of the existing groundwater-quality data in the upper Colorado River study unit has been recently reported by Apodaca (1998). This report includes an analysis of the groundwater data (well and spring data) available for the upper Colorado River study unit (Figure 5) from water years 1972 to 1992 for major cations and anions, metals and selected trace elements, and nutrients. The data used in the analysis of the groundwater quality in the Upper Colorado River study unit were predominantly from the U.S. Geological Survey National Water Information System and the Colorado Department of Public Health and Environment data bases. A total of 212 sites representing alluvial aquifers (Figure 6) and 187 sites representing bedrock aquifers (Figure 7) were used in the analysis. The available data were not ideal for conducting a comprehensive basinwide water quality assessment because of lack of sufficient geographical coverage.

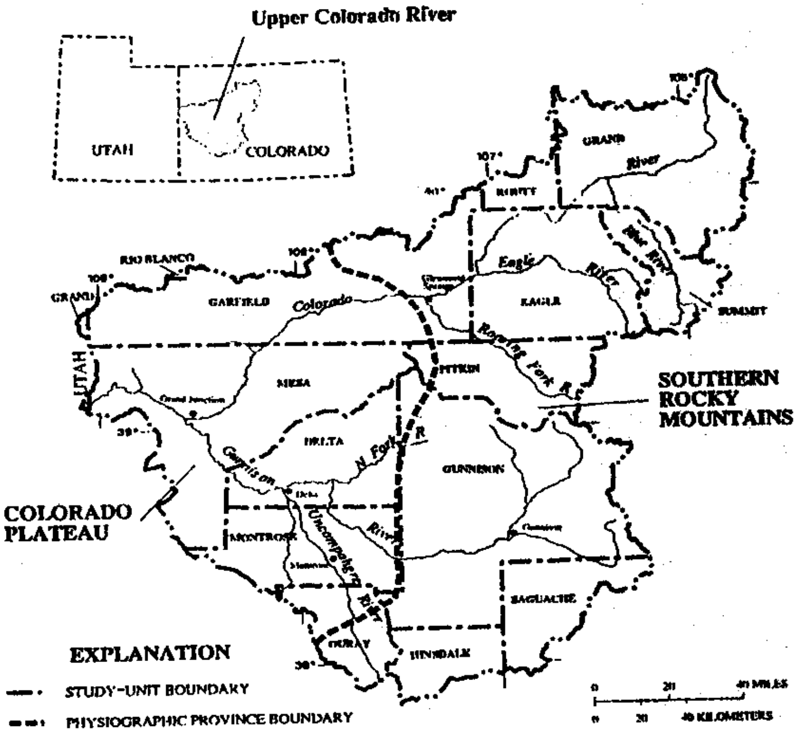


Figure 5. Location of the Upper Colorado River Study Unit and Physiographic Provinces (Gallant and others, 1989).

Evaluation of the groundwater data in the upper Colorado River study unit was based on the regional environmental setting, which describes the natural and human factors that can affect the water quality. The groundwater-quality information was evaluated by Apodaca (1998) on the basis of aquifers or potential aquifers (alluvial, Green River Formation, Measaverde Group, Mancos Shale, Dakota Sandstone, Morrison Formation, Entrada Sandstone, Leadville Limestone, and Precambrain), as shown in Figure 8 and land-use classification for alluvial aquifers.

[3] Taken from Apodaca (1998).

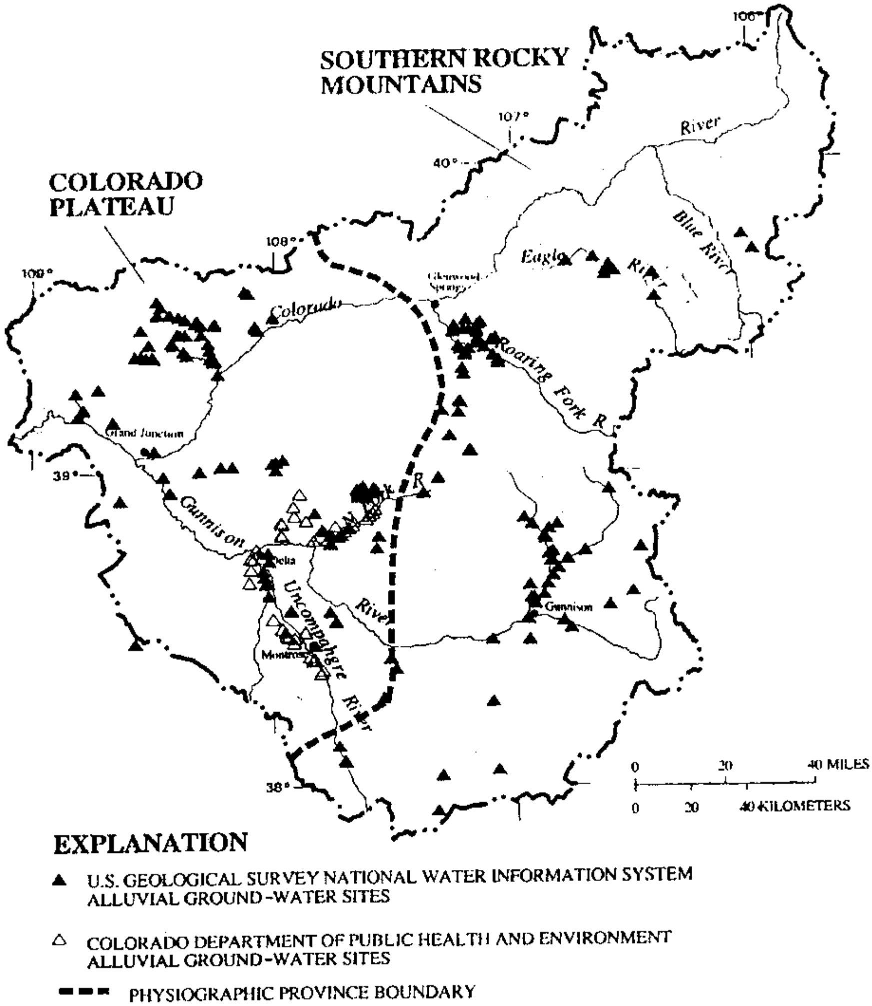


Figure 6. Locations of Selected Groundwater-quality Sites for Alluvial Aquifers in the Upper Colorado River Study Unit, Water Years 1972-92 (Apodaca 1998).

Most of the groundwater-quality data in the study unit were for major cations and anions and dissolved-solids concentrations (Tables 1 and 2). The aquifer with the highest median concentrations of major ions was the Mancos Shale. The U.S. Environmental Protection Agency secondary maximum contaminant level of 500 milligrams per liters for dissolved solids in drinking water was exceeded in about 75 percent of the samples from the Mancos Shale aquifer. The guideline by the Food and Agriculture Organization of the United Nations for irrigation water of 2,000 milligrams per liter was also exceeded by the median concentration from the Mancos Shale aquifer. For sulfate, the U.S. Environmental Protection Agency proposed that the maximum contaminant level for drinking water was exceeded by the median concentration for the Mancos Shale aquifer. A total of 66 percent of the sites in the Mancos Shale aquifer exceeded the proposed maximum contaminant level.

Metal and selected trace-element data were available for some sites, but most of these data also were below the detection limit. The median concentrations for iron for the selected aquifers and land-use classifications were below the U.S. Environmental Protection Agency secondary maximum contaminant level of 500 micrograms per liter for drinking water. Median concentration of manganese for the Mancos Shale exceeded the U.S. Environmental Protection Agency secondary maximum contaminant level of 50 micrograms per liter for drinking water. The highest selenium concentrations were in the alluvial aquifer and were associated with rangeland. However, about 22 percent of the selenium values from the Mancos Shale exceeded the U.S. Environmental Protection Agency maximum contaminant level of 50 micrograms per liter for drinking water.

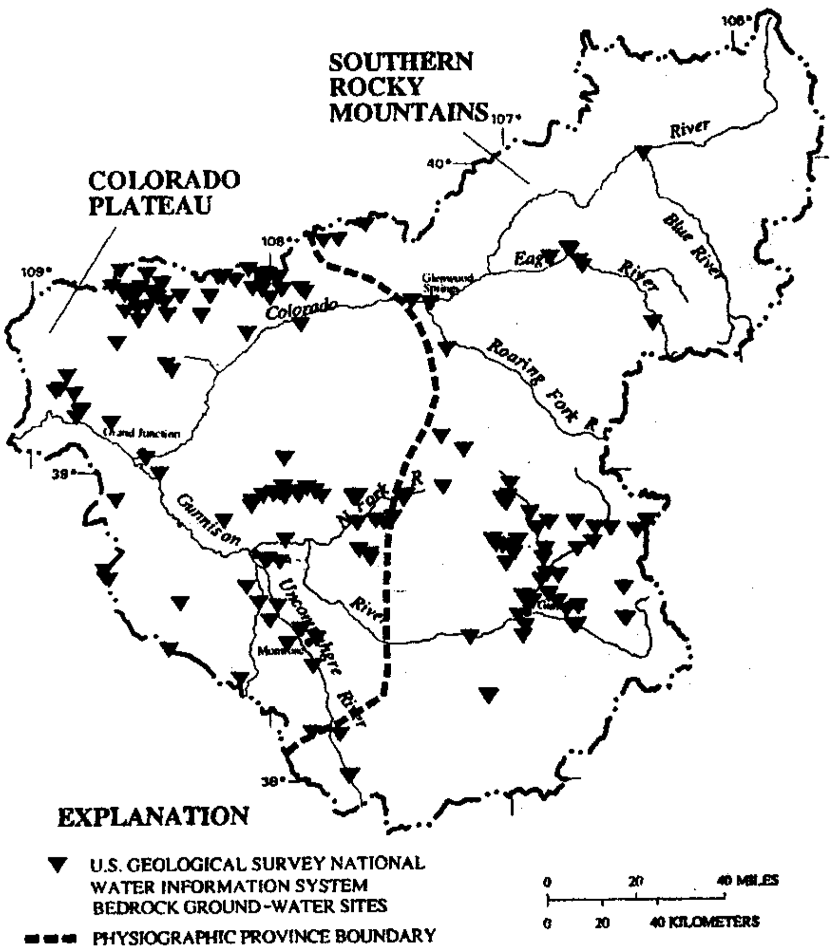


Figure 7. Locations of Selected Groundwater-quality Sites for Bedrock Aquifers in the Upper Colorado River Study Unit, Water Years 1972-92 (Apodaca 1998).

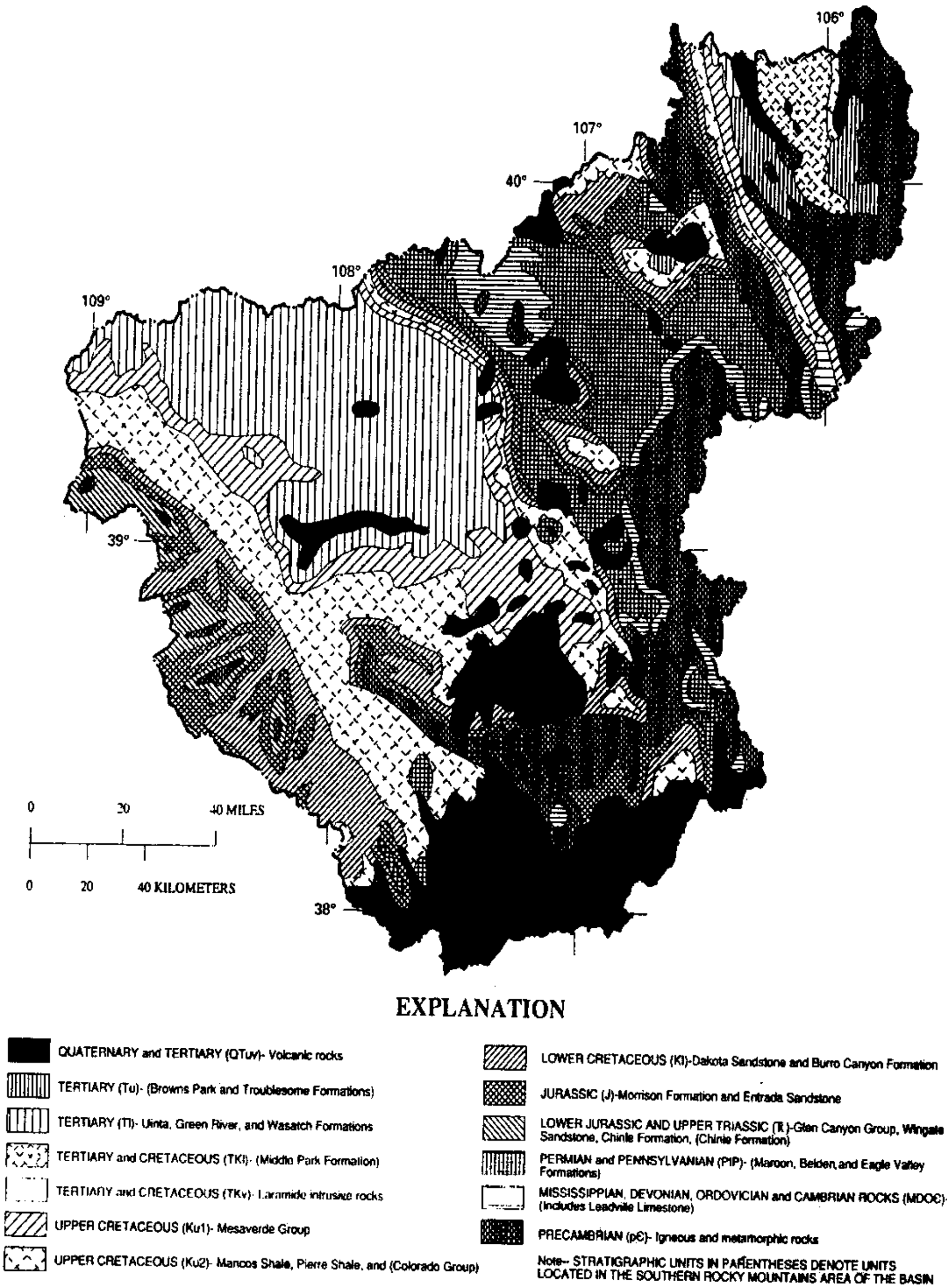


Figure 8. Generalized Bedrock Geology of the Upper Colorado River Study Unit (modified from Schruben and others, 1994; Tweto, 1979).

Table 1. Statistical Summary of Groundwater-quality Data for Selected Sites in the Upper Colorado River Study Unit by Aquifer, Water Years 1972-92 (Apodaca, 1998).

[Number in parentheses adjacent to the water-quality property or constituent is the data parameter code from the U.S. Geological Survey National Water Information System (NWIS); ----, no data < less than]

Aquifer	Number of Analyses	Value at Indicated Percentile				
		19th	25th	50th (median)	75th	90th
Specific Conductance, in Microsiemens Per centimeter at 25 Degreed Celsuis (00095)						
Alluvium	212	202	385	677	1,365	3,248
Green River Formation	53	498	573	658	902	1,267
Maesaverde Group	34	323	426	904	1,480	3,861
Mancos Shale	32	214	495	3.110	5,178	7,779
Dakota Sandstone	29	196	314	469	1,650	3,076
Morrison Formation	7	434	445	584	1,283	1,432
Entrada Sandstone	5	290	365	450	554	---
Leadville Limestone	11	201	338	744	1,775	13,540
Precambrian	15	50	96	206	461	650
Dissolved Solids, in Milligrams Per Liter (70301)						
Alluvium	197	119	246	474	1,085	2,932
Green River Formation	53	294	357	412	569	846
Maesaverde Group	33	188	232	568	857	2,302
Mancos Shale	33	192	488	3.745	5,235	7,644
Dakota Sandstone	29	114	202	331	1,083	2,300
Morrison Formation	7	244	245	350	779	908
Entrada Sandstone	5	169	207	219	298	---
Leadville Limestone	11	121	187	470	1,528	7,988
Precambrian	15	30	62	142	284	398
Sulfate, Dissolved as SO4, in Milligrams Per Liter (00945)						
Alluvium	212	7.4	22	110	438	1,513
Green River Formation	53	20	32	75	123	328
Maesaverde Group	34	2.6	5.7	22	98	183
Mancos Shale	33	23	152	2.300	3,438	4,790
Dakota Sandstone	29	6.8	13	69	140	452
Morrison Formation	7	1.0	6.8	43	101	204
Entrada Sandstone	5	20	36	43	52	---
Leadville Limestone	11	5.0	5.1	93	881	950
Precambrian	15	3.7	4.8	7.2	13	32

Few nutrient data were available for the study unit. The only nutrient species presented in this report were nitrate-plus-nitrite, as nitrogen and orthophosphate. Median concentrations for nitrate-plus-nitrate as nitrogen were below the U.S. Environmental Protection Agency maximum contaminant level of 10 milligrams per liter in drinking water, except for 0.02 percent of the sites in the alluvial aquifer and 0,03 percent of the sites in the Mancos Shale. Concentrations of orthophosphate did not vary significantly among aquifers or land-use classifications.

Historic water-quality data from wells and springs helped to characterize the regional distribution of groundwater quality information in the Upper Colorado River study unit. The historical groundwater data summarized by Apodaca (1998) will be used in the design of a groundwater-quality network.

About 85 percent of the land use in the study unit is designated as rangeland or forest. Agriculture (crops and livestock) and mining (mineral and energy) traditionally have been the most important economic activities in the study unit. A majority of the metal mining in the basin is located in the forested areas. However, the economy in the study unit has been greatly enhanced by tourism, which is a year-round activity. Urban and built-up land use is one of the smaller land uses in the study unit.

Population in 1990 in the study unit was about 234,000 and predominantly was located in rural communities (Bureau of Census, 1990). The largest population center is near Grand Junction, Colorado in the western part of the study unit.

Table 2. Statistical Summary of Groundwater-quality Data for Selected Sites in the Upper Colorado River Study Unit by Land-use Classification, Water Years 1972-92 (Apodaca, 1998).

[Number in parentheses adjacent to the water-quality property or constituent is the data parameter code from the U.S. Geological Survey National Water Information System (NWIS); ----, no data < less than]

Land use (Anderson and others, 1976)	Number of Analyses	Value at Indicated Percentile				
		19th	25th	50th (median)	75th	90th
Specific Conductance, in Microsiemens Per centimeter at 25 Degrees Celsius (00095)						
Agricultural	91	419	613	925	2,269	3,689
Forest	34	98	219	374	940	1,718
Rangeland	61	157	289	631	1,235	2,851
Urban and Built-up	20	175	380	535	795	2,196
Dissolved Solids, in Milligrams Per Liter (70301)						
Agricultural	82	252	384	684	2,280	3,578
Forest	32	70	122	251	649	1,234
Rangeland	59	99	187	394	896	2,174
Urban and Built-up	18	118	254	310	671	2,040

Water used in the study unit is predominantly surface water. Groundwater sources accounted for less than 1 percent of the water used (D.W. Litke, U.S. Geological Survey, written commun., 1995). The principal water use in the study unit is for irrigation, which accounts for about 97 percent of the offstream water use. The remaining 3 percent includes, in order of decreasing water use: livestock, domestic, power, industrial commercial, and mining. Estimated offsream water use in the study unit during 1990 totaled about 3,500 Mgal/d (D.W. Litke, U.S. Geological Survey, written commun., 1995).

2.3. Southeastern Uinta Basin[4]

2.3.1. Physical Setting

The southeastern Uinta Basin has an area of approximately 3,000 square miles in Utah and Colorado (Figure 9). The White River and Willow Creek tributaries of the Green River, drain most of the area. These drainages intersect a broad plateau to form benchlike mesas. The altitude of the land surface at its lowest point in the study area, on the Green River in Desolation Canyon, is about 4,600 feet above the National Geodetic Vertical Datum of 1929. The land surface gently rises to the south, reaching a maximum altitude of about 9,500 feet in the Roan Cliffs at the southern edge of the study area. Willow Creek and the tributaries of the White River trend northerly, forming steep-walled canyons 500 to 1,000 feet deep and as much as 5,500 feet wide, making travel difficult throughout the area.

The Uinta Basin contains a thick sequence of sedimentary rocks ranging in age from Precambrian to Tertiary. The rocks that are exposed in the Southeastern Uinta Basin have been described by Cashion (1967). The lithologic and water-bearing properties of the geologic units exposed in the study area are summarized in Table 3. The Tertiary rocks were deposited in a lake that were conveyed by the rivers that flowed into the Uinta Lake.

[4] Taken from Holmes and Kimball (1987).

