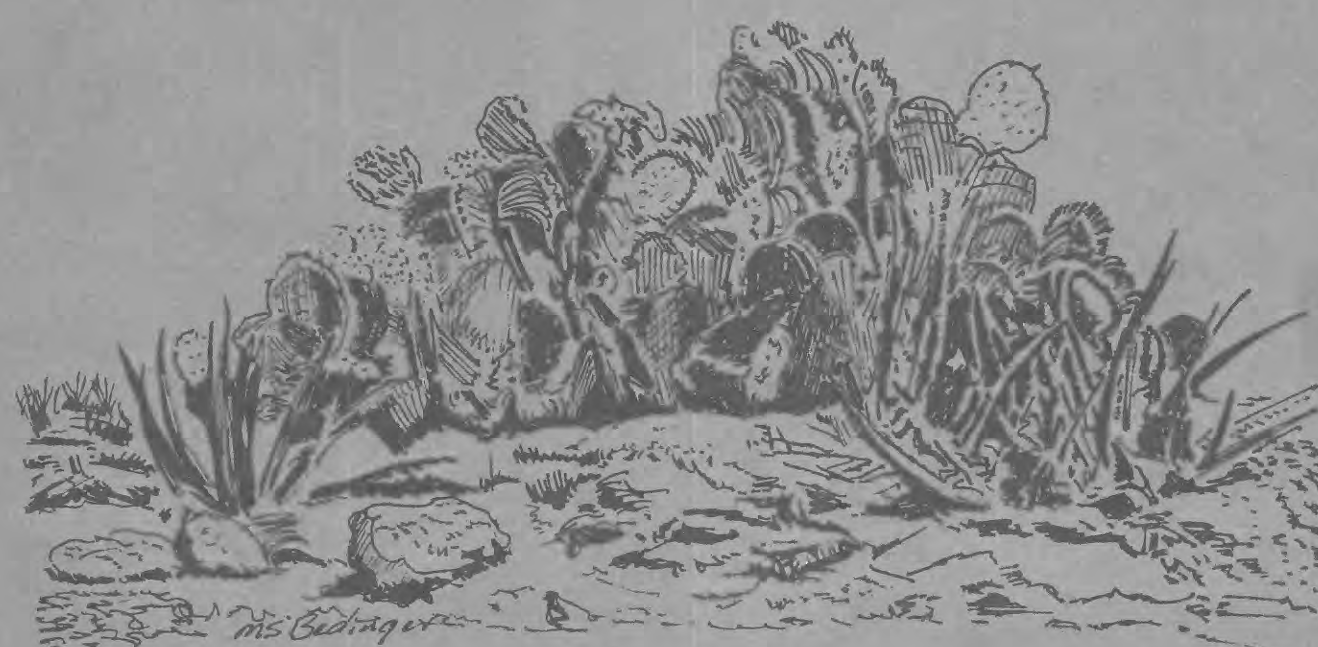
Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, For Isolation of High-Level Radioactive Waste— Basis of Characterization and Evaluation

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370-A

Prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah



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By M.S. BEDINGER, K.A. SARGENT, WILLIAM H. LANGER, FRANK B. SHERMAN, J.E. REED, *and* B.T. BRADY

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1989

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Bedinger, M. S.
Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste—basis of characterization and evaluation.

(U.S. Geological Survey professional paper ; 1370-A)
"Prepared in cooperation with the states of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah."
Bibliography: p.
Supt. of Docs. no.: I 19.16:1370-A
1. Geology—West (U.S.) 2. Water, Underground—West (U.S.) 3. Radioactive waste disposal in the ground—West (U.S.) I. Sargent, Kenneth A. II. Title. III. Series.
QE79.B44 1989 557.9 86-600319

For sale by the Books and Open-File Reports Section, U.S. Geological Survey, Federal Center, Box 25425, Denver, CO 80225

BASIN AND RANGE PROVINCE WORKING GROUP

U.S. Geological Survey Members

Chairman of the Province Working Group:
M.S. Bedinger
Hydrologist
Denver, CO

Member:
K.A. Sargent
Geologist
Denver, CO

State Members and Alternates

ARIZONA

Member:
Larry D. Fellows
State Geologist and Assistant Director
Arizona Bureau of Geology and Mineral Technology
Tucson, AZ

Alternate:
H. Wesley Peirce
Principal Geologist
Arizona Bureau of Geology and Mineral Technology
Tucson, AZ

CALIFORNIA

Member:
Robert Streitz
Geologist
California Division of Mines and Geology
Sacramento, CA