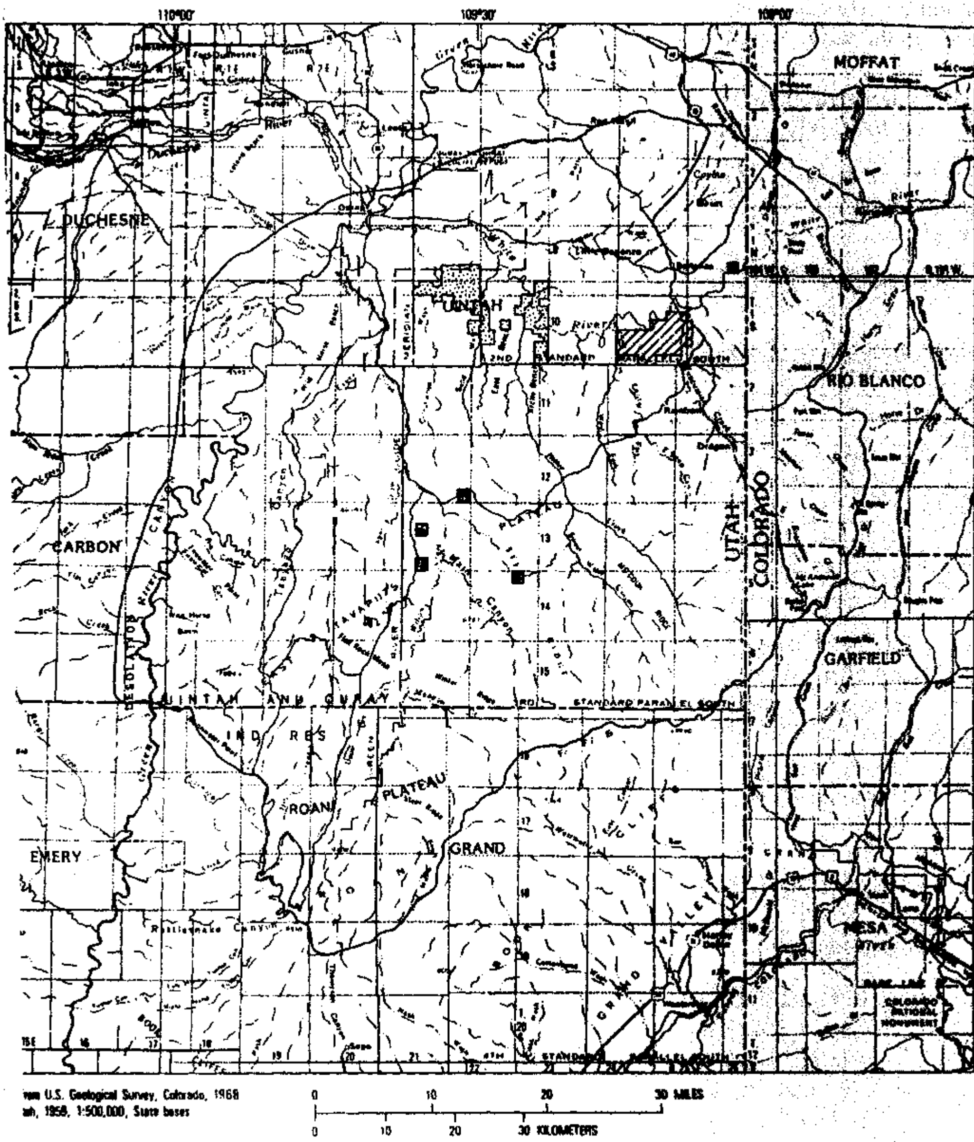


Figure 9. Location of Southeastern Uinta Basin Study Area.

Table 3. General Lithologic Character and Water-bearing Properties of Exposed Geologic Units (Holmes and Kimball, 1987).

Geologic Age	Geologic Unit	Thickness (feet)	Lithologic Character	General Water-bearing Properties
Quaternary	Unconsolidated alluvial deposits	0-150	Alluvium, fluvial deposits. Clays, silt, sand, and some gravel. Caliche always found near water table. Clays predominantly illite and illite-smectite.	Yield less than 1,000 gallons per minute. Locally saturated in major drainages, with slow movement of water.
	Uinta Formation	0.5,000	Fluvial deposits of mostly thinly-bedded siltstone, and fine-grained sandstone. Some beds of volcanic tuff cut in several places by gilsonite veins.	Not water-bearing in many areas where deeply incised by streams. Commonly yields less than 5 gallons per minute to springs.
	Parachute Creek Member of the Green River Formation	500-1,200	Lacustrine deposits of thinly-bedded claystone, siltstone (both called marlstone), fine-grained sandstone, limestone and some tuff. Contains prominent oil-shale deposits. Clays are illite and trioctahedral smectite,. Local cavities of evaporite minerals, mainly naheolite. Laterally continuous.	Overall permeability is minimal. Springs generally yield less than 10 gallons per minute. Wells associated with fractures may yield as much as 5,000 gallons per minute, according to model simulation. Contains bird's-nest aquifer locally. Equivalent to the bird's-nest zone of Cashion (1967).
Tertiary	Douglas Creek Member of the Green River Formation	200-1,300	Predominantly marginal lacustrine deposits of claystone, siltstone (marlstone), fine-grained sandstone, and limestone. Six tongues have been identified by Cashion (1967, P. 6-7). Clays mostly smectite and illite. Channel-form sandstone common. Beds commonly are discontinuous.	Permeability varies. Springs yielding as much as 50 gallons per minute discharge from sandstone. Contains several water-yielding beds that are part of the Douglas Creek aquifer, which yields 40-500 gallons per minute to wells.
	Renegade Tongue of the Wasatch Formation	0-1,000	Fluvial deposits of massive, irregularly-bedded sandstone and red and gray siltstone inter-tonguing with Douglas Creek Member of Green River Formation. Clays are smectite, illite, mixed layer chlorite and kaolinite.	More permeable than Green River Formation. Springs yield as much as 200 gallons per minute. Constitutes part of the Douglas Creek aquifer.

During the Eocene Epoch, Lake Uinta increased in size and finally receded, leaving a lens of lacustrine deposits surrounded by fluvial deposits. The lake changed in size and shape many times; and as a result, the lacustrine deposits also interfinger with the fluvial deposits. This interfingering between the lacustrine Green River Formation and the fluvial Wasatch Formation is shown in Figure 10.

The fluvial and much of the fluvial-deltaic environments are represented by the Wasatch Formation, particularly the Renegade Tongue, shown in Figure 10. The rocks of the Renegade Tongue are mostly massive channel-filling sandstone and siltstone from the river flood plains. These rocks reach a maximum thickness of 1,000 feet at the southern boundary of the study area, they thin to less than 100 feet in the vicinity of Bitter Creek, and they disappear to the north. The lacustrine-deltaic environment and some of the fluvial-deltaic environments are represented by the Douglas Creek Member of the Green River Formation and parts of the Parachute Creek Member of the Green River Formation, which consist of sandstone, marlstone (siltstone and claystone), and algal and oolitic limestone. The lacustrine deep-water environment is represented mostly by the Parachute Creek Member, whose beds are marlstone, sandstone, and muddy limestone. The marlstone, which has a large magnesium content and in many places has a large organic content, comprised the "oil shale" of the Green River Formation.

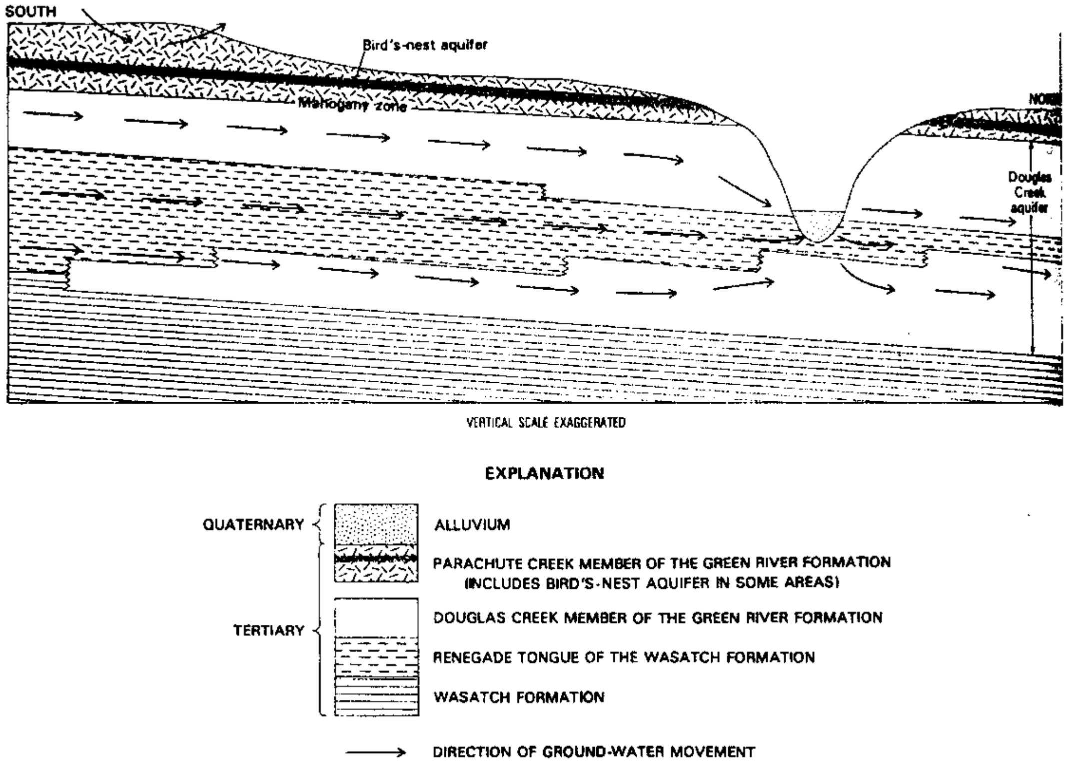


Figure 10. Diagrammatic Geohydrologic Section of Part of the Southeastern Uinta Basin Showing the Direction of Groundwater Movement. (Geology adapted from Cashion, 1967).

After the deposition of organic-rich marlstone, Lake Uinta began to recede. The water became saline, and local deposition of evaporite minerals occurred. As the area of the lake decreased, fluvial deposits were laid down where the lake had previously been. These fluvial deposits belong to the Uinta Formation of Tertiary age. The siltstone, sandstone, and tuff that it contains are exposed in a large area near the White River.

Deposits of Quaternary alluvium are present along almost every drainage in the study area. In some of the larger drainages, these deposits are more than 100 feet thick. They consist of material derived from the nearby Tertiary rocks, ranging in size from clay to gravel.

Groundwater in the southeastern Uinta Basin occurs in three major aquifers. Alluvial aquifers of small areal event are present in valley-fill deposits of six major drainages. Consolidated-rock aquifers include the Birds's-Nest Aquifer in the Parachute Creek Member of the Green River Formation, which is limited to the central part of the study area; and the Douglas Creek Aquifer, which includes parts of the Douglas Creek Member of the Green River Formation and parts of the intertonguing Renegade Tongue of the Wasatch Formation; this aquifer underlies most of the study area.

2.3.2. Alluvial Aquifers

The alluvial aquifers are recharged by infiltration of streamflow and leakage from consolidated-rock aquifers. Recharge is estimated to average about 32,000 acre-feet per year. Discharge from alluvial aquifers, primarily by evapotranspiration, also averages about 32,000 acre feet per year. The estimated volume of recoverable water in storage in alluvial aquifers is about 200,000 acre-feet (Table 4). Maximum yields for individual wells are less than 1,000 gallons per minute.

Table 4. Summary of Estimated Groundwater Storage and Recoverable Water in Storage in Alluvial Aquifers (Holmes and Kimball 1987).

Drainage Basin	Area of saturated alluvial deposits (acres)	Average thickness of saturated alluvial deposits (feet)	Volume of saturated alluvial deposits (acre-feet)	Estimated average porosity (percent)	Estimated specific yield	Volume of water in storage (acre-feet)	Volume of recoverable water in storage (acre-feet)
Bitter Creek	4,300	40	172,000	50	0.05	86,000	8,600
Evacuation Creek	1,800	21	37,800	40	.05	15,100	1,890
Green River	9,200	30	276,000	30	.20	82,800	55,200
Hill Creek	7,400	88	651,000	30	.10	195,000	65,100
White River	6,100	32	195,000	30	.20	58,500	39,000
Willow Creek	9,600	62	595,000	40	.05	238,000	29,800
Total (rounded)	38,000		1,900,000			675,000	200,000

2.3.3. Bird's – Nest Aquifer

Recharge to the Bird's-Nest Aquifer, primarily from stream infiltration and downward leakage from the overlying Uinta Formation, is estimated to average 670 acre-feet per year. Discharge from the Bird's-Nest Aquifer, which is primarily by seepage to Bitter Creek and the White River, is estimated to be at 670 acre-feet per year. The estimated volume of recoverable water in storage in the Bird's-Nest Aquifer is 1.9 million acre-feet. Maximum yields to individual wells in some areas may be as much as 5,000 gallons per minute.

A digital computer model of the flow system was used to evaluate the effects of oil-shale development on the Bird's-Nest Aquifer. Results of model simulations indicate that during construction of a vertical access shaft, a pumping rate of about 900 gallons per minute would be required to dewater the aquifer. The model also indicates that the construction of a proposed reservoir on the White River may raise water levels in the Bird's-Nest Aquifer near the reservoir site by as much as 5 feet.

The flow model was used to evaluate the potential groundwater supply available for oil-shale development. The results of the simulation indicate the Bird's-Nest Aquifer could supply about 10,000 acre-feet of water per year at that site, for a period of 20 years. Downdraw after 20 years of pumping would exceed 250 feet near the simulated well field. Based on the results of the model simulation, it is estimated that the aquifer could simultaneously supply another 10,000 acre-feet of water per year in the northern part of the study area, but some interference between well fields could be expected.

2.3.4. Douglas Creek Aquifer

The Douglas Creek Aquifer is recharged by precipitation and stream infiltration at an average rate of about 20,000 acre-feet per year. Discharge is estimated to be about the same and is primarily through springs and diffuse seepage. The estimated volume of recoverable water in storage is 16 million acre-feet. Maximum yields to individual wells are estimated to be less than 500 gallons per minute.

A model of the flow system in the Douglas Creek Aquifer indicates that the aquifer could supply about 700 acre-feet of water per year for oil-shale development. After 20 years of pumping, water levels in production wells would be near the base of the aquifer. Based on the results of the model simulation, it is estimated that the aquifer could supply another 700 acre-feet of water per year in the southern part of the modeled area, but some interference between wells could be expected.

2.3.5. Summary of Groundwater Salinity

Chemical quality of the groundwater in the Southeastern Uinta Basin varies considerably. Water from alluvial wells ranges from about 440 to 27,800 milligrams per liter of dissolved solids (Table 5a). Water from two consolidated-rock aquifers has dissolved-solids concentrations ranging from 870 to 5,810 milligrams per liter in the Bird's-Nest Aquifer (Table 5b), and from 640 to 6,100 milligrams per liter in the Douglas Creek Aquifer (Table 5c).Water from alluvial wells generally is a sodium sulfate-type, whereas water in both the consolidated-rock aquifers generally changes from a sodium sulfate-type to a sodium bicarbonate-type. All groundwater is very alkaline, and the alluvial aquifers contain very hard water. None of the water is suitable for public supply, but all the water could be used for industrial purposes, such as washing and cooling.

Changes in chemical composition of the groundwater can be attributed to several physiochemical processes, including mineral precipitation and dissolution, oxidation and reduction, mixing, ion exchange, and evaporative concentration. Mass-transfer modeling of these processes shows how they can account for the variability in the groundwater quality. The mass-transfer model of the Bitter creek alluvial aquifer shows that evaporative concentration, combined with precipitation of calcite, dolomite, gypsum, and release of carbon dioxide to the atmosphere, results in the documented changes in the pH and dissolved solids in the water. The water-quality changes in the consolidated-rock aquifers are a result of precipitation of calcium carbonate and perhaps dolomite (calcium magnesium carbonate) with the reduction of sulfate by organic carbon, as well as ion exchange of magnesium for sodium. These processes result in large values of pH and alkalinity in the water.

2.4. COLORADO PLATEAU[5]

2.4.1. General Description

Large supplies of groundwater that range from fresh to briny occur in aquifers in rocks of Paleozoic age throughout southeastern Utah and adjacent parts of Arizona, Colorado, and New Mexico (Figure 11). The discovery of these large supplies was an indirect result of the search for oil, gas, and sites for nuclear-waste repositories. The Paradox Basin (Figure 12) was the location of extensive drilling in search of oil and gas; also, it is being considered as a site for a nuclear-waste repository. Beneath some of the salt deposits is an areally extensive brine.

A study was developed to simulate regional groundwater flow in aquifers in Paleozoic rocks as part of the Upper Colorado River Basin Regional Aquifer-System Analysis (UCRB-RASA). These aquifers were selected for study because they contain large supplies of freshwater and because sufficient data exist for the development of a regional groundwater flow model. The study area was selected because it represents a somewhat hydrologically isolated regional groundwater system. An additional objective of the study was to analyze the flow of brine (Weiss, 1986).

[5] Taken from Weiss (1986) and Weiss (1989).

Table 5. Summary of Chemical Quality of Groundwater in Southeastern Uinta Basin (Holmes and Kimball, 1987).

Table 5a. Alluvial Aquifers.

Variable	White River alluvial aquifer			Evacuation Creek alluvial aquifer			Bitter Creek alluvial aquifer			Willow and Hill creek alluvial aquifers			Other alluvial aquifers (Coyote Wash, Cottonwood Wash, Hells Hole Canyon, Red Wash, and Southam Canyon)		
	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum
Water temperature (degreed Celsius)	13	10.9	8.5-13.5	12	11.2	7.5-180	29	10.8	7.0-16.5	18	11.1	6.0-14.0	88	12.0	6.0-32.0
Specific conductance (micromhos cm)	12	3.422	2.500-4.400	12	4.507	4.060-4.810	29	10.200	1.700-21.000	18	5.963	940-10.250	89	2.836	680-7.250
pH (log units)	11	7.7[1]	7.4-8.0	12	7.7[1]	7.4-8.2	28	7.7[1]	7.2-8.1	18	7.9[1]	7.2-8.3	70	[1]8.2	7.3-10.0
Dissolved solids (calculated), mg/l	13	2.738	1.765-3.654	12	3.615	3.130-3.900	29	10.645	3.056-27.795	19	4.730	660-8.654	78	2.408	435-6,672

[1]Geometric mean.

Table 5b. Bird's-Nest Aquifer.

Variable	Northeast			Southwest		
	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum
Water temperature (degrees Celsius) -	41	13.5	10.0-19.0	36	16.3	13.0-19.5
Specific conductance (micromhos/cm at 25 °C)	44	4.772	1.130-6,900	36	2.542	1.270-460
pH (log units)	40	[1]7.8	7.2-8.4	38	[1]8.9	7.4-10.7
Dissolved solids (calculated), mg/l	44	3.817	438-5.812	37	1,583	869-3.217

[1]Geometric mean.

Table 5c. Douglas Creek Aquifer.

Variable	Southern part of the aquifer			Central part of the aquifer			Northern part of the aquifer		
	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum	Number of samples	Mean	Minimum maximum
Water temperature (degrees Celsius)	4	19.1	16.5-22.0	6	25.5	22.0-28.0	3	23.3	17.0-31.0
Specific conductance (micromhos/cm)	4	1.070	940-1.300	5	1.670	1.350-1.770	3	2.287	1.600-3.250
pH (log units)	3	[1]8.2	7.2-8.8	6	[1]8.7	8.5-9.0	3	[1]8.4	7.8-8.7
Dissolved solids (calculated), mg/l	4	785	640-950	5	1.060	900-1.120	3	1.450	1.000-1.980

1Geometric mean.

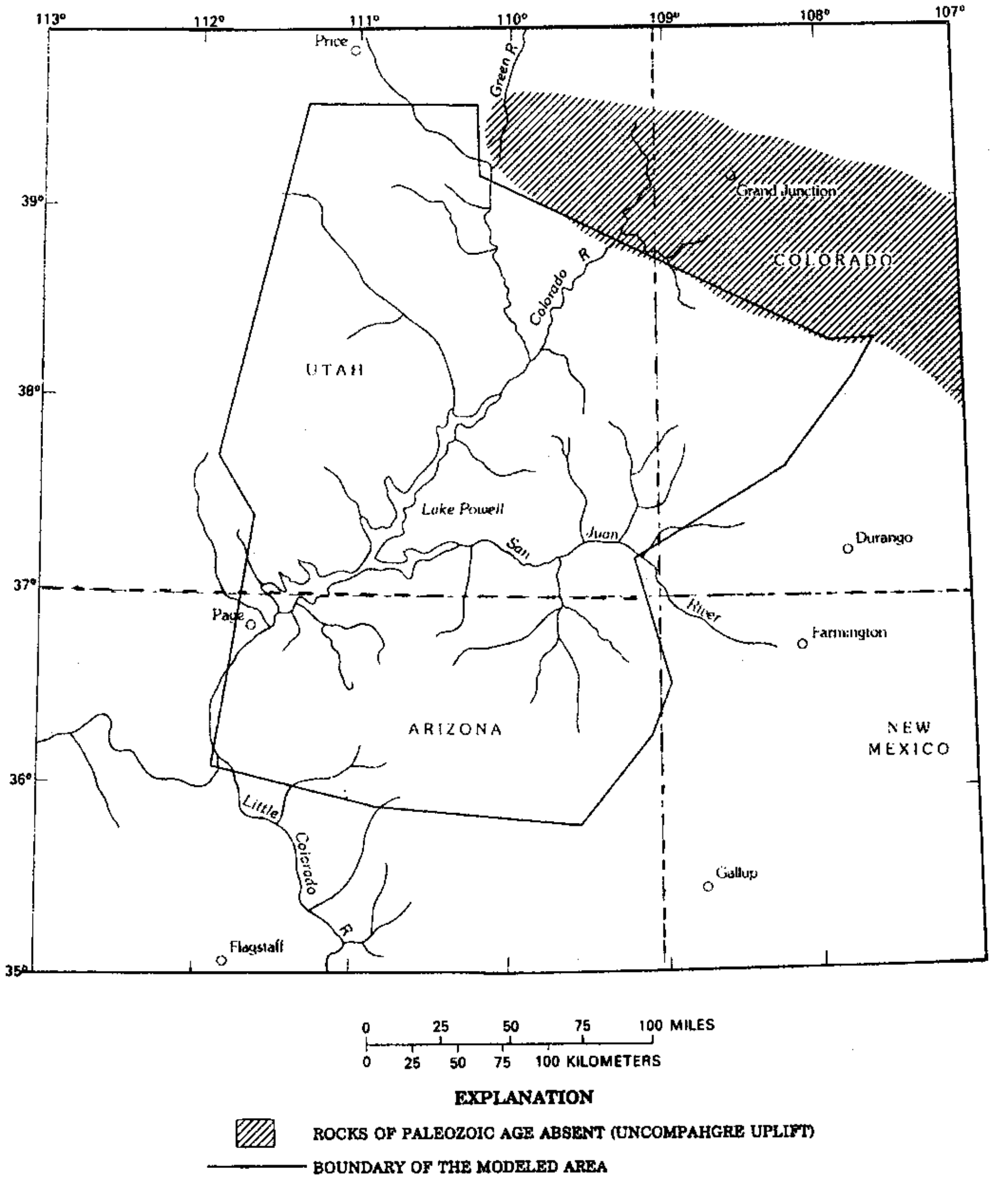
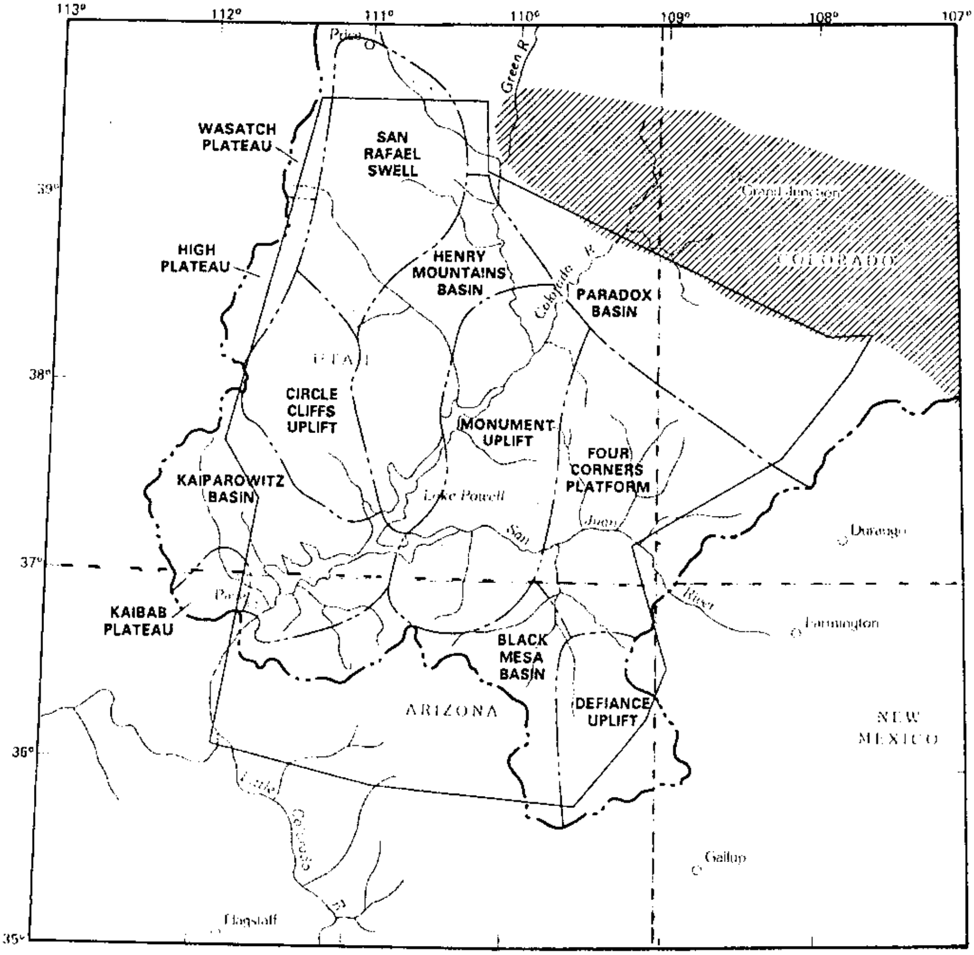


Figure 11. Location of Colorado Plateau Study Area (Weiss, 1989).

2.4.2. Groundwater Model Area

A groundwater flow system in Paleozoic rocks that includes part of the Upper and Lower Colorado River Basins and that is somewhat hydrologically isolated was defined as the system to be modeled. The modeled area is about 60,000 mi^2 in southeastern Utah and adjacent parts of Arizona, Colorado, and New Mexico. Relatively small quantities of groundwater are used for municipal, mining, and irrigation in this sparsely populated area (Weiss, 1989).



Modified from Lindner-Lunsford and others (1989)

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

EXPLANATION

- ROCKS OF PALEOZOIC AGE ABSENT (UNCOMPAHGRE UPLIFT)
- SOUTHERN UPPER COLORADO RIVER BASIN BOUNDARY
- BOUNDARY OF THE MODELED AREA
- BOUNDARY OF TECTONIC FEATURES IN UPPER COLORADO RIVER BASIN

Figure 12. Principal Tectonic Features of the Colorado Plateau Modeled Area (Weiss, 1989).

The modeled area extends from the Paleozoic outcrops of the Mogollon slope in the south to the Precambrian ancestral Uncompahgre Uplift in the north. In the west, the modeled area is bounded by the Kaibab, High, and Wasatch Plateaus, and, in the east, the modeled area is bounded by the Paleozoic outcrops of the Defiance and San Juan Uplifts (Figure 12).

The climate ranges from arid at the lower altitudes, where annual precipitation is 6 in. or less, to semiarid at the middle altitudes, where annual precipitation ranges from 8 to 11 in. In some small areas of the high plateaus, annual precipitation is as much as 20 in.; in smaller areas of the mountains, annual precipitation can exceed 30 in.

The high plateaus and mountains are the principal recharge areas for the aquifers in Paleozoic rocks. At low altitudes, many stream channels are deep canyons that cut into the Paleozoic rocks. Many of these canyons are discharge areas for aquifers. The Colorado, Green, and the San Juan River channels are principal drainages for the surface and groundwater systems (Figure 11). Canyonlands National Park around the confluence of the Green and Colorado Rivers illustrates the prevalence of canyons in the modeled area.

2.4.3. Modeled Geohydrologic Units

All of the modeled aquifers (Table 6) and the intervening confining unit extend over the entire modeled area. The sandstone and red-bed aquifer consists of all Permian rocks plus the Rico Formation of Early Permian and Late Pennsylvanian age, and Honaker Trail Formation of Late Pennsylvanian age. The aquifer primarily consists of sandstone and shale, but generally consists of extremely variable lithology.

Table 6. Modeled Geohydrologic Units Related to Time-stratigraphic Units (Weiss, 1989).

Erathem	System	Series	Modeled Unit
PALEOZOIC	Permian	Upper	Sandstone and red-bed aquifer
		Lower	
	Pennsylvanian	Upper	
		Middle	Confining unit not modeled
		Lower	
	Mississippian	Upper	Limestone and dolomite aquifer
		Lower	
	Devonian	Upper	

In the Henry Mountains Basin and the northern Monument Uplift areas (Figure 12), the Organ Rock Member of the Cutler Formation, a shale bed of Early Permian age functions as a confining unit between aquifers within the sandstone and red-bed aquifer. A more detailed study of the groundwater system probably would simulate the Organ Rock Member as a confining unit.

The other Pennsylvanian rock is defined as the middle confining unit of the geohydrologic system listed in Table 6. The confining unit consists primarily of shale and evaporite rocks. The shale beds are areally extensive throughout most of the modeled area and could contain osmotic-pressure gradients that would affect flow through them.

Throughout most of the Paradox Basin (Figure 12), the confining unit contains thin layers of black shales that have large quantities of organic debris interbedded with evaporite beds. The shale layers occur at vertical intervals of 100 to 300 ft (Baars, 1983, p. 70). Large evaporite salt deposits (predominantly halite) and associated diapirs characterize the confining unit in the Paradox Basin. About one-half of the modeled area is covered by these salt deposits.

2.4.4. Recharge and Discharge Areas

Outcrop areas and location of wells completed in the two aquifers are shown in Figures 13 and 14. Mean annual precipitation on outcrops also is shown in Figure 13. Outcrops around the boundaries of the modeled area are potential recharge areas; canyons near the center of the modeled area are areas with potentially substantial discharge (Weiss, 1989).

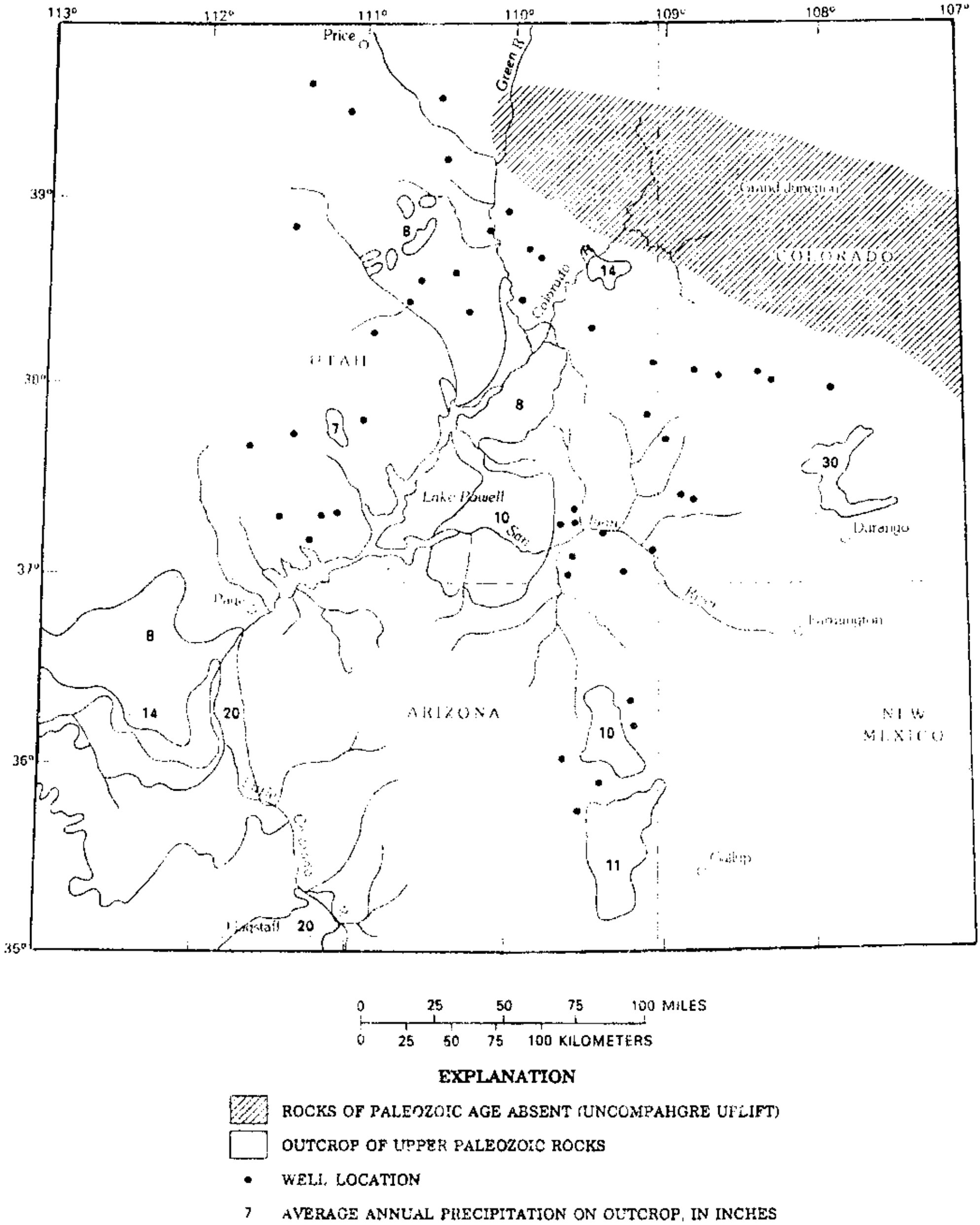


Figure 13. Outcrop Areas of the Sandstone and Red-bed Aquifer, Mean Annual Precipitation on Outcrops, and Location of Wells Completed in the Sandstone and Red-bed Aquifer (modified from Weiss, 1987).

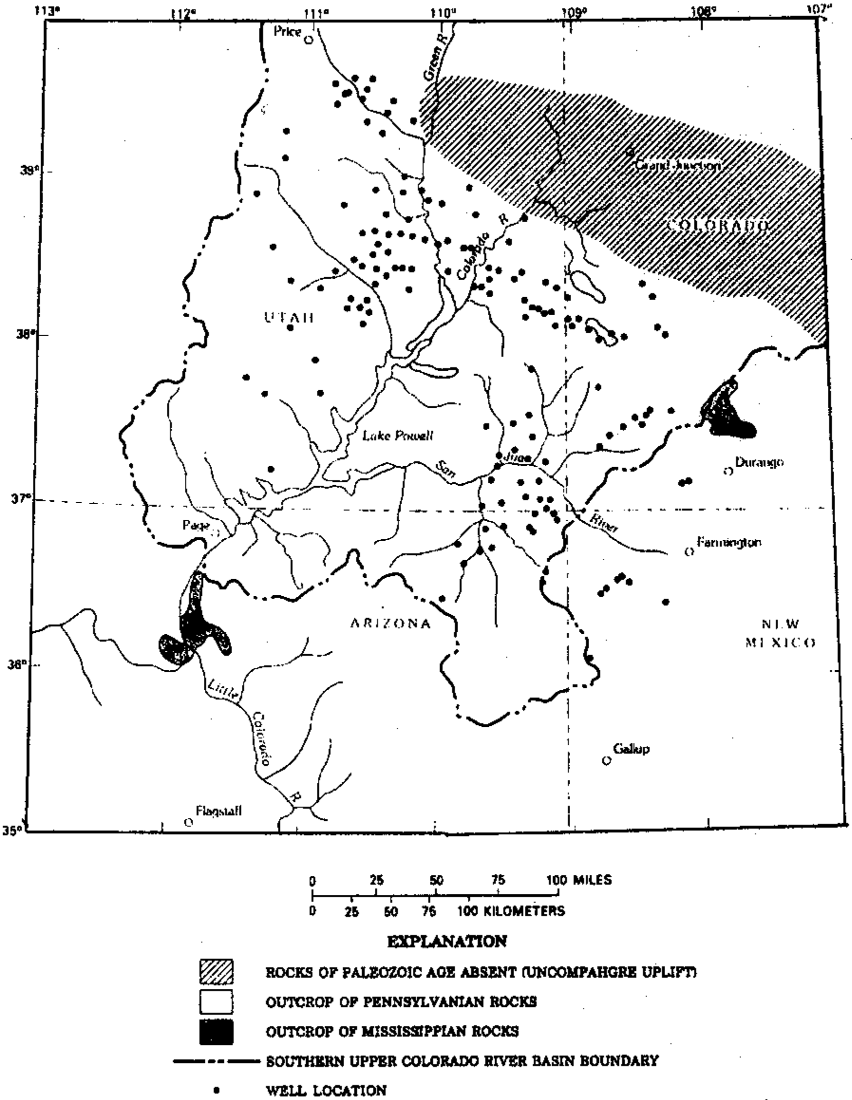


Figure 14. Outcrop Areas of Rocks of Pennsylvanian and Mississippian Age and Location of Wells Completed in the Limestone and Dolomite Aquifer (Weiss, 1989).

Large areas of the sandstone and red-bed aquifer are exposed near the center of the modeled area; in those areas, canyons cut deeply into the sandstone and red-bed aquifer almost into the limestone and dolomite aquifer. In the canyons, groundwater usually discharges from the exposed sandstone and red-bed on the walls of the canyons. Discharge from rocks of Permian and Pennsylvanian age has been observed in the canyons of southeastern Utah, but discharge from older rocks has not been observed (Dunbar and Thackston, 1985, p. 17-18). For the sandstone and red-bed aquifer, precipitation on the well-defined outcrop areas of the plateaus in the south and in the mountains in the east of the modeled area (Figure 13) accounts for much of the aquifer recharge. For the limestone and dolomite aquifer, precipitation on small outcrops in the mountains in the eastern part of the modeled area accounts for the westward flow. The absence of other outcrop areas indicates that the limestone and dolomite aquifer probably receives most of its recharge from outside the modeled area and from upward and downward leakage. Near the western boundary of the modeled area, where the sandstone and red-bed aquifer does not crop out, the sources of recharge to it probably are from outside the modeled area and from leakage. If groundwater is derived from outside the modeled area, the source of that water west of the modeled area is difficult to identify. Precipitation on the plateaus might move downward through faults to recharge both aquifers near the western boundary.

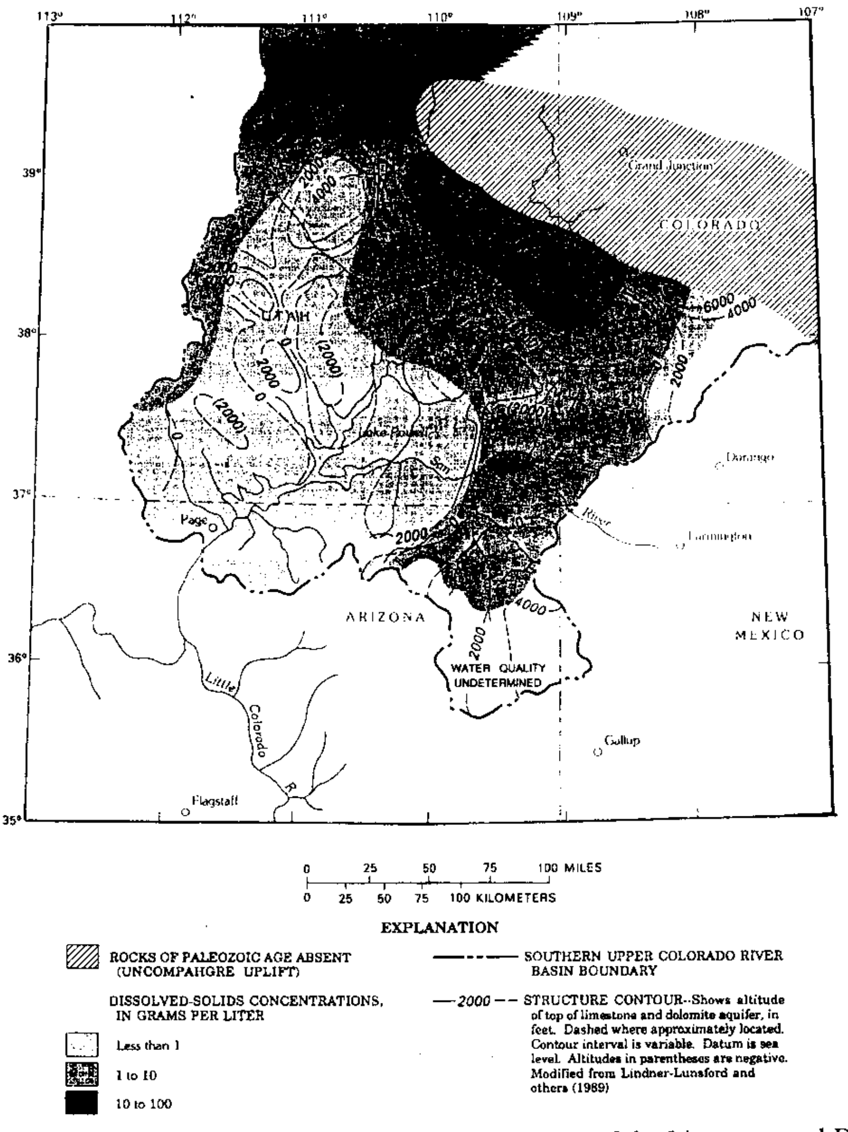


Figure 15. Dissolved-Solids Concentration in the Groundwater of the Limestone and Dolomite Aquifer and Altitude of the Top of the Limestone and Dolomite Aquifer (Weiss, 1989).

2.4.5. Brine Flow in the Limestone and Dolomite Aquifer

Because of the large concentrations of dissolved solids in brines, brine densities are substantially greater than freshwater densities. A dense brine exists in the limestone and dolomite aquifer along the southern boundary of the Uncompahgre Uplift (Figure 15). In the area of the brine (Paradox Basin), the top of the limestone and dolomite aquifer forms an elongated bowl-like surface that is approximately bisected by the Precambrian quartzite of the ancestral Uncompahgre Uplift. Blocked from northeasterly movement by an impermeable wall of quartzite, the dense brine would almost be stationary at the bottom of the dipping aquifer if not driven elsewhere by equivalent freshwater-head gradients or other forces. If the brine is stationary, no mixing or dispersion will occur. The primary mechanism of spreading would be molecular diffusion, which usually is a much smaller effect than dispersion in flowing groundwater.

2.4.6. Groundwater Simulations

2.4.6.1. *Sandstone and Red-bed Aquifer*

The best match to internal equivalent freshwater heads required a configuration of boundary elements that allowed discharge along the Colorado River and its tributaries in the center of the modeled area; the configuration was based on the location of Paleozoic rock outcrops in stream channels. The channel locations and stream altitudes were used for the location and equivalent freshwater heads at the nodes of boundary elements shown in the middle of Figure 16.

The model of the sandstone and red-bed aquifer was developed without adjusting any parameters to fit the internal measured equivalent freshwater heads. All parameters used in the model were the result of measurements and assumptions. Primarily, transmissivity was not adjusted. However, trial simulations were used to decide the need for internal recharge and discharge areas. Need was decided on the basis of hydrologic judgment and on the basis of the agreement between simulated and measured equivalent freshwater heads.

The simulation that used the boundary integral-equation configuration shown in Figure 16 achieved the best match to the internal equivalent freshwater heads. A large quantity of inflow to the aquifer occurs in the southwestern part of the model boundary; most of the inflow is discharged into the nearby Colorado River channel and the Marble Canyon. Other large inflows occur in the northwestern and northeastern areas of the modeled area (Weiss, 1989).

Initial simplifying approximations were part of the best simulation of the sandstone and red-bed aquifer and seem to be reasonable approximations:

[1]. The aquifer has the same transmissivity everywhere. Transmissivity was not an input to the simulation; consequently, the transmissivity was not estimated by the simulation. An estimate of transmissivity should be based on the thickness and the geometric mean value of permeability: 4 millidarcies per centipoise.

[2]. No inter-aquifer flow occurs for the sandstone and red-bed aquifer.

[3]. There is a no-flow boundary along the Uncompahgre Uplift.

[4]. Discharge at stream channels in the center of the modeled area is controlled by the altitude of the stream, except in Dark Canyon, which probably is a discharge area for local flow.

[5]. Discharge into the Marble Canyon is controlled by the altitudes of the Paleozoic rock outcrops.