IDAHO

Member:
Frank B. Sherman
Chief, Ground-Water Section
Idaho Department of Water Resources
Boise, ID

Alternate:
Darrel Clapp
Chief, Technical Services Bureau
Idaho Department of Water Resources
Boise, ID

NEVADA

Member:
John Schilling
State Geologist
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Reno, NV

Alternate:
Susan L. Tingley
Deputy to the State Geologist
Nevada Bureau of Mines and Geology
University of Nevada, Reno
Reno, NV

NEW MEXICO

Member:
James Hill
Chief, Bureau of Geology
New Mexico Energy and Minerals Department
Santa Fe, NM

Alternate:
Frank E. Kottlowski
Director
New Mexico Bureau of Mines and Mineral Resources
Socorro, NM

TEXAS

Member:
Christopher D. Henry
Geologist
Texas Bureau of Economic Geology
University of Texas at Austin
Austin, TX

Alternate:
Douglas Ratcliff
Geologist
Texas Bureau of Economic Geology
University of Texas at Austin
Austin, TX

UTAH

Member:
Genevieve Atwood
State Geologist
Utah Geological and Mineral Survey
Salt Lake City, UT

Alternate:
Don R. Mabey
Senior Geologist, Applied Geology
Utah Geological and Mineral Survey
Salt Lake City, UT

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CONVERSION FACTORS

For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

Multiply SI unit	*By*	*To obtain U.S. customary unit*
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
square centimeter (cm^2)	0.1550	square inches ($in.^2$)
	Flow	
meter per day (m/d)	3.281	foot per day (ft/d)
	Temperature	
degree Celsius (°C)	9/5(°C)+32 = °F	degree Fahrenheit (°F)
	Pressure	
pascals (Pa)	0.000009869	atmosphere

STUDIES OF GEOLOGY AND HYDROLOGY IN THE BASIN AND RANGE PROVINCE, SOUTHWESTERN UNITED STATES, FOR ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE—BASIS OF CHARACTERIZATION AND EVALUATION

By M.S. BEDINGER, K.A. SARGENT, WILLIAM H. LANGER, FRANK B. SHERMAN[1], J.E. REED, and B.T. BRADY

ABSTRACT

The geologic and hydrologic factors in selected regions of the Basin and Range province were examined to identify prospective areas for further study that may provide isolation of high-level radioactive waste from the accessible environment. The six regions selected for study were characterized with respect to the following guidelines: (1) Potential repository media; (2) Quaternary tectonic conditions; (3) climatic change and geomorphic processes; (4) ground-water conditions; (5) ground-water quality; and (6) mineral and energy resources.

The repository medium will function as the first natural barrier to radionuclide travel by virtue of associated slow ground-water velocity. The principal rock types considered as host media include granitic, intermediate, and mafic intrusive rocks; argillaceous rocks; salt and anhydrite; volcanic mudflow (laharic) breccias; some intrusive rhyolitic plugs and stocks; partially zeolitized tuff; and metamorphic rocks. In the unsaturated zone, the permeability and hydrologic properties of the rocks and the hydrologic setting are more important than the rock type. Media ideally should be permeable to provide drainage and should have a minimal water flux.

The ground-water flow path from a repository to the accessible environment needs to present major barriers to the transport of radionuclides. Factors considered in evaluating the ground-water conditions include ground-water traveltimes and quality, confining beds, and earth materials favorable for retardation of radionuclides.

Ground-water velocities in the regions were calculated from estimated hydraulic properties of the rocks and gradients. Because site-specific data on hydraulic properties are not available, data from the literature were assembled and synthesized to obtain values for use in estimating ground-water velocities. Hydraulic conductivities for many rock types having granular and fracture permeability follow a log-normal distribution. Porosity for granular and very weathered crystalline rock tends to be normally distributed; porosity of fractured crystalline rock probably follows a log-normal distribution.

The tectonic setting needs to prevent an increase in radionuclides to the accessible environment. Data on historic seismicity and heat flow, Quaternary faults, volcanism, and uplift were used to assess the tectonic conditions. Long-term late Cenozoic rates of vertical crustal movement in the Basin and Range province range from less than 2 meters per 10^4 years to greater than 20 meters per 10^4 years. Short-term rates of vertical movement may be more than an order of magnitude greater, based on geodetic leveling. Changes in tectonic and climatic processes may potentially cause changes in hydrologic conditions and geomorphology that could affect the integrity of a deep, mined repository either adversely or beneficially.

The transition from a full-glacial climate to the current interglacial condition has occurred within the past 15,000 years. Reconstructions of the last full-glacial climate indicate that, at that time, there was greater water availability for runoff and vegetation growth than there is now. Based on the increased water availability and depending on seasonal distribution of precipitation, on soil characteristics, on topography, and on other characteristics, ground-water recharge during the full-glacial climate is estimated to have been possibly 2 to 10 or more times the modern rate. During the full-glacial climate, more than 100 lakes occupied closed basins in the province. Any increase in ground-water recharge and refilling of Pleistocene lakes will tend to decrease the distance of ground-water flow and its time of travel. The unsaturated zone—this zone is considered a potential host medium where the thickness is greater than 150 m—will be decreased by these changes. In contrast, incision of streams and other geomorphic, tectonic, or climatically induced changes that lower the ground-water discharge level will tend to increase the thickness of the unsaturated zone. Aggradation in basinal troughs may either decrease or increase the thickness of the unsaturated zone. Aggradation in basins that causes the ground-water discharge level to rise will tend to decrease the thickness of unsaturated zone in the adjacent uplands; aggradation in basins where the ground-water discharge level remains the same or is lowered will increase the unsaturated thickness of basin fill.

Records show that, throughout late Cenozoic time in the Basin and Range province, continued vertical crustal movements have tended to maintain mountain ranges and closed basins, whereas aggradation of the basins and erosion of the mountain ranges have tended to decrease the topographic relief. Maximum rates of denudation for small basins in areas climatically similar to the Basin and Range province are about 2 meters per 10^4 years. For sites unaffected by stream incision and scarp retreat, a conservative estimate of erosion affecting long-term changes in depth of burial would appear to be 2 meters per 10^4 years, or, equal to the long-term rate of vertical crustal movement where greater than 2 meters per 10^4 years. The response of the ground-water conditions to climatic and geomorphically induced boundary conditions is significant from the points of: (1) The potential maximum change in the ground-water flow system; (2) the time of response of the ground-water system; and (3) the present state of the ground-water system as a result of past changes. Effects of long-term climatic and tectonic changes on hydrologic and geomorphic conditions differ from area to area, and rates of change of geomorphic and hydrologic conditions may vary significantly. Therefore, site-specific studies need to be made to assess the long-term integrity of deep, mined repositories.

[1]Idaho Department of Water Resources.

Manuscript approved for publication, January 16, 1985.

INTRODUCTION

By M.S. Bedinger and K.A. Sargent

BACKGROUND AND PURPOSE OF STUDY

A study by the U.S. Geological Survey to evaluate potential hydrogeologic environments for isolation of high-level radioactive waste in the Basin and Range physiographic province was begun in May 1981, with the introduction of the study to the Governors of eight Basin and Range States—Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, and Utah—and to Indian tribes in those States. Accordingly, these States were invited to participate in the study by designating an earth scientist to serve on a Province Working Group with the U.S. Geological Survey—membership of the working group is shown following the title page. State representatives have provided consultation in selecting guidelines, assembling geologic and hydrologic data, and assessing such information to identify environments that meet the guidelines for further study.

The first phase of the study—geologic and hydrologic characterization and evaluation of the Basin and Range province, relative to the disposal of high-level radioactive waste—comprises guidelines for screening the Basin and Range province (Bedinger, Sargent, and Reed, 1984), geologic and hydrologic data for characterizing the province (Sargent and Bedinger, 1985), and evaluation of the province and identification of potential regions that meet the guidelines for further study (Bedinger, Sargent, and Brady, 1985). The regions identified in the first phase of the study that contain potential areas for further study are shown in figure 1. The regions were selected on the basis of the adopted guidelines and of information obtained from available sources on: (1) The distribution of rock types that may be host media for radioactive waste; (2) characteristics of the province related to tectonic stability—seismicity, late Cenozoic volcanism, Quaternary faulting, late Cenozoic regional uplift, and heat flow; and (3) the hydrology of ground-water flow systems.

This report, Chapter A of Professional Paper 1370, is one of a series of eight chapters (A through H) that describe the evaluation of potential hydrogeologic environments for the isolation of high-level radioactive waste in the Basin and Range physiographic province. These chapters present the results of the second phase of study. The titles of chapters in this series are:

A Basis of characterization and evaluation
B Characterization of the Trans-Pecos region, Texas
C Characterization of the Rio Grande region, New Mexico and Texas
D Characterization of the Sonoran region, Arizona
E Characterization of the Sonoran region, California
F Characterization of the Death Valley region, Nevada and California
G Characterization of the Bonneville region, Utah and Nevada
H Evaluation of the regions.