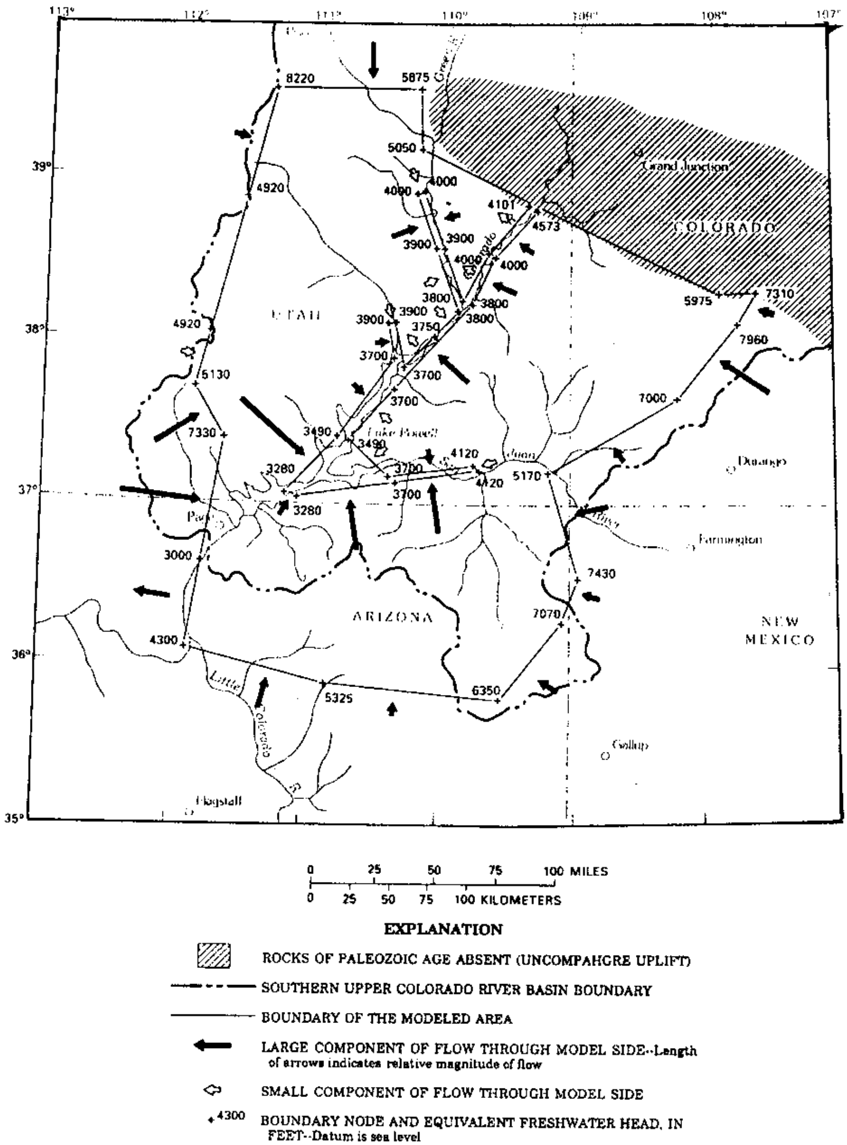


Figure 16. Model of the Sandstone and Red-bed Aquifer using the Boundary Integral-equation Method (modified from Weiss, 1987).

2.4.6.2. *Limestone and Dolomite Aquifer*

The best match to internal equivalent freshwater heads required a boundary-element configuration of discharging stream channels near the center of the modeled area. The configuration of boundary elements follows the Pennsylvanian rock outcrops in canyons shown in Figure 14. The boundary-element configuration does not include the Pennsylvanian rock outcrop in Dark Canyon. Approximations in the simulation of the limestone and dolomite aquifer that seem to be reasonable are:

- The boundary of the brine area is a no-flow boundary.
- Discharge at Pennsylvanian rock outcrops in stream channels at the center of the modeled area is controlled by the altitude of the stream.
- Discharge into the Marble Canyon is controlled by the altitudes of the Paleozoic rock outcrops.

The limestone and dolomite aquifer was also developed without adjusting any parameters. All parameters used in the model were the result of measurements and assumptions; no adjustment was made to fit the internal measured equivalent freshwater heads.

A brine that has concentrations of dissolved solids as large as 374 g/L is present in the limestone and dolomite aquifer in the Paradox Basin area. The interpolated equivalent fresh water heads at grid points in the modeled area and in the brine area of the limestone and dolomite aquifer defined 11 flow paths that have an equivalent freshwater-head difference that drives water out of the brine area. However, the gravitational force pulling the more dense brine downslope into the Paradox Basin prevents the brine from flowing out of the basin along most flow paths.

The principal problem in simulating accurate flow in the limestone and dolomite aquifer was simulating equivalent freshwater heads that were small enough to match measured equivalent freshwater heads. To do this, additional discharge was needed. Discharge occurred primarily in the stream channels at the center of the modeled area. This discharge probably was larger in the model than it should have been because in the model it flowed directly from the aquifer to the stream channel instead of flowing from the aquifer through the confining unit to the stream channel, as it would have done onsite, if onsite discharge to the stream channel occurs. Consequently, discharge to the stream channels seems to be maximized in the simulation of the limestone and dolomite aquifer; and onsite discharge from the limestone and dolomite aquifer probably occurs in and near the stream channels, instead of only in the stream channels of the model. However, differences in equivalent freshwater head between the aquifers generally do not support this hypothesis (Weiss, 1989).

2.5. San Juan Basin[6]

2.5.1. Physical Description

The study area coincides approximately with the San Juan structural basin as defined by Kelley (1951). The boundaries of the study area include the San Juan and La Plata Mountains of Colorado on the north side, the Defiance Uplift and New Mexico-Arizona State line on the west side, the Suni Mountains and Interstate 40 on the south side, and the Nacimiento Uplift and Rio Grande rift on the east side (Figure 17). This area covers about 18,000 square miles. Population centers include Durango and Cortez, Colorado and Farmington, Gallup, and Grants, N. Mex. Mean annual rainfall in the basin varies from about 6 inches at lower elevations to more than 20 inches in the mountains.

The San Juan Basin is rich in energy resources. Oil production began near Shiprock in the early 1900's and continues in several fields (Figure 18). Since the 1950's, natural gas produced from a large area near the center of the basin has been the principal hydrocarbon product. Surface coal mining and mine-mouth power generation began in 1962 near Farmington. Surface mining has also produced coal near Gallup since 1961 (Shomaker and others, 1971). Uranium

[6] Taken from Lyford (1979), Dam (1995) and Kernodle (1996).

production in the Grants mineral belt on the south end of the basin (Figure 18) has been one of New Mexico's principal industries since the 1950s.

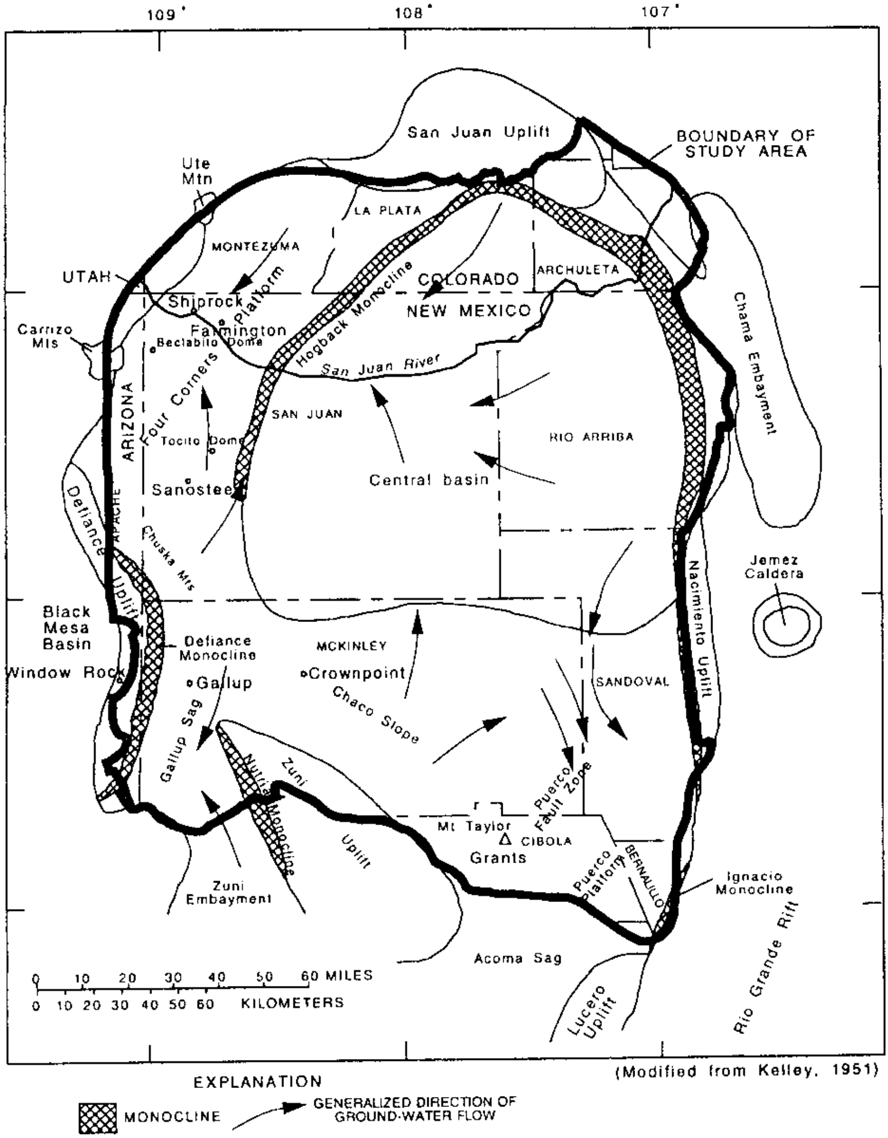


Figure 17. Structural Elements of the San Juan Structural Basin and Adjacent Areas and Generalized Pattern of Groundwater Flow in Rocks of Jurassic and Cretaceous Ages (Dam, 1995).

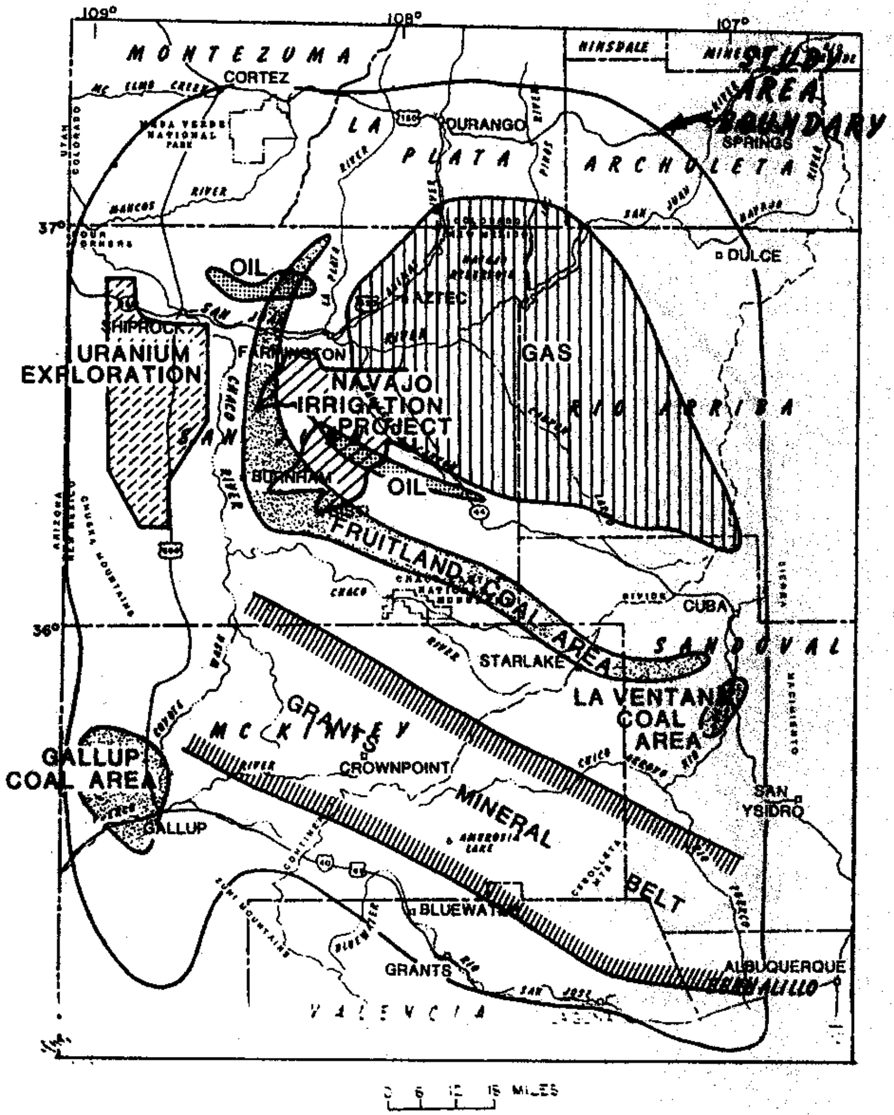


Figure 18. Major Areas of Current and Proposed Resources Development n the San Juan Basin (Layford, 1979).

Proposed energy-resource developments include several surface coal-mining operations in the Fruitland coal area, underground mining of coal seams in the Menefee Formation near Cuba, and surface mining of coal seams in the Menefee near Crownpoint. The feasibility of installing at least one additional power plant is being studied. Numerous underground uranium mines have either been started or are in the planning stage throughout most of the Grants mineral belt. An industry of considerable importance is the Navajo Indian Irrigation Project south of Farmington, which added 110,000 acres of irrigated land by the late 1980s. Irrigation began on the first 10,000-acre tract in 1976 (Lyford, 1979).

2.5.2. Geologic Setting

Geologic units in the San Juan Basin range in age from Cambrian to Quaternary. With the exception of the Permian San Andres Limestone and Glorieta Sandstone near Grants, the better aquifers are found in sandstones of Jurassic, Cretaceous, and Tertiary ages. Quaternary deposits filling stream channels are capable of yielding sufficient quantities of water for stock and domestic use in many areas.

Aquifers discussed by Lyford (1979) are of Jurassic age or younger. These include, in ascending order, the Entrada Sandstone, the Morrison Formation (principally the Westwater Canyon Member), the Gallup Sandstone of the Mesaverde Group, younger Sandstones of the Masaverde Group (Dalton Sandstone Member of the Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone), and the Tertiary section (the Ojo Alamo Sandstone, Nacimiento Formation, San Jose Formation, and Chuska Sandstone). All aquifers are separated by shale units. The oldest rocks crop out on the edge of the basin and dip under younger rocks toward the deepest part of the basin near Navajo Reservoir. Figure 19 shows the major aquifers in a highly generalized section through the deepest part of the basin. Detailed descriptions of some of the sandstone aquifers are given by Shomaker and Stone (1976). General descriptions of most geologic units in the San Juan Basin are given by Ridgley and others (1978).

Many discontinuous faults of small displacement exist throughout the basin. These faults may be significant conduits for the inter-aquifer transfer of groundwater. Two major structural features, the Hogback Monocline in the northwest and the Rio Puerco fault belt at the edge of the Rio Grande valley (Figure 17), strongly affect the groundwater flow regime in these localities because of water movement along vertical fractures (Lyford, 1979).

2.5.3. Gallup, Dakota and Morrison Aquifers

2.5.3.1. *Gallup Aquifer*

The Gallup Aquifer is a hydrogeologic unit corresponding to the Gallup Sandstone. The Gallup Sandstone is of Late Cretaceous age (Molenaar, 1973, 1974). The unit has a smaller areal extent than the other major Upper Cretaceous sandstones in the San Juan structural basin and occurs only in New Mexico and a small part of Arizona. The Gallup crops out in an accurate pattern around the western and southern margin of the basin where it typically forms erosion-resistant cliffs and dip slopes. Thickness of the Gallup decreases from about 600 ft near the outcrops along the margin of the basin to zero along the northwest-trending pre-Niobrara erosion limit. Depth to the top of the Gallup Sandstone ranges from zero in areas of outcrop to about 4,500 ft in an area about 20 mi south of the town of Farmington (Kernodle and others, 1989). The altitude of the top of the Gallup decreases from a maximum of about 7,500 ft northeast of Window Rock, Arizona, to about 1,500 ft above sea level southwest of Farmington. The Gallup represents the first major regression of the Upper Cretaceous sea in the San Juan structural basin and also represents deposition in marine and nonmarine environments. As originally defined by Sears (1925) and discussed in detail by Dane and others (1957), the Gallup consists of various rocks including sandstone (the predominant rock type), conglomerate, shale, carbonaceous shale, and coal. Minerals found in the Gallup include quartz (70-90 percent), feldspar (5-25 percent), glauconite, chlorite, sericite, chert, zircon, tourmaline, hematite, limonite, magnetite, ilmenite, dolomite, and ankerite (Kaharoeddin, 1971).

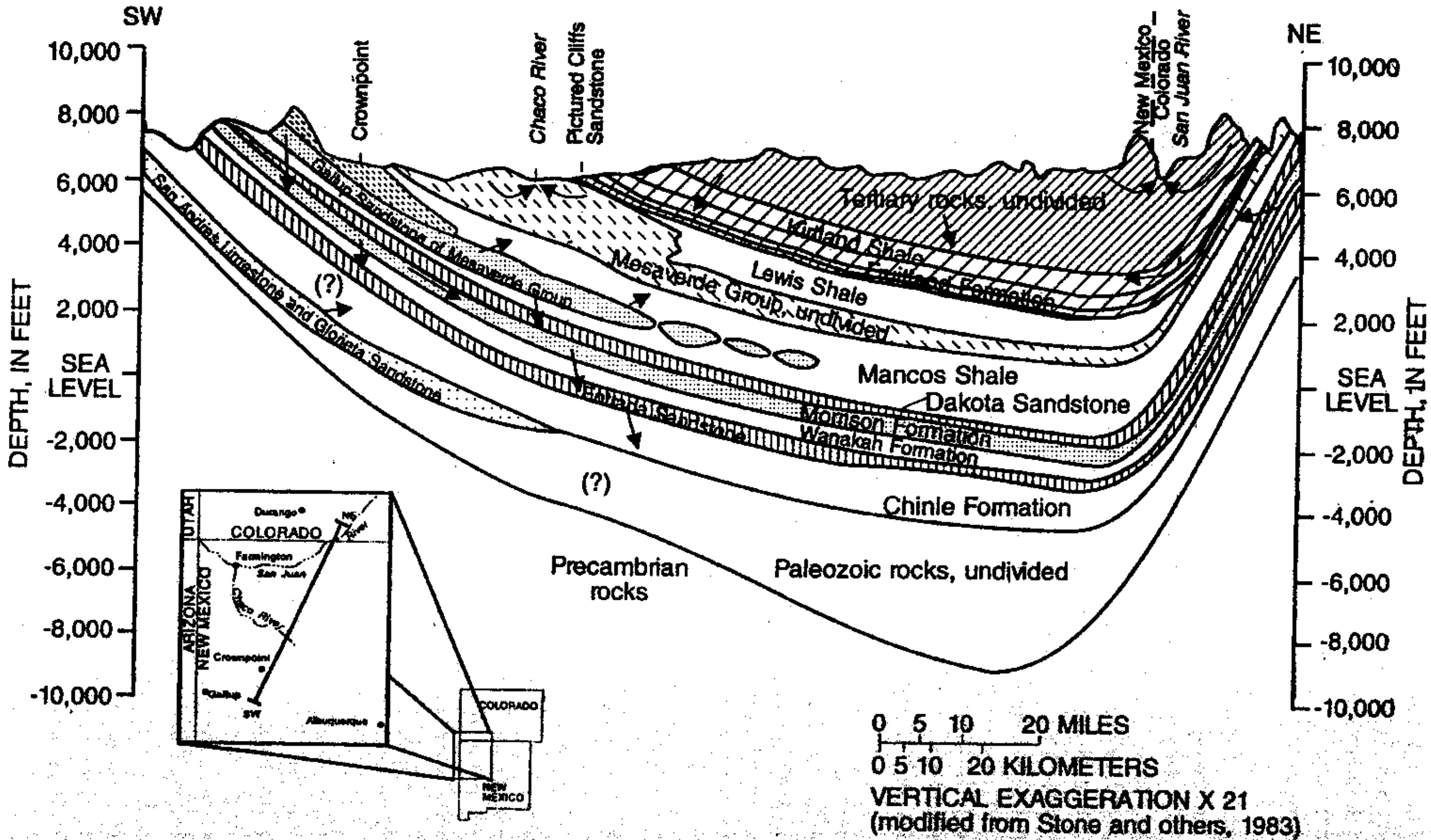


Figure 19. Generalized Hydrogeologic Section of San Juan Basin Showing Major Aquifers (Stippled) and Confining Beds (Blank) (modified from Stone and others, 1983), along with Direction (Arrows) of Groundwater Flow (modified by Kernodle, 1996).

The Gallup Aquifer is a source of water for domestic, livestock, municipal, and industrial uses. Recharge to the aquifer is from infiltration of precipitation and stream flow on outcrops and from vertical leakage of water through confining beds. Areas of recharge are in the southwestern and northeastern parts of the basin. Groundwater flow from these areas moves generally toward the central part of the basin and to the west, northwest, and southeast parts (Figure 17). However, the remaining body of the Gallup Aquifer is cut off in a northwest-southeast pattern such that the flow of water is not continuous throughout the entire basin. The Gallup Aquifer occurs under both water-table and artesian conditions. Water wells (Figure 20) generally are near the western and southern margins of the basin and primarily in McKinley County; flowing wells are mostly in the northern part of the county. The reported or measured discharge from 32 water wells completed in the Gallup Aquifer ranges from 1 to 645 gal/min and the median is 30 gal/min (Kemodle and others, 1989). Water levels significantly below the land surface were found in the Grants mineral belt near Crownpoint and near Gallup, New Mexico, and Window Rock, Arizona (Dam, 1995).

Chemical analysis was done for samples from 25 wells (Table 7). The dissolved solids were less than 1,000 mg/l for 14 samples from 13 wells, between 1,000 – 2000 mg/l for samples from 9 wells, and greater than 2000 mg/l for samples from 3 wells.

Table 7. Selected Properties of and Constituents in Water from the Gallup Aquifer (Modified from Dam, 1995).

Well number	Date of sample	Field pH	Temperature (°C)	Dissolved solids
1	07-01-88	7.90	16.7	455
2	04-22-86	8.20	32.8	1,799
	10-21-87	8.33	32.9	2,000
3	04-21-86	8.60	32.7	1,900
4	07-15-88	8.57	24.4	559
5	06-30-87	8.81	26.0	1,200
	06-28-88	8.81	25.0	--
6	06-30-88	8.99	19.9	639
7	06-28-88	9.00	20.7	374
8	12-03-87	8.73	18.4	2,000
9	04-29-86	9.10	18.0	330
	08-11-87	8.83	18.0	330
10	06-30-88	9.20	16.9	444
39	05-26-64	7.8	18.5	3,200
40	07-03-74	8.0	--	2,700
41	10-29-74	8.5	--	1,600
42	10-14-64	7.8	--	210
43	09-08-69	8.2	--	390
44	01-28-72	8.2	--	430
45	01-20-71	8.0	--	450
46	03-10-70	7.8	--	650
47	07-31-70	8.4	32.0	810
48	09-19-62	8.2	24.5	2,190
49	10-02-62	7.9	24.0	1,100
50	10-14-64	8.5	--	680
51	07-18-73	8.1	--	1,100
52	09-18-62	8.8	20.0	1,100
53	08-30-57	8.4	15.5	1,200

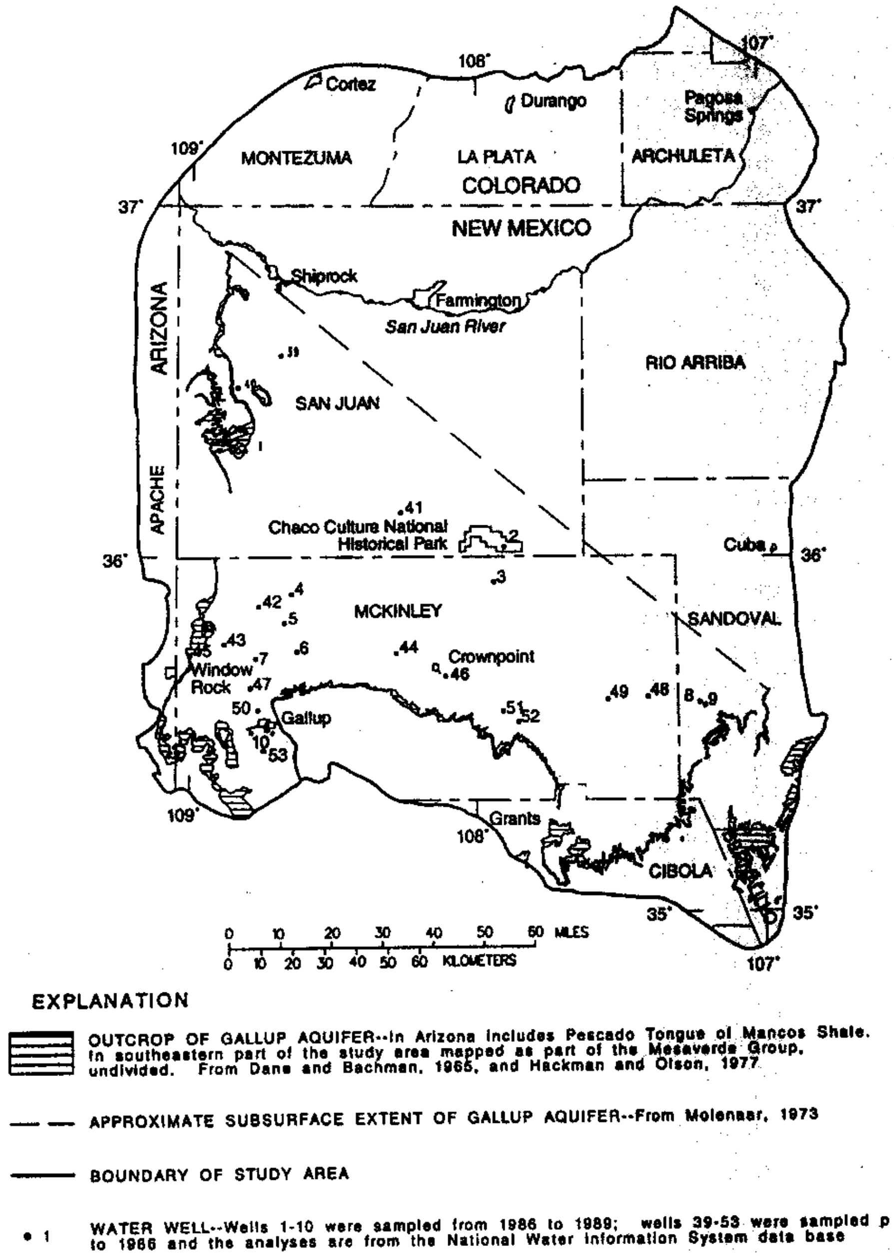


Figure 20. Location of Sampled Water Wells Completed in the Gallup Aquifer (Dam, 1995).

2.5.3.2. *Dakota Aquifer*

The Dakota Aquifer is a hydrogeologic unit corresponding to the Dakota Sandstone. The Dakota Sandstone generally is thought to be of earliest Late Cretaceous age, although the lowermost part may be of latest Early Cretaceous age (Fassett, 1977, p. 225). The Dakota crops out around the basin margins where it typically caps mesas and forms erosion-resistant dip slopes and hogbacks. The Dakota Sandstone unconformably overlies the Morrison Formation

(Late Jurassic age) throughout much of the basin; however, it unconformably overlies the Burro Canyon Formation (Early Cretaceous age) in the northern part of the basin. The upper contact of the Dakota is conformable with the Mancos Shale, and intertonguing of these two units is common near the contact. Stratigraphy of the Dakota is complex. The unit consists of a main sandstone body in the north, which branches into various members and tongues depending on location in the San Juan Basin. Thickness of the Dakota generally ranges from a few tens of feet to about 500 ft; Stone and others (1983, p. 37) reported that a range of 200 to 300 ft probably is common. Data reported by Molenaar (1977, p. 160-161) and Stone and others (1983, Figure 66) and data obtained from Petroleum Information Corporation, Denver, Colorado, indicate that the thickness of the Dakota generally increases from the western, northwestern, and northern margins of the basin toward the eastern, southeastern, and southern margins. Depth to the Dakota ranges from zero in areas of outcrop to about 8,500 ft in the northeastern part of the basin. The top of the Dakota decreases from a maximum altitude of about 9,500 ft along the northern basin margin to about 1,500 ft below sea level in the northeastern part of the study area (Craigg and others, 1989).

The Dakota Aquifer is a source of water for domestic, livestock, and industrial uses, and water wells generally are near the margins of the basin. Water in the Dakota Aquifer occurs under both watertable and artesian conditions. Recharge to the aquifer is from infiltration of precipitation and streamflow on outcrops and from vertical leakage of water through confining beds. Within the basin, areas of stress from groundwater development in the Dakota Aquifer are localized. These areas may represent oil or gas production, injection for disposal of brine, secondary recovery or repressurization of producing zones, or uranium-mine dewatering of the underlying Morrison Aquifer that induces downward flow in the Dakota Aquifer. The reported or measured discharge from 29 water wells completed in the Dakota Aquifer ranged from 1 to 200 gal/min and the median is 13 gal/min (Craigg and others, 1989). Water levels in numerous wells were several hundred feet below land surface. Only one well, in the northwestern part of the basin, was flowing (Dam, 1995).

The results from chemical analysis of water samples collected at nine wells (Figure 21) is listed in Table 8. Three wells had dissolved solids of approximately 500 mg/l or less, which would be suitable for human consumption. Three wells had dissolved solids greater than 2,000 mg/l, while the remaining three wells had intermediate values ranging from 1,000- 2,000 mg/l.

Table 8. Selected Properties of and Constituents in Water from the Dakota Aquifer (modified from Dam, 1995) {See Figure 21 for location of wells; concentrations in milligrams per liter}

Well number	Date of sample	Field pH	Temperature (°C)	Dissolved solids
11	07-23-87	8.47	18.1	1,300
12	06-29-88	8.78	18.1	262
13	04-29-86	8.90	19.5	1,900
	12-03-87	8.91	19.5	--
54	04-27-60	7.6	15.5	2,320
55	09-21-66	8.0	--	3,780
56	06-27-52	--	--	2,080
	09-21-66	8.4	--	2,060
57	07-22-70	8.6	--	961
	09-24-74	8.6	--	1,040
58	06-08-67	9.4	--	302
	01-08-70	9.4	--	310
59	07-03-74	8.2	--	512

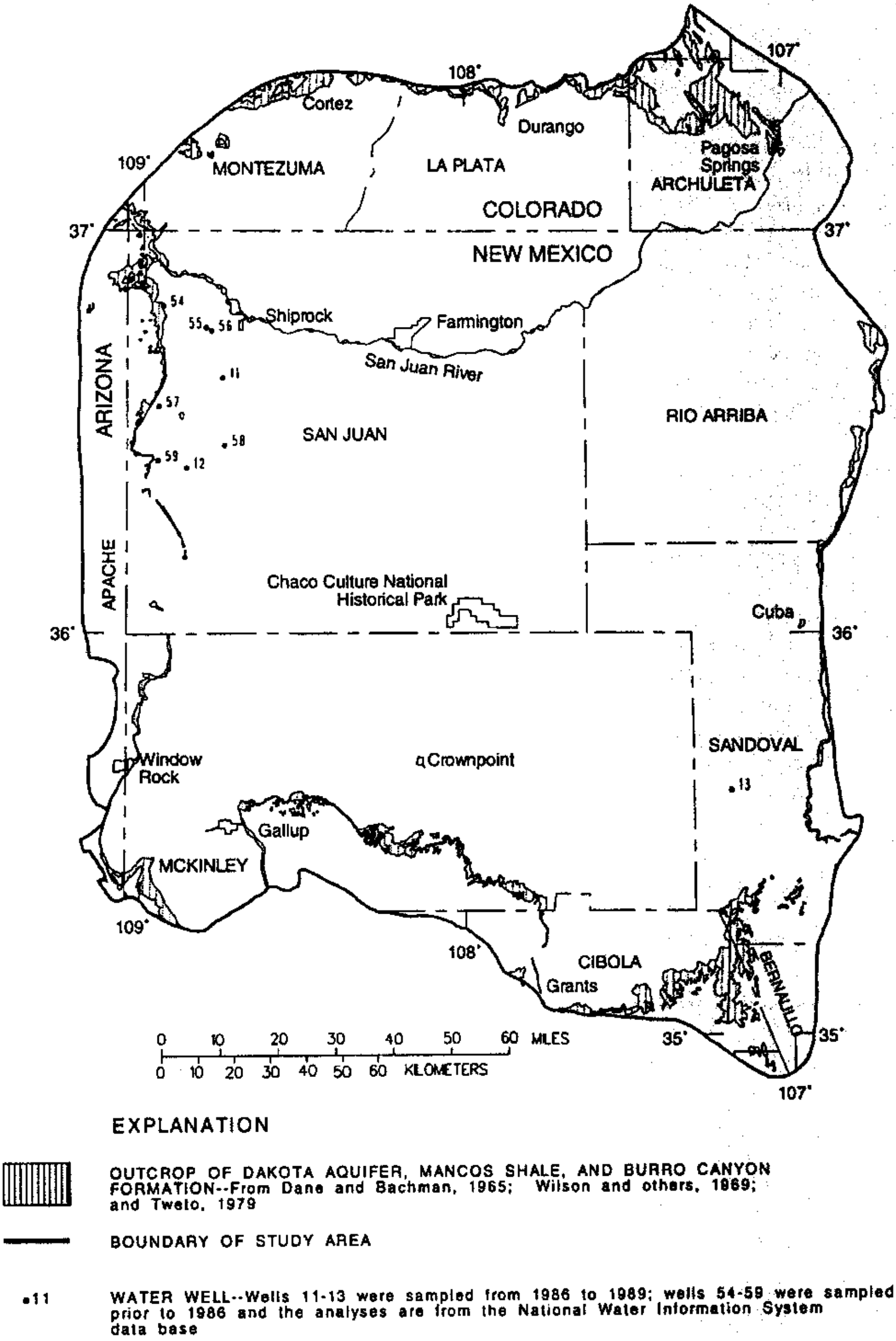


Figure 21. Location of Sampled Water Wells Completed in the Dakota Aquifer (Dam, 1995).

2.5.3.3. *Morrison Aquifer*

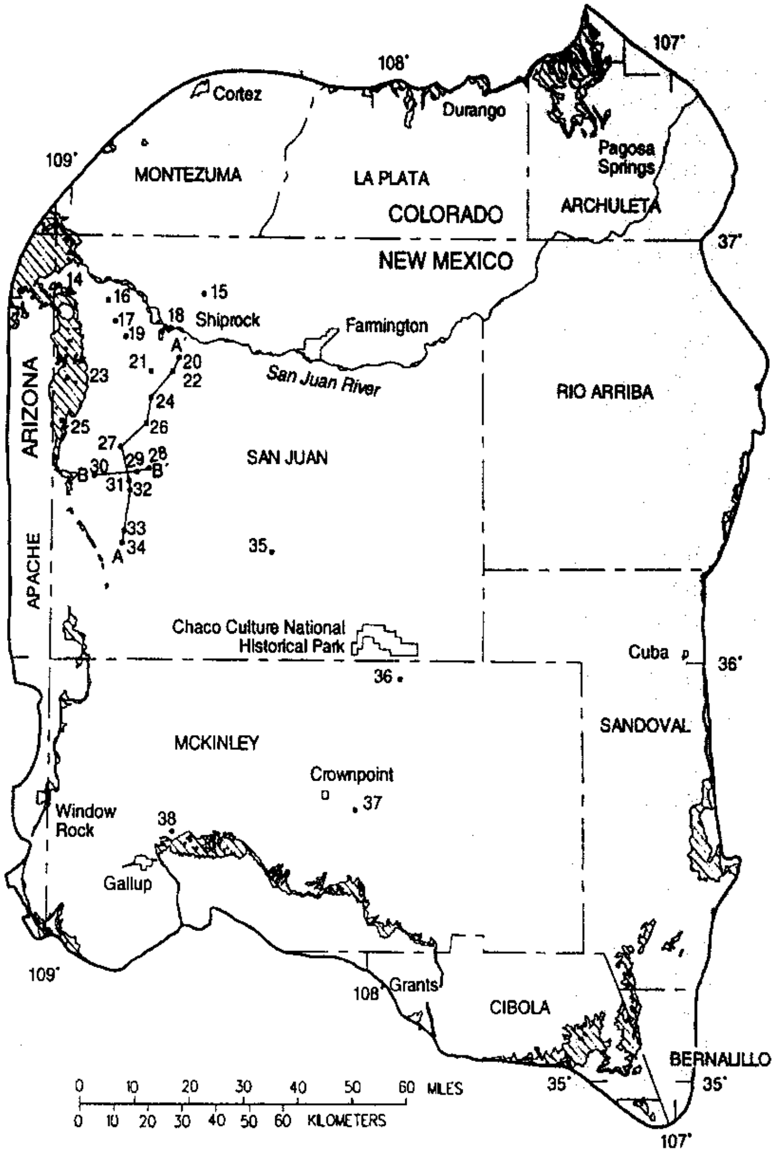
The Morrison Aquifer is a hydrogeologic unit corresponding to the Morrison Formation. The Morrison Formation is of Late Jurassic age (Cadigan, 1967, p. 6) and crops out around the basin margins. Major sandstones in the Morrison typically form erosion-resistant cliffs and dip slopes, whereas shale units form topographic saddles. The Morrison is present throughout the San Juan Basin (Green and Pierson, 1977, p. 151) and conformably overlies the Wanakah Formation or Cow Springs Sandstone of Late Jurassic age (Condon and Peterson, 1986, p. 24) throughout most of the basin. In the northern part of the basin, the Morrison conformably overlies and probably intertongues with the Junction Creek Sandstone of Late Jurassic age. In the San Juan Basin, the Morrison Formation consists of five members (Gregory, 1938; Craig and others, 1955; Cadigan, 1967; Green and Pierson, 1977, Owen, 1984). These members, in ascending order, are: the Salt Wash Member, Recapture Member, Westwater Canyon Member, Brushy Basin Member, and Jackpile Sandstone Member. The thickness of the Morrison ranges from about 200 ft near Grants to about 1,100 ft in the northwestern part of the basin (Dam and others, 1990a). Depth to the top of the Morrison ranges from zero in areas of outcrop to about 8,500 ft in the northeastern part of the basin (Dam and others, 1990a). The top of the Morrison decreases from a maximum altitude of about 10,000 ft along the northern basin margin to about 1,500 ft below sea level in the northeastern part of the basin. Morrison Formation strata were deposited in various continental environments including eolian, stream channels, flood plains, and lakes (Green and Pierson, 1977, p. 151; Tumer-Peterson and others, 1986). A semiarid to arid climate existed during deposition of the Morrison (Tumer-Peterson and Fishman, 1989).

The initial interpretation of the groundwater flow system in the Morrison Aquifer is based on work by Kelly (1977), Frenzel and Lyford (1982), Stone and others (1983), and data from the files of the U.S. Geological Survey, Albuquerque, New Mexico. The conceptual model of the flow system in the Morrison Aquifer assumed the Westwater Canyon Member to be the only significant regional aquifer (Kelly, 1977); the other members were considered important only as local aquifers. The Brushy Basin and Recapture Members were thought to serve as semiconfining layers above and below the Westwater Canyon throughout the basin except in the southwestern part where the Brushy Basin is absent.

The discharge areas for the Morrison are considered to be in the northwestern part of the area near Four Comers where the San Juan River has breached the Morrison Aquifer, the southwestern part of the area southwest of Gallup, and the southeastern part of the area northeast of Grants (see Figure 17 for general areas of discharge as indicated by converging arrows). In the northwestern part of the basin north of the Chuska Mountains, the general gradient is to the north; in the area northeast of the city of Gallup, areas of localized dewatering for uranium mining have resulted in substantial head declines.

The reported or measured discharge from 53 water wells (Figure 22 shows some of them) completed in the Morrison aquifer ranges from 1 to 401 gal/min; the median discharge is 32 gal/min (Dam and others, 1990a). Heads of wells completed in the Morrison Formation are typically above land surface in San Juan County and below land surface in McKinley and Cibola Counties (Dam, 1995).

Forty-three water samples were collected from 25 water wells for chemical analysis (Table 9). The dissolved solids were less than 500 mg/l for 12 wells; 500-1,000 mg/l for five wells; 1,000-2,000 mg/l for one well; and seven wells weregreater than 2,000 mg/l.



EXPLANATION

OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

BOUNDARY OF STUDY AREA

A —— A' LINE OF GEOHYDROLOGIC SECTION--See figure 11

• 14 WATER WELL--Wells 14-38 were sampled from 1986 to 1989

Figure 22. Locations of Sampled Water Wells Completed in the Morrison Aquifer and of Geohydrologic Sections (Dam, 1995).

Table 9. Selected Properties and Constituents in Water from the Morrison Aquifer (modified from Dam, 1995). {See Figure 22 for location of wells; concentrations in milligrams per liter}.

Well number	Date of sample	Field pH	17.0Temperature (°C)39.9	Dissolved solids
14	06-10-88	7.56	17.0	361
15	07-21-87	7.52	39.9	6,000
16	06-24-86	9.20	19.9	350
	06-08-88	9.37	20.1	350
17	07-02-86	8.50	23.0	2,700
18	06-16-86	8.00	31.0	2,600
	06-09-87	8.03	31.1	3,200
19	07-14-87	7.74	29.1	3,800
20	06-19-86	7.60	33.0	5,000
	06-10-87	7.80	31.0	3,800
21	06-18-86	8.30	--	2,600
22	06-19-86	8.00	28.8	2,900
	06-10-87	8.03	30.5	3,000
23	06-10-88	9.65	17.1	308
24	07-01-86	8.10	18.0	920
25	06-09-88	8.87	16.9	213
	04-25-89	9.12	16.0	167
26	06-17-86	9.30	27.2	300
	07-22-87	9.39	27.6	290
	07-01-88	9.33	27.1	310
27	06-18-86	9.40	23.9	220
	06-11-88	9.65	23.9	230
28	06-30-86	9.33	22.0	370
	07-17-87	9.45	21.3	570
	07-01-88	9.26	21.3	430
29	06-29-88	9.51	23.3	290
	11-22-88	9.41	20.9	297
30	07-23-87	8.37	24.0	220
	01-05-89	8.58	16.1	216
31	01-05-89	9.06	22.0	174
32	06-24-86	9.05	21.9	190
	07-15-87	9.31	22.4	190
	06-11-88	9.42	23.6	190
33	07-15-87	9.52	26.6	290
	06-29-88	9.53	--	290
	11-23-88	9.25	21.3	
34	07-16-87	8.96	25.5	509
	11-22-88	8.88	23.9	510
35	06-11-87	7.88	51.8	840
36	04-24-86	8.20	42.2	1,099
	10-22-87	8.31	37.4	1,100
37	10-02-87	9.05	30.5	550
38	07-01-87	7.64	15.0	720
	07-14-88	7.64	15.4	750

2.5.4. Groundwater Model[7]

In the San Juan structural basin, the terms "aquifer" and "confining bed" have been associated, for the most part, with the formal name of a geologic unit (formation, member, or tongue) that forms a significant part of the aquifer or confining bed (Table 10). It is recognized that the aquifers and confining beds are not necessarily restricted to one geologic unit, but may include all or parts of several geologic units; however, data on relative permeabilities were inadequate for more precise delineation of aquifers and confining units. Figure 23 shows the relation of geologic units to regional hydrogeologic units and model layers.

The range of values for specific conductance and dissolved solids, as well as mean values, used in the groundwater model are given in Tables 11, 12, 13 and 14. The hydrogeologic units conform with those shown in Figure 23. The upper number in these tables are the number of samples, the middle numbers are the range of values, and the lower number is the median value.

The distinction between aquifer and confining bed can also be one of the perspectives. In many cases, units that are considered confining beds on a regional scale can, and do, yield small quantities of water to wells from localized lenticular sandstones. These wells often supply water for stock use and represent a significant percentage of the total number of water wells in the basin. From a regional perspective, however, these units are considered to be confining beds in the evaluation of groundwater resources and the development of a three-dimensional, steady-state groundwater flow model. For example, the Menefee Aquifer is considered to be an aquifer on a local scale and a confining bed on a regional scale because water is found in localized, discontinuous lenticular sandstones.