These chapters are closely integrated and contain a minimum of repetition. The reader needs to consult Chapters A and H and the appropriate regional Chapters B through G in order to achieve a complete understanding of the characterization and evaluation of an individual region.

Various members of the Province Working Group and their staff members have made specific contributions to this series of reports. These contributions are acknowledged by reference to their work and by authorship of their respective sections of reports. This joint effort does not oblige the States to accept any final choices or priorities resulting from the screening, but it does mean that technical representatives of the States have participated in the screening process from its inception, and that conclusions presented in these reports represent a general (but not necessarily unanimous) technical consensus.

Resources and time did not permit study in the present, second, phase of all potential regions identified in the first phase of study. The potential regions selected for further study were selected on the basis of available information. The regions selected for study and revised subdivisions are shown in figure 2. This chapter presents the methods used in characterizing and evaluating the regions. Other chapters in this series provide the geologic and hydrologic information characterizing the regions and evaluation of the potential areas for further study of environments for high-level waste isolation. Chapter H of this series describes the areas determined to be most prospective.

Although the primary objective of this study was to identify prospective areas for further study in the search for hydrogeologic environments to isolate high-level radioactive waste, the study is equally applicable to the disposal of other hazardous solidified toxic waste.

DEVELOPMENT OF GUIDELINES

Since the preparation of the guidelines for evaluation of the suitability of hydrogeologic conditions for isolation of high-level radioactive waste (Bedinger, Sargent,