In a simplified conceptual model of the groundwater flow system in the San Juan structural basin, water enters the groundwater flow system from precipitation on outcrops and from stream channel losses as streams cross the outcrop. Recharge from direct precipitation occurs only after near-surface demands for moisture are met by the water that does not run off and a residual amount of water reaches the zone of saturation. These near-surface demands include evaporation, sublimation, and transpiration.

Once water is in the groundwater flow system it moves down-gradient to areas of natural or human-induced discharge in accordance with Darcy's Law. Areas of natural discharge include springs and seeps in topographically low parts of the outcrop, discharge from the outcrop to stream channels, and upward movement across less permeable beds to the surface along fault planes, fractures, and, less commonly, along dikes. Examples of spring discharge along fault planes and fractures are the southern end of the Nacimiento Uplift in the southeastern part of the study area (Figure 17).

Another important method of natural discharge is water moving from one aquifer, across a less permeable unit, to another aquifer that has lower hydraulic head. Water also might move across a less permeable unit directly to land surface where it would contribute to soil moisture, and hence, to evaporation or transpiration.

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[7] Taken from Kernodle (1996), as well as Levings, Kernodle and Thorn (1996).

Table 10. Summary of Geologic Nomenclature and Lithologic Characteristics of Regional Units in the San Juan Structural Basin (Levings, Kernodle and Thorn, 1996).

System	Formation	Approximate maximum thickness (feet)	General lithologic description
Tertiary	San Jose Formation	2,700	Interbedded, very fine to coarse-grained, locally conglomeratic, arkosic sandstone and variegated siltstone and shale.
	Nacimiento Formation	1,300	Interbedded gray shale and discontinuous lenses of arkosic sandstone; locally constant carbonaceous lenses.
	Animas Formation	2,700	Interbedded, tuffaceous sandstone, conglomerate, and shale; McDermott Member distinctly purple in color.
	Ojo Alamo Sandstone	400	Overlapping, sheetlike sequences of arkosic sandstone and conglomerate; locally contains interbedded lenses of shale.
Cretaceous	Kirtland Shale		Interbedded, repetitive sequences of lenticular sandstone, siltstone, and shale and claystone.
	Fruitland Formation		Interbedded, repetitive sequence of lenticular sandstone, siltstone, and shale with coal common.
	Pictured Cliffs Sandstone	400	Upward-coarsening, very fine to medium-grained sandstone, with thin interbeds of dark shale in lower part.
	Lewis Shale	2,400	Dark shale and silty shale with thin interbeds of silty limestone, siltstone, and fine-grained sandstone in lower part.
	Cliff House Sandstone	Depends on location and tongues present; maximum 1,000	Consists of several very fine to fine-grained sandstone tongues. Interbeds of dark shale are common.
	Menefee Formation	2,000	Interbedded sequences of lenticular sandstone, siltstone, and dark shale and claystone. Carbonaceous shale and coal common in lower and upper parts.
	Point Lookout Sandstone	350	Very fine to medium-grained sandstone with thin interbeds of dark shale in lower part.
	Mancos Shale	2,300	Dark shale and silty shale with thin interbeds of silty limestone, siltstone, and fine-grained sandstone.
	Crevasse Canyon Formation	700	Interbedded sequence of lenticular sandstone, siltstone, and shale and claystone with carbonaceous shale and claystone with carbonaceous shale and coal common in lower and upper parts where deposited in fluvial environments and coal swamps.
	Gallup Sandstone	600	Sandstone with some conglomerate, shale, carbonaceous shale, and coal.
	Dakota Sandstone	500	Consists of several members and tongues of sandstone. Fine-to coarse-grained sandstone, with dark shale, siltstone, and minor carbonaceous shale.
Jurassic	Morrison Formation	1,100	Fine-to coarse-grained locally conglomeratic sandstone, sandy siltstone, and shale and claystone; also contains thin limestone beds.
	Entrada Sandstone	330	Crossbedded silty sandstone and very fine to medium-grained quartzose sandstone.
Triassic	Chinle Formation	1,600	Consists of nonmarine deposits of claystone and shale, siltstone, and sandstone from various depositional (stream-channel, flood-plain, eolian, and locustrine) environments.

GEOLOGIC UNITS	REGIONAL HYDROGEOLOGIC UNITS	MODEL LAYER
Chuska Formation	Chuska aquifer	
San Jose Formation	San Jose aquifer	1
Animas and Nacimiento Formations	Animas and Nacimiento aquifers	2
Ojo Alamo Sandstone	Ojo Alamo aquifer	3
Kirtland Shale	Kirtland aquifer	
Fruitland Formation	Fruitland aquifer	
Pictured Cliffs Sandstone	Pictured Cliffs aquifer	4
Lewis Shale	Lewis confining unit	5
Cliff House Sandstone and La Ventana Tongue	Cliff House aquifer	6
Menefee Formation	Menefee confining unit	7
Point Lookout Sandstone	Point Lookout aquifer	8
Hosta Tongue	Upper Mancos confining unit	VK
Crevasse Canyon Formation		
Upper Mancos Shale		
Gallup Sandstone / Mancos Shale	Gallup aquifer	9
Lower Mancos Shale	Lower Mancos confining unit	VK
Dakota Sandstone	Dakota aquifer	10
Morrison Formation	Morrison aquifer	11
Wanakah Formation	Wanakah confining unit	VK
Entrada Sandstone	Entrada aquifer	12
Chinle Formation	Chinle confining unit	

EXPLANATION

AQUIFER

CONFINING UNIT

NOT SIMULATED

VK-Implicitly simulated using a computed vertical harmonic leakance

Figure 23. Relation of Geologic Units to Regional Hydrogeologic Units and Model Layers (Leving, Kernodle and Thorn, 1996).

Human-induced discharge occurs at flowing or pumped wells or in conjunction with open-pit or subsurface mining operations. Free-flowing wells are commonplace in the basin and most are completed in multiple aquifers; the percentage of water contributed by each aquifer is unknown. Pumped wells or controlled flowing wells also are common and supply water for municipal, small-community, private-domestic, and livestock needs. The majority of these wells are windmill powered and result in small yields, but some are capable of yielding large quantities of water. Mine-dewatering operations have been a major source of groundwater discharge in the south-central part of the basin. Some mines required the removal of as much as -3 ft^3/s of groundwater to keep the mine from flooding. All of the mines presently are closed, dewatering has ceased, and groundwater levels are now recovering from reductions in head that commonly exceeded 1,000 ft.

Table 11. Selected Properties of and Constituents in Water from Hydrogeologic Units in Rocks of Tertiary Age (Levings, Kernodle and Thorn, 1996).

Hydrogeologic unit	Specific conductance (microsimens per centimeter at 25 degrees Celsius)	pH (standard units)	Temperature (degrees Celsius)	Dissolved solids, sum of constituents mg/l.
Chuska Aquifer	11	--	9	4
	102-501	--	6.5-14	138-219
	250	--	11	209
San Jose Aquifer	97	89	65	67
	350-8,000	4.6-9.6	8.5-19	193-4,300[72]
	1,160	8	13	750
Namcimiento Aquifer	14	14	1	12
	953-12,700	6.8-9.1	18	660-6,800[100]
	2,780	8.1	--	2,800
Animas Aquifer	111	106	103	80
	201-4,920	7-9.8	4-23	115-3,490[34]
	680	7.8	12	400
Ojo alamo Aquifer	47	40	24	39
	160-9,350	6.3-9.8	4-18	56-7,300[72]
	1,130	7.9	12	640

Table 12. Selected Properties of and Constituents in Water from Hydrogeologic Units in Rocks of Createaceous Age (Levings, Kernodle and Thorn, 1996).

Hydrogeologic unit	Specific conductance (microsimens per centimeter at 25 degrees Celsius)	pH (standard units)	Temperature (degrees Celsius)	Dissolved solids, sum of constituents mg/l.
Kirtland Aquifer	15	14	9	14
	710-31,500	6.9-8.6[7]	8.5-59	449-30,100[93]
	3,920	7.7	11	2,925
Fruitland Aquifer	23	23	24	23
	535-25,600	6.6-12[26]	10-45	310-20,000[78]
	4,150	7.8	14	2,390
Pictured Cliffs Aquifer	31	30	20	31
	345-59,200	6.8-12.3[23]	8-52	340-46,000[97]
	8,000	8.1	19	6,600
Lewis Confining Unit	19	19	13	3
	490-5,870	5.9-8.7[5]	9-17	1,300-5,700[100]
	1,875	7.4	12	3,460
Cliff House Aquifer	66	54	37	48
	239-13,500	4.3-9.2[22]	3-33	130-6,800[90]
	2,580	7.7	13	1,750
Menefee Confining Unit	131	85	71	104
	179-7,000	5.3-10[52]	6-50	130-4,400[86]
	1,600	8.6	15	995
Point Lookout Aquifer	78	56	42	71
	211-5,500	7-9.2[55]	6-35.5	150-5,100[93]
	1,310	8.6	15	900
Upper Mancos Confining Unit	32	21	17	25
	398-4,950	6.8-8.9[30]	11-22	242-4,470[92]
	1,270	8.3	15	1,070
Gallup Aquifer	78	57	72	75
	351-10,200	7.1-9.2[17]	6.5-72	210-6,000[75]
	1,220	8	19	830
Lower Mancos Confining Unit	30	23	21	25
	460-13,600	6.5-9.1[13]	10-58.3	207-11,400[92]
	2,278	7.9	17	1,570
Dakota Aquifer	69	59	73	52
	297-12,100	6.5-9.7[32]	10-92	171-9,380[71]
	1,490	8.4	24	979
Burro Canyon Aquifer	1	1	1	1
	1,300	7.7	17	834[100]
	--	--	--	--

Table 13. Selected Properties of and Constituents in Water from Hydrogeologic Units in Rocks of Jurassic Age (Levings, Kernodle and Thorn, 1996).

Hydrogeologic unit	Specific conductance (microsimens per centimeter at 25 degrees Celsius)	pH (standard units)	Temperature (degrees Celsius)	Dissolved solids, sum of constituents mg/l.
Morrison Aquifer	66	56	51	56
	290-12,700	6.6-9.9[48]	10.5-42.2	166-6,000[52]
	845	8.4	23.3	511
Morrison Aquifer (Brushy Basin Member)	1	1	1	1
	1,747	7.5	18	1,140[100]
	--	--	--	--
Morrison Aquifer (Westwater Canyon Member)	57	57	30	52
	370-2,870	6.4-9.6[19]	11-61	221-2,310[50]
	904	8	17	502
Morrison Aquifer (Recapture Member)	2	2	2	2
	600-2,830	7.4-8.3	15-20	381-2,300[50]
	1,715	7.8	17	1,340
Morrison Aquifer (Saltwash Member)	3	2	1	2
	430-630	8.0-9.2[50]	14.5	293-297
	490	8.6	--	295
Junction Creek Aquifer	8	7	4	7
	927-30,100	7.9-8.7[29]	16.5-24	602-22,000[100]
	1,355	8.3	19	1,020
Cow Springs Aquifer	4	4	3	3
	420-941	7.2-8.2	10.24	361-602[67]
	640	7.7	24	528
Wanakah Confining Unit	2	1	1	2
	274-442	7.7	4.5	170-262
	358	--	--	216
Todilto Limestone Aquifer	4	4	12	4
	2,340-4,030	7.5-7.7	16.5-88	1,790-3,270[100]
	3,070	7.6	65	2,455
Entrada Aquifer	17	13	19	14
	540-31,500	7.4-9.4[23]	11-83	250-21,000[57]
	2,810	7.9	68	680

Table 14. Selected Properties of Constituents in Water from Hydrogeologic Units in Rocks of Triassic age (Levings, Kernodle and Thorn, 1996).

Hydrogeologic unit	Specific conductance (microsimens per centimeter at 25 degrees Celsius)	pH (standard units)	Temperature (degrees Celsius)	Dissolved solids, sum of constituents mg/l.
Wingat Aquifer	9	7	6	9
	638-2,040	7.7-9[71]	15-19	390-1,220[78]
	1,040	9	17	689
Wingate Aquifer (Rock Point Member)	1	--	1	1
	881	--	7	559[100]
	--	--	--	--
Chinle Confining Unit	56	40	24	32
	350-31,900	6.5-9.1[22]	9.5-28.5	218-3,070[66]
	1,320	8.2	14	725
Chinle Confining Unit (Petrified Forest Member)	4	--	1	3
	679-13,400	--	12	398-2,460[67]
	3,510	--	--	1,790
Chinle Confining Unit (sonsela Sandstone Member)	6	4	1	4
	581-33,800	7.3-8.5	13	429-22,300[75]
	939	8	--	580
Chinle Confining Unit (Shinarump Member)	5	4	1	4
	247-15,500	7.3-9[25]	21	187-623[25]
	460	8	--	247

The groundwater flow system has been altered in parts of the basin because it has been a major source for energy fuels--oil, gas, uranium, and coal. The exploration and production of these resources have had a significant effect on groundwater development since the 1950's. To date, more than 26,000 oil- or gas-test holes have been drilled in the basin, the majority penetrating no deeper than the bottom of Cretaceous rocks. This activity has resulted in the production of significant amounts of water as a by-product. The water produced is disposed of in one of several ways: (1) reinjection into producing zones to repressure the zone; (2) reinjection into zones for disposal; and (3) evaporation in surface pits. In the late 1980's and early 1990's, the production of coal-bed methane from the Fruitland Aquifer in the central basin was the major energy-related activity. Considerable volumes of groundwater were produced in conjunction with natural gas, which has resulted in the need for additional disposal wells in the area.

Although the uranium era in the basin began in the late 1940's, its effect on groundwater resources peaked in the late 1970's when most production was from underground mines in the Grants Uranium Belt. Production in the area was primarily from the Morrison Aquifer and secondary production was from a localized aquifer within the Wanakah confining unit (the permeable Todilto Limestone Member of the Wanakah Formation), and from the Dakota Aquifer. With ore being mined from a deep as much as 3,000 to 4,000 ft below the land surface, large quantities of groundwater were pumped to dewater the producing units. Most of the water was from the Morrison Aquifer and overlying Dakota aquifer. By 1992 all active underground mines had ceased operation. Dewatering was not the only activity to affect groundwater resources. Exploratory drilling for uranium-resources evaluation in the northwestern part of the study area resulted in many of the test holes being completed as water wells. These wells tap the Morrison Aquifer and in some instances underlying units. Most of these wells have sufficient head to flow at the land surface. Many of these wells are allowed to flow constantly, resulting in a lowering of the pressure head in the Morrison Aquifer in this area.

The mining of commercial coal resources in Upper Cretaceous rocks in the San Juan structural basin has had a localized effect on groundwater resources. In the immediate area of the strip mines, groundwater flow in the host rocks has been interrupted where strip mines have intercepted the water table, causing groundwater to enter the pits.

In the simplest conceptual model, movement of water is from areas of recharge (outcrops) downdip to areas of discharge in response to differences in the altitude of the potentiometric surface. Recharge to the aquifers is from infiltration of precipitation and streamflow on outcrops. In the San Juan structural basin, three discharge areas to stream or river reaches generally are recognized: (1) the lower reach of the San Juan River, (2) the Puerco River drainage in the southwestern part of the study area, and (3) parts of the Rio Puerco and Rio San Jose in the southeastern part of the study area. Subsurface discharge from the basin probably occurs in two areas; however, the magnitude is small. One area of discharge is the Four Corners area across the Four Corners Platform, and the other is along the southeastern part of the study area into the Rio Grande Rift. In addition to the horizontal component of flow, there is a vertical component between some aquifers.

Stream-aquifer interaction, direct recharge from precipitation, and downward leakage from the Chuska Sandstone were the external boundary conditions that were simulated. Streambed leakage contributed 135 cubic feet per second to the aquifer system, direct recharge contributed 56 cubic feet per second, and downward leakage from the Chuska Sandstone contributed 4 cubic feet per second. A computed discharge of 195 cubic feet per second to the lower reaches of the major streams and rivers in the basin balanced the steady-state water budget of the groundwater-flow system. The total steady-state outflow from the aquifer system is computed to be 195 cubic feet per second, which basinwide is equivalent to 0.14 inch per year or about 1 percent of the average annual precipitation in the basin (Kernodle, 1996).

3. GROUNDWATER SALINITY IN THE LOWER COLORADO RIVER BASIN[8]

3.1. GENERAL DESCRIPTION

The lower Colorado region is in the semiarid to arid Southwestern United States and comprises most of Arizona and adjacent small parts of California, Nevada, New Mexico, and Utah (Figure 24). The region has been divided into three socioeconomic subregions for planning purposes, and the socioeconomic subregions are superimposed on the water provinces (Figure 24). In general, the region is the Colorado River drainage basin downstream from Lees Ferry, Arizona. The Colorado River and the tributary Little Colorado, Virgin, and Gila Rivers and their tributaries drain most of the region. A few basins are drained internally, and small areas in the south and southeast drain directly southward into Mexico and the Gulf of California. The total drainage area of the lower Colorado River upstream from the Mexican border near Yuma is about 135,000 mi^2, of which about 114,000 mi^2, is in Arizona.

The southwestern part of the region generally is warm to hot, and rainfall and cloud cover are sparse. Owing partly to air-conditioning, population growth since 1950 makes it one of the fastest growing areas in the nation. The central and northeastern parts are cool to warm and receive from 8 to about 40 inches per year of rainfall. The population of the region in 1975 was between about 2.5 and 3 million. The growing season in much of the southwestern part of the region is very long, and two or three crops can be harvested from one plot during the year. However, precipitation is insufficient to mature crops, necessitating irrigation with surface water and pumped groundwater.

The economy of Arizona and the Las Vegas, Nevada, area dominate the economy of the region. The major sources of income in Arizona are from agricultural production, 21 percent; manufacturing, mainly light industry and high-technology industry, 41 percent; mining, 25 percent; and tourism, 13 percent (Valley National Bank of Arizona, 1975). The total income from these sources was about $5¼ billion per year during 1975.

Crops generate about 40 percent of the total agricultural income, and crop production is the largest consumer of water in the region. Consumption for public supply and mining is significant, and production of electrical energy is becoming a significant water-consuming industry.

3.2. GROUNDWATER PROVINCES

The Lower Colorado River Basin comprises three water provinces, which have major differences in geology, physiography, altitude, climate, and availability and use of groundwater. These water provinces are: The Basin and Range lowlands province in the southern and western parts of the region; the Plateau uplands province in the northeastern part of the region; and the Central highlands province, a traditional zone between the other two provinces (Figure 24). Groundwater use and storage calculations are presented for the socioeconomic subregions that overlap the water provinces.

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[8] Taken from Davidson (1979).

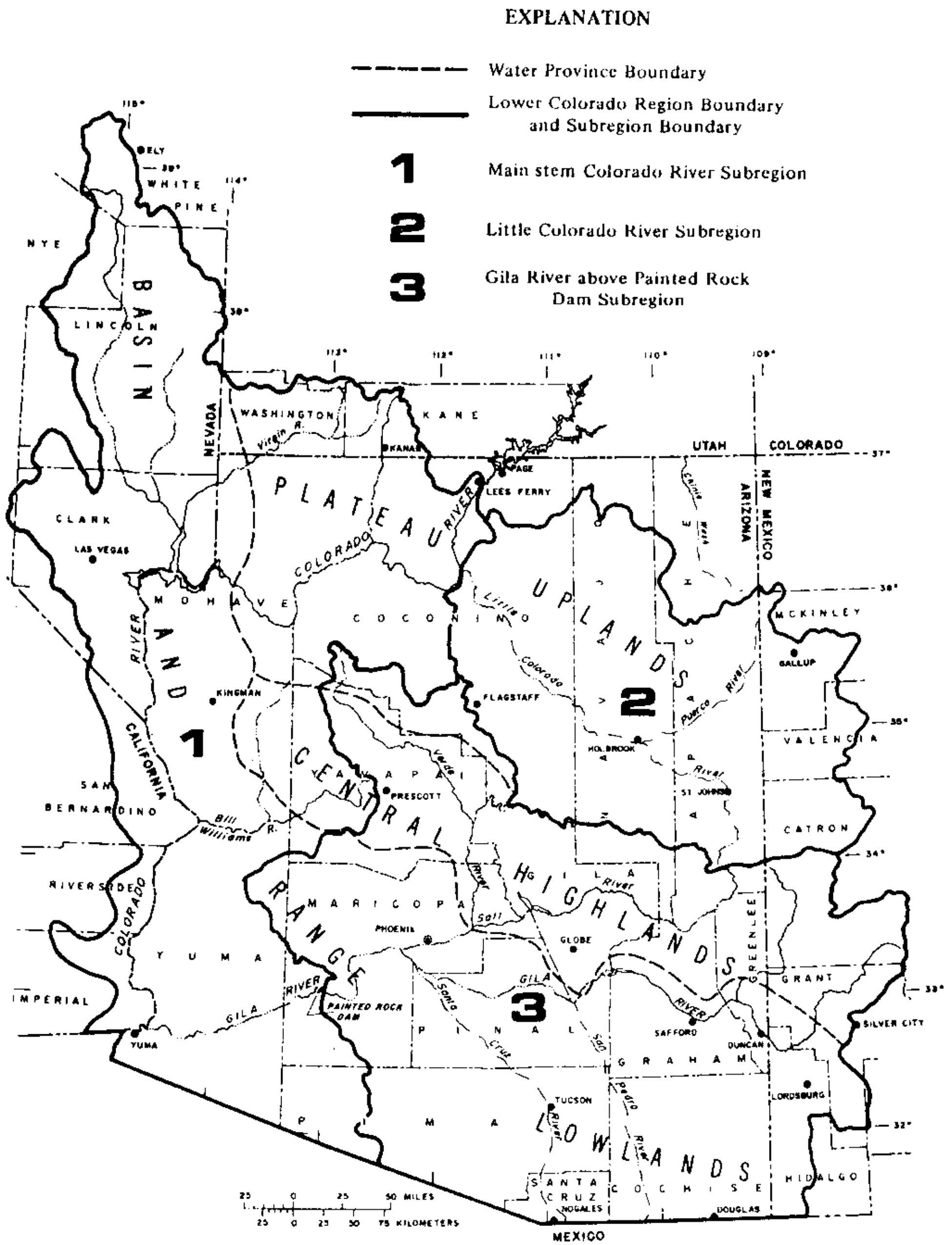

Figure 24. Water Provinces and Subregions in the Lower Colorado River Basin.

3.2.1. Basin and Range Lowlands Province

The Basin and Range lowlands province contains most of the population, is most intensively developed, and is characterized by north- to north westward-trending broad and gently sloping basins that surround and separate steep and rugged mountains. The basin surfaces are at altitudes of 100-4,500 ft above mean sea level, and the ranges crest from 1,000 to 4,000 ft higher. The average annual precipitation ranges from a low of 3 in. near Yuma to 35 in. in mountainous areas (Green and Sellers, 1964). Because of the latitude, altitude, and physiography, the lowlands is the warmest province; it has the longest growing season, the most available water, and more land suitable for agriculture than the other two provinces.

3.2.2. Plateau Uplands Province

The sparsely settled Plateau uplands province is characterized by plateaus, canyons, buttes, and mesas and contain a few dispersed volcanic mountains. Most of the province is 5,000-7,000 ft above mean sea level; the canyons are as low as 4,000 ft and the highest peaks are about 13,000 ft above sea level. Average annual precipitation ranges from 6 in. to 30 in. (Fig. 3; Green and Sellers, 1964). The climate is cooler and the growing season shorter than in the Basin and Range lowlands; the land is not as suitable for farming, either because of topography or lack of sufficient quantity or usable quality of water. Ranching and recreation are the dominant land uses.

3.2.3. Central Highlands Province

The Central highlands province is mountainous and very sparsely settled. The topography is precipitous, and the altitude ranges from 2,500 to 11,000 ft above mean sea level. Because of the mountainous terrain, the highlands are cool and receive the most precipitation. Precipitation ranges from 16 to 40 in. per year (Green and Sellers, 1964). Much of the streamflow used in the adjacent lowlands and uplands provinces originates in this province. Ranching, recreation, and mining are the dominant land uses.

3.3. Groundwater Availability and Salinity

3.3.1. Basin and Range Lowlands Province

The Basin and Range lowlands province contains extensive highly developed aquifers, which store vast quantities of good-quality water that can be pumped at rates sufficient for economic irrigated agriculture. In addition, large quantities of streamflow are stored in reservoirs and used for agriculture. The total consumptive use of groundwater is greater than the renewal of the supply, thus causing a steady decline of water levels in the aquifers.

The extensive thick sediment that fills the basins are the aquifers into which precipitation and streamflow infiltrate and are stored as groundwater. The basins are filled to depths of 5,000 to at least 10,000 ft with discrete layers to poorly-sorted deposits of clay, silt, sand and gravel. The mountains contain only small amounts of groundwater; however, precipitation increases in direct proportion to altitude, and a substantial part of the water recharged to the aquifers originates as runoff of precipitation from mountainous terrain. The mountains in Arizona and New Mexico are composed of granitic, volcanic, and some sedimentary rocks. In Nevada, many of the ranges are limestone and associated sedimentary rocks.

In general, the coarser material in the basins is found near the mountains, and fine-grained material is deposited along the axes and in the deeper parts of the basins. Volcanic rocks and evaporite deposits are interbedded with the elastic sediment in many basins. Most of these deposits are weakly to moderately consolidated, and the more deeply buried deposits are the more strongly cemented. Unconsolidated sand and gravel occur along streams and as a blanketing deposit; some are being deposited at the present time by active streams (Cooley and Davidson, 1963).

The more permeable sand and gravel beds in the uppermost parts of the basins are the most extensively developed sources of groundwater; saturated and permeable sand and gravel beds along stream channels or in blanketing deposits yield the greatest amount of water to wells, but the vast quantity of underlying thick sediment stores the greatest volume of water. In most basins, the water-yielding beds are hydraulically connected and the contained water is unconfined at shallow depths; however, in some places, and generally as depth increases, water-bearing beds are more completely separated by the less permeable beds, and semiconfined artesian conditions prevail.

The chemical quality of most groundwater is suitable for most purposes, either with no beneficiation or with minor treatment, such as softening. The dissolved-solids concentrations range from less than 100 to more than 100,000 mg/l and generally are less than 1,000 mg/l. Groundwater that contains more than 1,000 mg/l dissolved solids occurs mainly along and near the Gila River from Safford to Yuma, Arizona along the southernmost reach of the Colorado River; in the southeastern part of Nevada; and near Wilcox, Casa Grande, and Tucson. The dissolved-solids concentrations in groundwater differ areally and with depth owing to differences in the chemical character of the aquifers. For example, 1,000 ft-deep wells in the Casa Grande area penetrate mainly sand and gravel and minor thicknesses of gypsum and salty clay. Studies of water in these wells show that significant amounts of dissolved solids originate near the gypsum and salty beds. Because many wells in the region are open to the entire section of sedimentary deposits penetrated by the well, poor-quality water from such beds is mixed with better-quality water and the final well-discharge product may be so poor as to make the water nearly unusable. Additionally, because of such well construction, groundwater having high concentrations of dissolved solids may migrate through the well and into other parts of the aquifer, thereby contaminating groundwater formerly of good quality.

Generally because of increased residence time or because of greater opportunity for groundwater to pass through and dissolve chemicals from the enclosing rocks, groundwater at depth contains more dissolved solids than that nearer the surface. In some places, the concentration decreases with depth concurrent with a change in water type. In the Willcox and Tucson areas, in Pinal County, and in the Beardsley area of northwest Maricopa County, Arizona, the water grades with increasing depth from a calcium bicarbonate to a sodium bicarbonate type (Kister, 1973). Near Tucson, groundwater shows a decrease in calcium relative to sodium with increasing depth, and water at a depth of 2,000 ft contains less dissolved solids than groundwater nearer the surface (Kister, 1973; Laney, 1972).

The chemical quality of groundwater contained in rocks of the mountain blocks generally is similar to that of precipitation and surface flow and contains a lower concentration of dissolved solids than groundwater in the sedimentary rocks of the basins. The dissolved-solids concentrations, generally, are less than 1,000 mg/l. However, well yields are small compared with those in aquifers of the basin, and generally wells in mountainous areas are adequate only for individual domestic or stock supplies.

3.3.2. Plateau Uplands Province

The Plateau Uplands Province is underlain chiefly by consolidated sedimentary rocks, which consist mainly of sandstone, siltstone, claystone, and limestone. The sandstone and limestone form the chief aquifers in the area, the siltstone and claystone are nearly impermeable and form confining beds throughout most of the area. Where water-bearing beds of sandstone and limestone alternate with the confining beds, the water in the sandstone is under artesian pressure. Sand and gravel deposits along major streams form isolated "shoestring" aquifers of limited areal extent. The water in the "shoestring" aquifers is unconfined. The quantity and chemical quality of water are dependent mainly on precipitation and streamflow, but in some places these aquifers are supplied by groundwater discharging from the underlying consolidated sedimentary rocks. Ground -water generally can be produced in the eastern part of the uplands, but adequate supplies are not easily available in the western part. Despite the large amount of groundwater available in the eastern part, low well yields and poor to fair chemical quality of water restrict its use (MeGavock and Edmonds, 1974).

The dissolved-solids concentrations in groundwater in the rocks of the uplands range from 90 to more than 1,000 mg/l (Kister, 1973). The greatest concentrations are in groundwater in the Black Mesa area and in aquifers along the Zuni River and the lower reach of the Little Colorado River. Although gradation between chemical types of groundwater is common, most water with less than 500mg/l of dissolved solids is a calcium or sodium bicarbonate type, and most with more than 500 mg/l is a sodium or calcium sulfate or sodium chloride type. Very highly salinized water, however, commonly is a bicarbonate sulfate type (Kister, 1973).

3.3.3. Central Highlands Province

The Central highlands province is similar geologically to the Basin and Range lowlands, except that the mountains dominate the adjacent basins. Crystalline igneous old metamorphic rocks form much of the Central highlands; they do not store large amounts of groundwater per unit area. Small amounts of groundwater can be obtained from fractures in these rocks and from the thin sand and gravel deposits along streams that drain the mountainous terrain. Where geologic conditions are favorable in the highlands province, extensive bedded deposits of volcanic rocks and some of the few sediment -bed basins store and yield large amounts of water; the greatest water production is obtained from wells tapping these rocks.

Groundwater draining from the rocks in and near the central highlands is the source of perennial flow in the Mesa, Salt, and Verde Rivers. The dissolved-solids concentration of the water generally is less than 1,000 mg/l; however, several springs yield saline water. Clifton Salt Springs yield sodium chloride type water containing more than 9,000 mg/l dissolved solids to the San Francisco River (Kister, 1973; pl. 2). Springs along the Salt River yield sodium-chloride type water that contains more than 37,000 mg/l dissolved solids, and springs on the tributary White River yield sodium chloride water that contains more than 8,000 mg/l dissolved solids.

3.4. Groundwater Levels

In much of the region, groundwater is pumped from storage in excess of replacement, and the pumping depth to water increases in direct proportion to the volume of water pumped and the physical character of the aquifer. The most severe water-level declines are in the extensively developed Basin and Range lowlands province. Here, as water levels decline, the rate of decline commonly increases even though the pumping rate is held constant, because the aquifers tend to be more firmly cemented and less porous and permeable with depth. This combination of water-level lowering caused by removal of water from storage and the increased rate of lowering per unit of production tends to increase the cost of pumping at a geometric rather than arithmetic rate. In addition, the currently increasing cost of energy is accelerating the increase in cost of pumping. Incidence of land subsidence and earth cracks that are related to water-level decline also are a factor in the total cost of continued groundwater depletion. These hazards are relatively minor now, but increased groundwater decline probably will increase the cost to mitigate the damage attributable to subsidence.

To compare water-level changes from one year to another, the depth to water usually is measured just prior to the pumping season when water levels have recovered or nearly recovered to a uniform or virtually nonchanging level. This is called the "static" water level, even though the levels are known to be constantly changing with time. The water levels under pumping conditions generally are 100-150 ft lower than static levels in areas where large-capacity wells are producing in the range of 1,000-1,500 gal/min. The following discussion of depth to groundwater and change in water level refers to the static water level.

3.4.1. Basin and Range Lowlands Province

In most of the Basin and Range Lowlands Province, the depth to water in 1975 was less than 500 ft below the land surface, and in a large part of the area the depth to water was less than 200 ft. Water levels are shallowest along the major stream channels in the lowest parts of the basins. In a few areas, the water level is at or very near the surface, and some wells that tap artesian aquifers flow. In heavily pumped areas, the maximum annual declines are as great as 10 ft and commonly range from 2 to 6 ft (Brown, 1976, sheet 2; Babcock, 1976, sheet 2). Water-level declines since pumping started in the early 1920's generally are greater than 150 ft in most moderately to heavily pumped areas and locally are as great as 400 ft. Land subsidence of inches to about 10 feet has accompanied withdrawal of groundwater in much of central Arizona and in the Las Vegas area in Nevada. The volume of subsidence may be from 5 percent to slightly more than 30 percent of the volume of water withdrawn. In the basins, subsidence is accompanied by earth cracks or fissures, inches to feet wide and tens of feet to many miles long. The land on either side of some cracks is vertically displaced as much as 3 ft. The cracks present a hazard to highways, railroads, pipelines, buildings, etc. Some potential locales for earth cracks have been identified, but generally, potential fissure locales cannot yet be accurately predicted.

3.4.2. Plateau Uplands Province

In the Plateau Uplands Province, the depth to water is greater than 500 ft in much of the area and is less than 200 ft mainly along the Little Colorado and tributary Puerco and Zuni Rivers. Near Flagstaff, Arizona, the depth to water in municipal wells is 1,100-1,300 ft below the land surface and to the west is as great as 2,840 ft (Babcock, 1976, sheet 2). Because withdrawal in the uplands does not generally exceed recharge, water levels generally show no decline. Declines of about 2 ft per year have occurred in small areas near Snowflake, Arizona and along the Little Colorado River northeast of Snowflake.

3.4.3. Central Highlands Province

In the mountainous areas of the Central Highlands Province, water levels in wells range from a few tens to about 300 ft below the land surface. In the parts of the area underlain by volcanic rocks, depths to water are from a few feet along major streams to more than 500 ft elsewhere. In the few sediment-filled basins, the water levels generally are less than 200 ft below land surface along streams and deeper away from the streams. Any change in water levels in this province generally is temporary because of ample recharge, except for a few areas where water levels decline about 1-2 ft per year (Brown, 1976, sheet 2; Babcock, 1976, sheet 2).

3.5. WELL YIELDS

The greatest yield of water to wells in the lower Colorado region is in the Basin and Range Lowlands Province (Brown, 1976, sheet 3; Babcock, 1976, sheet 2). Large diameter water wells tapping the permeable sand and gravel beds in the basins and along the Colorado River are capable of yielding more than 2,500 gal/min, although most wells in the basins are pumped at 500 to 1,500 gal/min. In the mountainous parts of the province, well yields generally are less than 100 gal/min and commonly are less than 10 gal/min.

The major aquifers of the Plateau uplands are capable of yielding at least 10 gal/min of water to wells, and locally irrigation wells produce as much as 2,000 gal/min. Wells in the sand and gravel beds along streams generally can produce 100 gal/min or more from shallow depths. In contrast, wells tapping the sandstone and limestone aquifers generally must be 500-1,000 ft deep to produce the same yield. In some areas it may be possible to produce, at high cost, good-quality water from depths of thousands of feet, but the deeper units have not yet been adequately prospected.

In the Central Highlands Province, well yields generally range from about 10 gal/min in the mountainous areas to 1,000 gal/min in places along streams or where wells are in thick saturated sediment or volcanic rock.

3.6. Groundwater Storage

The alluvial aquifers in the lower Colorado region contain vast amounts of physically recoverable groundwater in storage (Table 15). Along the main stem of the Colorado River and in the Gila River drainage basin, about 1 billion acre-ft of groundwater is estimated to be recoverable from storage in the aquifers from the water table to a depth of about 700 ft below the land surface; in addition, about 150 million acre-ft of recoverable groundwater is stored in a typical 100-ft-thick section of aquifer in the Little Colorado River subregion of the Plateau uplands province. These large quantities are in marked contrast to the usable capacity of the principal surface-water reservoirs; their capacity is 32 million acre-ft in the lower Colorado River Basin and 65 million acre-ft throughout the Colorado River Basin. However, groundwater storage has accumulated over hundreds to thousands of years, but the surface-water storage is replenished yearly.

3.7. Summary of Groundwater Use

Almost 6 million acre-ft of groundwater was pumped in the Lower Colorado region in 1975 (Table 16). The increase in pumpage for the region over the years parallels the pumpage increase in Arizona (Figure 25). The major use of this water is for irrigated agriculture. Industrial uses, especially for mining and power generation, are increasing, as is municipal use because of the increase in population in some parts of the region. However, in 1975 industrial and municipal uses accounted for less than 10 percent of the total. Rural, domestic, and livestock supplies accounted for only a minor amount of the total groundwater pumped in the region.

The largest use of groundwater is in the Basin and Range lowlands, particularly in the Gila River above Painted Rock Dam subregion (Figure 24, Table 16). In 1975, almost 85 percent of the total region pumpage was extracted and applied in the Gila River subregion and most of that was pumped in Arizona. Of that total subregion pumpage of almost 4.9 million acre-ft, about 8 percent, 412,000 acre-ft, was used for industrial and municipal purposes. Some small part was pumped for drainage and for rural, domestic, livestock, and miscellaneous uses- 91 percent, 4.4 million acre-ft, was used for irrigation of crops. The next largest use is in the main stem Colorado River subregion, where almost 860,000 acre-ft was pumped in 1975. As in the Basin and Range lowlands, the major use (about 90 percent) was for irrigation, including a substantial amount of pumpage to drain waterlogged land to permit irrigated agriculture. The pumpage in the Little Colorado River subregion, which encompasses most of the Plateau uplands water province, was only about 75,000 acre-ft in 1975 (Table 16) and agriculture accounted for about 41 percent-- considerably less than in the other two subregions.

Table 15. Estimated Volume of Recoverable Groundwater in Storage in the Main Alluvial Aquifers in the Lower Colorado River Basin (Davidson, 1979). {Modified from Brown (1976). Numbers rounded. See Figure 24 for subregion boundaries}.

	Volume of recoverable groundwater, in millions of acre-feet				
Subregion and State	From land surface to 200 ft below land surface[1]	From water table to 100 ft below water table	From water table to 700 ft below land surface	From 700 ft to 1,200 ft below land surface	From water table to 1,200 ft below land surface
Main Stem Colorado River Subregion					
Arizona	27	56	290	140	430
Nevada	12	53	140	45	180
Utah[2]					
California[3]					
Rounded total for subregion	40	110	430	190	610
Little Colorado River Subregion:		[4]150			
Gila River above Painted Rock Dam subregion:					
Arizona	58	96	520	260	780
New Mexico	12	18	78	15	93
Rounded total for subregion	70	110	600	280	870
Rounded total for lower Colorado region (excludes Little Colorado River subregion)	110	220	1,030	470	1,480

1 Depth to water is 200 feet or less below the land surface in 13,600 square miles-10,900 squares miles in Arizona, 1,500 square miles in Nevada, and 1,200 square miles in New Mexico. The total square miles constitutes about 10 percent of the region.

2 The quantity of groundwater stored in the alluvial aquifers in Utah is minor, the quantity in consolidated rocks is not calculated.

3 The quantity of groundwater in the California segment is poorly known; because it is considered to be minor, it was not calculated for this study.

4 The Little Colorado River subregion is underlain by the D, N, and C aquifers, which are mainly consolidated rocks; groundwater storage in the alluvial aquifers is minor. About 16 million acres are underlain by the three aquifers, and about 150 million acre-feet of groundwater are stored in a typical 100-foot-thick section of aquifer.

Slightly more than 175,000 acre-ft of groundwater was used in 1975 for industrial use, and more than half of this was used for mining. Most of the remainder was used for energy production.

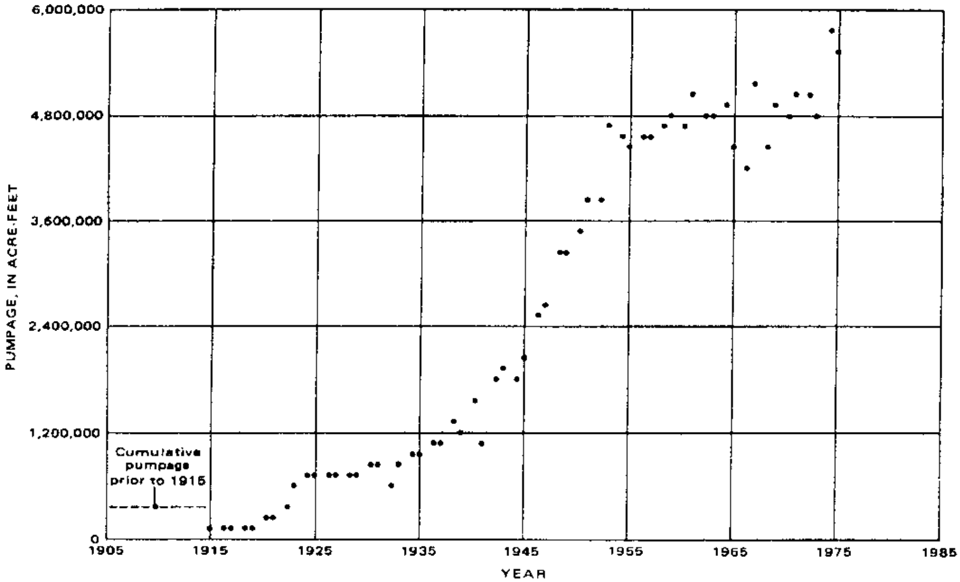

Figure 25. Pumpage in Arizona from Prior to 1915 to 1975.

Table 16. Estimated Groundwater Pumpage by Subregion and Use in the Lower Colorado River Basin, 1975 (Davidson, 1979).

[Data from U.S. Bureau of Reclamation (1975) and from the files of the U.S. Geological Survey offices in Arizona, Nevada, New Mexico, and Utah. Numbers rounded to nearest 100 acre-feet except as indicated. See Figure 24 for subregion boundaries].

Subregion and State	Pumpage, in acre-feet				
	Agriculture	Drainage associated with agriculture	Industrial	Public supply, domestic, and other	Total (rounded to nearest 500 acre-feet)
Main stem Colorado River subregion					
Arizona	312,400	368,000	7,800	4,200	692,500
California	19,500		200	7,800	27,500
Nevada	48,800		15,700	60,300	125,000
Utah	10,500		1,000	1,000	12,500
Total	391,200	368,000	24,700	73,300	857,500
Little Colorado River subregion:					
Arizona	30,800		18,300	13,900	63,000
New Mexico	900		8,200	3,400	12,500
Total	31,700		26,500	17,300	75,500
Gila River above Painted Rock Dam subregion:					
Arizona	4,358,100	16,000	124,500	285,300	4,784,000
New Mexico	83,000		20	2,100	85,000
Total	4,441,100	16,000	124,520	287,400	4,869,000
Grand total	4,864,000	384,000	175,700	378,000	5,802,000

Water used in energy production is becoming a more significant consumptive use every year in the lower Colorado region; evaporation of water to condense exhaust steam accounts for the greatest consumption (Davis and Wood, 1974, p. 3). The average rate of water use per unit of energy capacity is about 15 acre-ft per year per megawatt (1,000 kilowatts) for fossil-fueled plants, 22 acre-ft per year per megawatt for nuclear-fuel plants, and 48 acre-ft per year per megawatt for geothermal power plants (Davis and Wood, 1974, p. 8). Water consumption in the region for electric power in 1965 was reported as 9,600 acre-ft (Pacific Southwest Interagency Committee, 1971c, p. 129), and by 1970 in Arizona alone the consumption had increased to 36,000 acre-ft (Murray and Reeves, 1972, p. 24). Groundwater made up slightly more than 95 percent of the consumption. Since then, consumption of groundwater has increased, and two new plants using Colorado River water have started in operation. The consumption in the region in 1975 was about 67,000 acre-ft, of which about 35,000 acre-ft, or 52 percent, was supplied from groundwater.