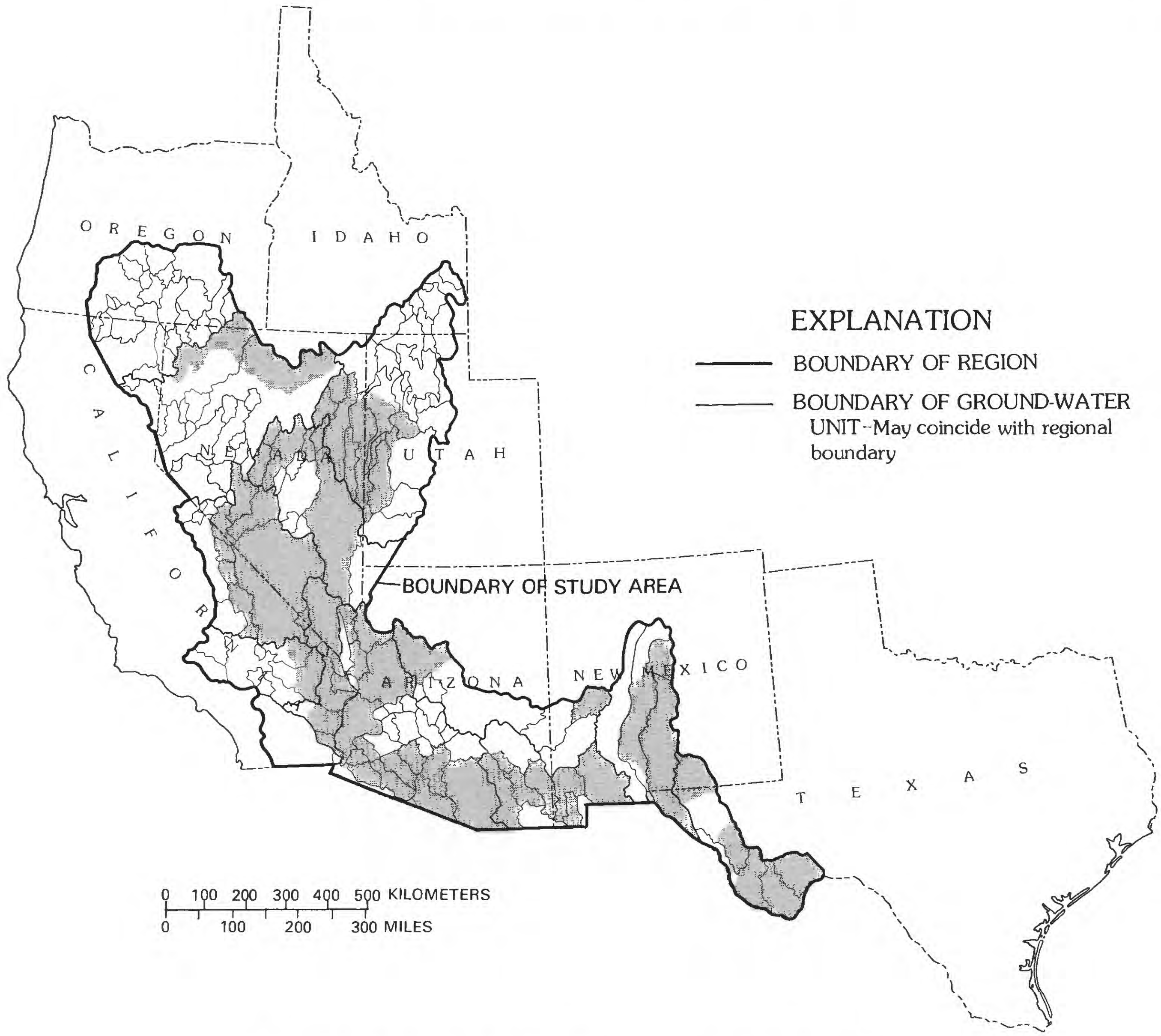


FIGURE 1.—Regions (shaded) identified as prospective for further study.

and Reed, 1984), the U.S. Nuclear Regulatory Commission (1983) published final criteria for licensing high-level waste repositories. As required by the Nuclear Waste Policy Act of 1982, the U.S. Department of Energy (1983) has released draft guidelines to be used in evaluating the suitability of sites for repositories. The final criteria of the U.S. Nuclear Regulatory Commission (1983) and the guidelines of the U.S. Department of Energy (1983) differ in part from earlier drafts of proposed criteria developed by the Commission and from some of the guidelines adopted by the Basin and Range Province Working Group. Although the final criteria of the Commission in 1983 did not address criteria for repositories in the unsaturated zone, the Commission has since considered such issues. The Commission (Ostrowski and others, 1984) has concluded that disposal in the unsaturated zone can be acceptable and is a viable alternative to the saturated zone. The Commission report (Ostrawski and others, 1984) therefore proposes amendments to previously developed criteria relative to disposal in the unsaturated zone.

The U.S. Nuclear Regulatory Commission (1983) recommends a minimum depth of 300 m for repositories as a favorable but not required condition for disposal. This depth in saturated media is considered deep enough to minimize disturbance, especially by human

FIGURE 2.—Regions (shaded) selected for study.

intrusion. With subsequent interest in the advantages of isolation of waste in an unsaturated zone, attention has been placed on the possibility of shallower burial. Rather than follow an arbitrary minimum depth criteria, the Province Working Group decided that the hydrogeologic environment and processes be evaluated to determine the depth of burial necessary to acceptably minimize the risk of exhumation, inadvertent human intrusion, and surface-induced effects from the waste (for example, temperature increase at the surface). These considerations apply to depth requirements at sites intended for both unsaturated and saturated zones. An additional constraint applies to locating a repository in the unsaturated zone. Because a repository site in the unsaturated zone is designed for effective operation in that zone only, the site must remain above the water table for the effective duration of the repository.

The accessible environment is defined by the U.S. Nuclear Regulatory Commission (1983) as that part of the atmosphere, hydrosphere, and lithosphere outside the controlled area. The controlled area will be established as that area within an arbitrary distance from the repository. The definition of the accessible environment preferred by the Basin and Range Province Working Group (Bedinger, Sargent, and Reed, 1984) is those parts of the environment directly in contact with human activities or readily available for use by humans. It includes the Earth's atmosphere, land surface, and surface water. It also includes presently used and potentially usable aquifers containing potable or otherwise usable water and presently mined and potentially mineable natural resources. The Commission's definition of accessible environment is a practical definition for evaluation of a known site, whereas the Province Working Group's definition is more appropriate for use in screening large areas. The Province Working Group definition follows its overall guideline philosophy for evaluating accessiblity and traveltime of ground water and retardation of radionuclides in flow paths from potential host rocks to ground-water discharge areas.

The Nuclear Waste Policy Act of 1982, requires that the U.S. Department of Energy issue guidelines for the selection of sites including a suite of criteria for nongeologic factors. The U.S. Department of Energy (1983) proposed nongeologic criteria for such factors as socioeconomic impacts, transportation, population density, and environmental quality. The present study is designed to consider only earth-science factors bearing on the favorability of areas for further study. Nongeologic factors should be used in combination with the earth-science factors, however, in determining areas suitable for further study.