Yearly increases in peak demands of 400 to almost 1,400 megawatts are estimated by the Electric Power Work Group of the framework study for the period 1970 to 2000 (Pacific Southwest Interagency Committee, 1971b, p. 49) compared to increases of 160-180 megawatts in the period 1955-65. Energy capacity estimates of the Economic Work Group that contributed to the same framework study are in the lowermost range (Pacific Southwest Interagency Committee, 1971a, p. 140) of peak demand predicted by the energy group. Some of the power to meet this demand will be generated outside the lower Colorado region.

The water demand anticipated by the Energy Work Group for 1980 is about 36,000 acre-ft and in the year 2000 is 106,000 acre-ft (Pacific Southwest Interagency Committee, 1971b, p. 36, 38; 1971c, p. 129). A water demand of 37,800 acre-ft in 1980-plus 7,400 acre-ft of initial supply for pumpback-power generation was calculated by the Economics Work Group (Pacific South-west Interagency Committee, 1971c, p. 144). However, in the year 2000, the calculation based on the economic analysis is a consumptive use of only 38,800 acre-ft-plus 9,300 acre-ft for initial supply in pumpback-power generation (Pacific Southwest Interagency Committee, 1971b, p. 144) or less than 40 percent of the amount predicted by the Energy Work Group (Pacific Southwest Interagency Committee, 1971b). Both estimates may be low; on the basis of ongoing power-generation station construction and announced plans for new construction, a consumptive use of at least 100,000-150,000 acre-ft per year should be anticipated. Estimates prepared for the Energy Research and Development Administration predict a 10-fold growth between 1975 and 2000 in water consumption for energy development (MITRE Corp., 1977, p xiv).

3.8. GROUNDWATER POTENTIAL

The history of water development in the lower Colorado region is one of surface-water supplies being "supplemented" by water from storage in the groundwater reservoirs. The State of Arizona projected alternative levels of water development that are thought to bracket the range of possible future consumptive use in the State (Arizona Water Commission, 1977). The report concludes that "water supplies of the State would either have to be augmented, or groundwater overdraft increased substantially, for that "uses be reduced to a level that can be sustained with existing dependable supplies without resorting to appreciable groundwater overdraft" (Arizona Water Commission, 1977, p. xiii). The projections (Table 17) are for consumptive use of all water estimated for 1970 and projected to 1990 and 2020. Projections for the parts of Nevada, California, Utah, and New Mexico in the region might show the same ratio of increase for urban use, mineral production, and electric generation, probably resulting in a reduction in agricultural use. In 1975 the use of groundwater was more than 1.5 times that of surface water, and the potential for further economic or large-scale groundwater development was constrained by location and availability, depth to water, poor chemical quality, and potential hazards.

Table 17. Projections of annual water depletion in Arizona.

[All values in thousands of acre-feet per year. Source: Arizona Water Commission (1977, p. 2-5, 67-72)].

Consumptive water use	Estimated for 1970	Projected for	
		1990	2020
Urban	328	423-568	542-950
Steam-electric generation	20	109-178	248-787
Mineral production	131	236-337	265-841
Agricultural	4,300		
Highest		4,600	4,500
"Zero overdraft"		3,800	2,500

Large-scale withdrawal of groundwater presents some problems, particularly in the Basin and Range Low-lands. Land subsidence has occurred in the Lass Vegas area in Nevada and in Arizona. Earth cracks, many miles long and that range from a few inches to several feet wide, are widespread in central Arizona, mainly on the perimeter of the areas of greatest water level decline and particularly where much of the withdrawn groundwater was stored under partially confined (semiarteasian) conditions (Schumann, 1974). Increased pumping of groundwater in these areas will increase the problems of subsidence and earth cracks. Likewise, continued large-scale withdrawal of groundwater from areas not yet affected probably will cause additional land subsidence and earth cracks. In some areas in this part of the lower Colorado region, a part of the recoverable groundwater in storage contains dissolved solids substantially in excess of 1,000 mg/L and requires treatment to make it suitable for most uses. Some areas where large amounts of groundwater are stored are remote from areas of potential use. Use of this water requires either transport of the water or very high cost of new developments in the immediate vicinity of the supply. Large amounts of water can be obtained from some of the deeper basins, but much of the untapped groundwater reserves are at depths of more than 500 ft. Use of this water is costly and would require detailed well design and spacing and the construction of much deeper wells than currently exist in most areas.

In the Plateau uplands the few alluvial aquifers do not store large amounts of groundwater. However, the sandstone and limestone aquifers store very large quantities of recoverable groundwater, but the potential for large-scale future use is limited by low to moderate well yields.

In the Central Highlands the storage of groundwater is not large per unit area except in a few basins. In these basins and in some parts of the Uplands province in eastern Arizona and western New Mexico, where volcanic rocks dominate, water supplies are large and dependable enough to support small communities and industries. The water supply in the Central Highlands province probably is adequate for most foreseeable developments, largely because the terrain is not conducive to large-scale agriculture or heavy industry, except mining. The mining industry may be able to design for lower water consumption than is the current normal practice. Water use for tourism and recreational facilities is the largest use of ground and surface water in the area.

Sewage effluent is discharged onto permeable areas where it infiltrates to groundwater or is reused for irrigation or industrial purposes. In some places the effluent is discharged into a flowing stream or a body of water; for instance, some of the treated effluent from the Las Vegas area is discharged via Las Vegas Wash into Lake Mead. The dissolved-solids concentration of the effluent may be less than that of the native groundwater in the area of discharge. This condition hlods for the Phoenix, Tucson, and Las Vegas areas. In other places, particularly the smaller cities and towns, the reverse is true. The principal disadvantage of recharged sewage effluent is its concentrations of boron, nitrate, and phosphate. Sufficient concentrations of boron are injurious to growing plants, nitrate concentrations greater than 10 mg/l are a health threat to infants (National Academy I of Sciences and National Academy of Engineering, 1973, p. 73), and nitrate and phosphate compounds encourage unwanted vegetal growth where effluent wet surface soil or enters surface-water bodies.

In most parts of the region, sewage effluent is considered a cheaply available source of water, and considerable effort has gone into reusing the resource. The Tucson metropolitan area now uses effluent to water a park and hopes to use a major part for industrial purposes and possibly to irrigate crops. Effluent from the Phoenix metropolitan area is used for irrigation, and effluent from Las Vegas is used for irrigation of crops and a minor amount in power generation. Effluent from most other communities in the region is not consciously reused and is either discharged to flowing streams, recharged to groundwater, or evaporated.

The trend in the region seems to be toward greater use of sewage effluent in industrial processes, such as copper-ore beneficiation, power generation, and cooling. Much effluent is used to irrigate forage crops, but owing to cost and conservation factors that might give higher priority to public supply and industrial use, irrigation usage seems likely to diminish.

Saline water generally is not used in the Lower Colorado River Basin. Large quantities of saline groundwater occur, and as much as 50,000-70,000 acre-ft per year may be lost to evaporation or to uncontrolled transpiration by plants. However, the cost of treatment to allow use of saline water is so high as to be prohibitive if other water sources are available.

In northern Arizona, considerable water is lost to evapotranspiration along the Little Colorado River (Figure 24). There, saline water underlies freshwater, and a mixture of both is near the surface and adds to the river flow. Withdrawal of the fresh groundwater for projected expansion of a thermal powerplant in the area will reduce the head in the entire aquifer, and with time the flow of both freshwater and saline water to the surface will diminish. It is not now economic to use saline water in powerplants, but in this case, usage of freshwater will reduce loss of both freshwater and saline water.

In other parts of the region, large quantities of saline groundwater are available, and as freshwater becomes more and more expensive to pump or transport, these saline-water bodies will be developed. Depending on the location and the quantity withdrawn, the quantities in storage (Table 15) will assure a 30- to 100-year supply or perhaps longer. Large reserves of saline groundwater are present along the Little Colorado, Gila, and the Salt Rivers in Arizona, and small to moderate amounts are present along other smaller rivers in the region (Feth and others, 1965). The opportunity to produce large permanent supplies is poor, but the prospect for some short-term developments, roughly 30 years, is good. Additionally, use of saline water will keep such water from migrating into and contaminating adjacent bodies of freshwater. This use is particularly indicated where the groundwater flow is from the area of saline water toward the area of freshwater, and the flow rate is increased with time because of removal of freshwater.

In some areas near cities in Arizona, groundwater contains concentrations of nitrate, fluoride, and chromium in excess of the recommended or mandatory drinking water standards of the National Academy of Sciences and National Academy of Engineering (1973). Some of this water is too highly mineralized to be used directly, but it could be mixed with better-quality water and used for public supply.

4. GROUNDWATER SALINITY ISSUES

4.1. GROUNDWATER OVERVIEW

There are tremendous differences in groundwater availability and use between the Upper Colorado River Basin (UCRB) and the Lower Colorado River Basin (LCRB). The surface water supplies are highly developed with reservoir storage exceeding four times the mean annual flow of less than 15 maf. The LCRB is entitled to 7.5 maf per year, with roughly another 6 maf of groundwater pumpage. In contrast, the UCRB is annually extracting more than 6 maf, whereas groundwater pumpage is only 2-3 percent of this amount.

To provide an overview of the groundwater situations presented in Section 2 (UCRB) and Section 3 (LCRB), the various groundwater study areas have been placed on a map of the Colorado River Basin (Figure 26). This will facilitate the presentation of information in this Section 4.

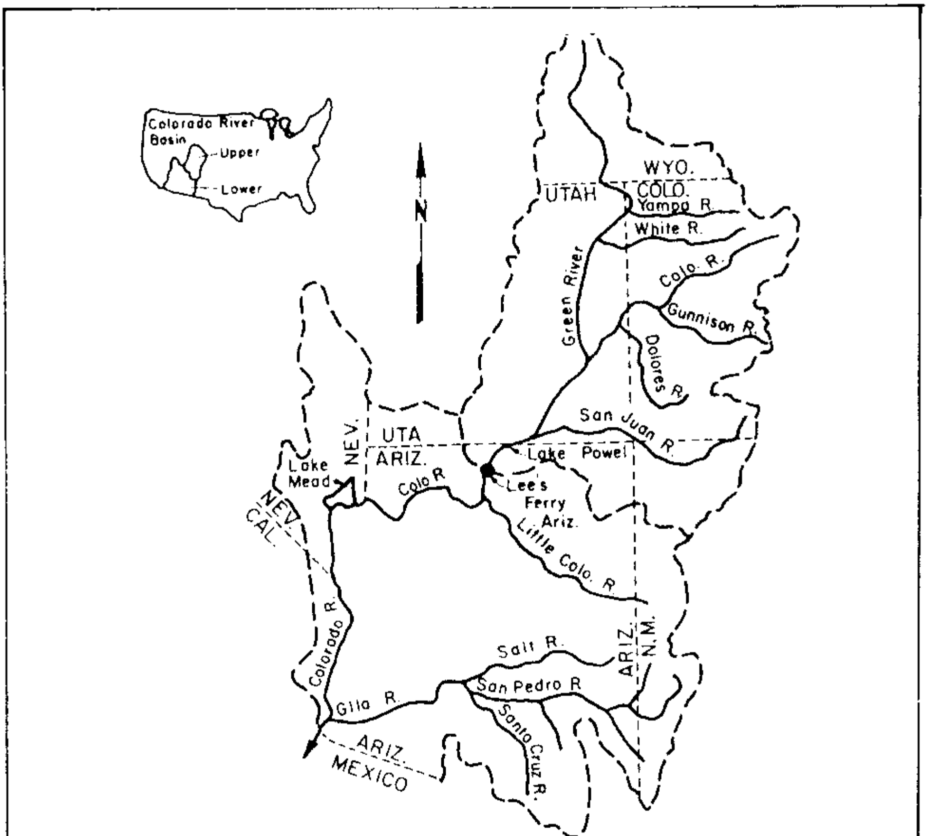

Figure 26. Location of groundwater study areas in the Colorado River Basin.

4.1.1. Upper Colorado River Basin

There are two areas that were not presented in Section 2: (a) the Upper Green River in the state of Wyoming; and (b) the Upper Uinta Basin in the state of Utah. Much of the agriculture in these areas support livestock production. The surface water supplies are rather ample. There is a paucity of data regarding groundwater use in Wyoming. For the Upper Uinta Basin, irrigated agriculture is quite developed, with the vast majority of the irrigation supply being very good quality surface water.

For the Upper Colorado River (Section 2.2), the Mancos Shale is the geologic formation very high in salts, with a median value of 3,745 mg/l of total dissolved solids (TDS), which is greater than the median value of electrical conductivity (3,110 microsiemens) because this formation is high in calcium sulfates (Table 1). The Mancos Shale is prevalent in the agricultural areas surrounding the cities of Montrose, Delta and Grand Junction (Figures 5 and 8), thereby precluding the use of groundwater. The other geologic formations generally have good quality groundwater suitable for irrigation, with much of this subsurface water also good for human consumption. Of the total water use in this region, groundwater represents only one percent.

The groundwater potential in the southeastern Uinta Basin (Section 2.3) is only 200,000 acre-feet (Table 4). Most of the groundwater is unsuitable for drinking or irrigation. The mean TDS is commonly 2,000-6,000 mg/l and often higher (Table 5). The primary utility of this groundwater is to support the future processing of oil shale, where the brine water can be used for cooling.

As a result of searching for oil, gas and sites for nuclear waste repositories, large supplies of groundwater have been discovered in the Colorado Plateau (Section 2.4) in Plaeozoic formations throughout southeastern Utah. A large area surrounding Lake Powell (Figure 15) has a groundwater salinity of less than 1,000 mg/l, part of which can be used to support tourism and recreation. However, much of the Colorado Plateau contains groundwater ranging from 1,000 – 10,000 mg/l (Figure 15), which can be used to support energy development (coal and oil shale).

The San Juan River is a major tributary to the Colorado River (Figure 1). Groundwater in the San Juan Basin (Section 2.5) has been heavily investigated. The groundwater is used for a wide variety of purposes; however, the high degree of investigation is related to proposed energy developments, particularly coal and uranium. Natural gas and thermal power production are also important. The primary sources of groundwater are alluvial materials underlying river channels, the Gallup Aquifer, Dakota Aquifer and Morrison Aquifer. Nearly half of the wells in these aquifers had a TDS of less than 1,000 mg/l, while about one-fourth had TDS values ranging from 1,000-2,000 mg/l and the remaining wells were greater than 2,000 mg/l. A model study of these aquifers disclosed the total groundwater outflow to be 195 cfs.

Recognizing the extreme variability in groundwater salinity throughout the UCRB, indicates that the withdrawal of groundwater from a well must be carefully done regarding which geologic formations are selected for well-casing perforations or screens. Another major concern is that heavy groundwater withdrawals will likely result in more saline groundwater from an underlying or overlying formation moving into the fresh water formation. Also, many of these geologic formations will only provide small well yields, sometimes less than 100 gal/min (7 lps).

4.1.2. Lower Colorado River Basin

The Basin and Range Lowlands (Figure 24) in the lower portions of the Lower Colorado River Basin (LCRB) is the major groundwater producing area for the entire Colorado River Basin, where large-capacity wells range from 1,000-1,500 gal/min (63-94 lps). Most of the groundwater has a total dissolved solids (TDS) of less than 1,000 mg/l. There are wells at depths of 1,000 feet in some locations that encounter gypsum and salty clays, while at other places there are wells 2,000 feet deep that have better quality water than found at shallower depths in the same locations.

The surface water allocation to the LCRB is 7.5 maf/yr., which is being fully utilized. The annual groundwater pumpage is nearly 6 maf/yr. (Table 16). The mult-billion-dollar Central Arizona Project began pumping from the Colorado River in the last half of the 1980s, which will reduce the groundwater overdraft to 2.5 maf/yr. Fortunately, the estimated volume of recoverable groundwater to a depth of 1,200 feet below the ground surface (Table 15) is 1,480,000,000 acre-feet (af).

In most of the Basin and Range Lowlands, the depth to water was less than 500 feet twenty-five years ago, with some areas less than 200 feet. The annual decline in groundwater levels is 2-6 feet, with some areas as much as 10 feet per year. During the first 50 or more years of pumping, groundwater levels have been lowered by more than 150 feet in most moderately to heavy pumped areas (Davidson 1979). Presently, groundwater levels have been likely lowered another 160 feet or more, implying that since pumping began in the 1920s, water levels have declined by more than 250 feet.

The large declines in groundwater levels have resulted in serious problems of land subsidence, which has amounted to as much 10 feet (3 m). This subsidence results in earth fissures from a few inches to a few feet in width and sometimes miles in length. The vertical displacement on the two sides of the fissure can be as much as three feet. These earth fissures are particularly damaging to a wide variety of structures (Davidson 1979).

4.2. AGRICULTURE

4.2.1. Livestock

There is a considerable livestock industry in the UCRB. The Bureau of Land Management (BLM), US. Dept. of the Interior and the U.S. Forest Service manage the rangelands, forests and mountain landscapes. Each rancher has a permit for so many animal-months, in a specified land area. Thus, during the summer months, most livestock are grazing on these rather extensive areas. In the fall, each rancher collects their cattle and herd them to pasture areas in the more low-lying valleys. These animals are fed during the winter from forage and grain crops produced on irrigated lands during the summer in the low-lying valleys.

4.2.2. Irrigation

Along the valley floors in the UCRB, lands are irrigated. Much of the irrigated lands produce alfalfa and grain crops for feeding animals during the cold winter months when the croplands lie dormant. There are also high elevation meadows that produce grasses that are harvested for animal feed during the winter. In addition, there are some orchard crops.

There is also livestock production in the LCRB, but there is scant rainfall so the potential is much less than in the UCRB. More important, is commercial agriculture being practiced throughout the year. Some common irrigated crops are citrus, melons and vegetables. For the western U.S.A., most of the winter vegetables in the food supermarkets have been grown in southern Arizona and southern California. Arizona uses surface waters tributary to the Colorado River and extensive groundwater pumpage. Southern California mostly uses water diverted from the Colorado River.

4.3. URBAN GROWTH

The estimated population for the UCRB in 1980 was more than 400,000, which has been projected to become 700,000 by the year 2020. The water supply required for this increased population can be readily acquired from groundwater, or water transfers from irrigated agriculture to urban areas.

For the LCRB, the 1980 population of 3,000,000 is expected to become 7,000,000 by the year 2020, with much of this urban growth occurring in the areas surrounding the cities of Phoenix and Tucson in Arizona. The Central Arizona Project, which has been operational for ten years, can satisfy the future domestic and industrial water demands. In addition, most of the irrigated land surrounding Phoenix is now urbanized, so that groundwater can now be used for municipal and industrial uses, rather than irrigated agriculture.

4.4. ENERGY DEVELOPMENT

The Colorado River Basin is extremely important to the U.S.A. in terms of future energy development. There are extensive coal reserves, which are presently being strip-mined; in some cases to fuel nearby thermal power plants, with the electricity tied into an extensive grid covering the western U.S.A. Uranium mining has been important since the 1940s, with extensive deposits still remaining. Also, natural gas is being produced, which will be further expanded in the future.

There are extensive oil shale deposits in the UCRB. Many of the private oil companies have been doing research for a few decades, including pilot plants. About 1980, the required price per barrel of oil was $14 for oil shale processing to be economical. Consequently, the future processing of oil shale is highly dependent upon world oil prices. When oil prices become roughly $25-30 per barrel, then the oil shale operations will most likely begin.

Most of the groundwater investigations reported in Section 2 were instigated because of potential energy development. Although well yields in many aquifers will be low, so that the cost of obtaining water will be high, such costs are almost insignificant in constructing energy facilities. Fortunately, fairly saline groundwater can be used for some purposes, such as cooling. The greater difficulty will be acquiring potable groundwaters, which requires considerable technical expertise, but this can certainly be accomplished,. The major value of groundwater is that it is more extensively available over the landscape when compared with surface water supplies.

4.5. MANAGING AMERICA'S MOST FULLY UTILIZED RIVER BASIN

Energy development will occur in the Upper Colorado River Basin. This will involve a fair degree of groundwater development over the next 20-30 years, as well as surface water transfers, most likely from irrigation. The basin-wide non-degradation salinity policy for the lower stem of the Colorado River requires that each development offset any salinity detriments by making improvements on-site or somewhere else in the basin (off-site).

Salt concentrating effects will occur if the salinity of the groundwater supply for energy development is more than the salinity in the lower stem of the Colorado River, or if the surface water supply is less saline, then the lower stem of the Colorado River. Such effects can be eliminated by mixing a saline water supply with a high quality water source in such proportions that the average salinity is equal to present salinities in the lower stem of the Colorado River.

Processed oil shale waste disposal piles or coal strip-mining operations have potential for salt pickup from either-surface runoff or subsurface percolation. Good management practices will alleviate much of this potential water quality degradation. Surface return flows can be collected, ponded and evaporated. Subsurface return flows can be collected by using skimming wells.

There are advantages in allowing the salinity detriments resulting from an energy complex to be alleviated by off-site improvements. One of the most viable alternatives is to make improvements in an irrigation system, including canal lining and on-farm irrigation improvements. Such investments benefit agricultural productivity, as well as decrease irrigation diversion requirements.

With modification to western water laws (Skogerboe and Radosevich, 1982), economic incentives and administrative programs could be provided so that decreased diversion requirements could be sold, contracted or rented to other water demands (e.g. oil shale or coal gasification) with the revenues being used largely for further irrigation system improvements that would reduce the salt loads reaching the Colorado Rvier.

During the 1990s, the Metropolitan Water District of Southern California has been investing more than U.S.$ 100 million for improvements in the Imperial Irrigation District, which receives water diverted from the Colorado River near Yuma, Arizona. The water savings will be pumped over the mountains in the existing Colorado River Aquaduct to serve the metropolitan areas from Los Angeles to San Diego. Undoubtedly, similar water transfers will occur a number of times during the next century to meet water demands outside of the Colorado River Basin. During this process, marginal irrigated lands will be taken out of production and the remaining croplands will become increasingly more productive as better water management practices are implemented.

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