ACKNOWLEDGMENTS

This report and the other reports in this series were prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah. Each of these States was represented by members of the Basin and Range Province Working Group. The cooperating agencies in each State and members of the Province Working Group are listed following the title page. Frank E. Kottlowski of New Mexico, Susan L. Tingley of Nevada, and Don R. Mabey of Utah, alternate members of the Province Working Group, contributed significantly to the study. The following individuals provided continued advice and assistance to the Basin and Range Province Working Group and in overall planning and execution of the work in preparation of this series of reports: John W. Hawley and William J. Stone of the New Mexico Bureau of Mines and Mineral Resources; Robert B. Scarborough of the Arizona Bureau of Geology and Mineral Technology; T.L.T. Grose of the Nevada Bureau of Mines and Geology and the Colorado School of Mines; and George A. Dinwiddie and George I. Smith of the U.S. Geological Survey.

The authors acknowledge the contributions of Isaac J. Winograd, U.S. Geological Survey, in providing continued advice, consultation, and constructive criticism during the study and technical review of the concepts and conclusions presented in the reports. Newell J. Trask, U.S. Geological Survey, provided a draft of the guidelines for the screening effort which was used in preparation of this and previous reports of this project and has continued to provide review and advice during the project. Technical advice and assistance were given by Edwin P. Weeks, U.S. Geological Survey, in establishing methods of analysis and presentation of the information on ground-water hydraulics.

REGIONAL CHARACTERIZATION AND GUIDELINES FOR EVALUATION

By M.S. Bedinger, K.A. Sargent, Frank B. Sherman[1], William H. Langer, and B.T. Brady

INTRODUCTION

Characterization of the geology and hydrology of the individual regions allows for a more comprehensive analysis of the suitability for isolation of high-level radioactive waste than was accomplished during the first phase of this study. Characterization of the regions included compilation of hydrogeologic and stratigraphic sections, evaluation of erosion and aggradation, compilation of data on tectonics, analysis of relative ground-water traveltimes, evaluation of retardation of radionuclides in the ground-water flow system, and compilation of mineral and energy resources data.

In this study, the regions are characterized and evaluated with respect to the extent of potential host rocks in the subsurface at repository target depths, traveltime of ground-water flow, radionuclide transport and retardation as related to the geologic framework and properties of the rock units and ground water, mineral and energy resources, ground-water conditions in response to climatic and geomorphic change, tectonic hazards, and geomorphic processes.

POTENTIAL REPOSITORY MEDIA

The host medium constitutes the first natural barrier to radionuclide migration, excluding engineered barriers of the waste form and of the repository. Potential media that are effective barriers to flow include rocks with minimal permeability in the saturated zone and permeable rocks with minimal water content and water flux in the unsaturated zone.

SATURATED ZONE

Below the water table, host media ideally should retard ground-water movement from the repository and have the capacity to adsorb radionuclides. The rate of ground-water movement needs to be slow in rocks with substantial effective porosity and minimal hydraulic conductivity, and the hydraulic gradient needs to be slight.

Buffer zones surrounding the repository need not be the same lithologic type as the host rock, although a homogeneous rock sequence will allow greater confidence in calculations of nuclide transport than will a heterogeneous rock sequence with numerous different lithologic interbeds or zones with significantly different permeability. In general, the greater the thickness of the buffer zone between the repository and any overlying or underlying aquifer, the greater the confidence that the host rock can contain the waste for long periods of time.

In the saturated zone, a host rock ideally must have sufficient thickness and lateral extent and minimal permeability to provide a medium for waste disposal. In the Basin and Range province, the granitic, intermediate, and mafic intrusive rocks; argillaceous rocks; salt and anhydrite; volcanic mudflow (laharic) breccias; some intrusive rhyolitic plugs and stocks; and some partially zeolitized tuff have been inventoried for possible future examination of their host-rock properties in the saturated zone. Some metamorphic rocks, such as granite gneiss, phyllite, and argillite, also have been inventoried.

UNSATURATED ZONE

Winograd (1972, 1974) first proposed placing nuclear waste in the unsaturated zone and recently (Winograd, 1981) discussed the concept with respect to the hydrogeology, paleoclimatology, and neotectonics of a specific region. Roseboom (1983) has reviewed the potentially favorable and nonfavorable environmental and engineering factors regarding storage of high-level waste in the unsaturated zone. Many rock types may be potential host media in the unsaturated zone; however, the suitability of the unsaturated zone is more dependent on the mineability and hydrologic properties of the rocks and their hydrogeologic settings than on the specific type of rock. The unsaturated-zone media ideally should be permeable to provide drainage, have sufficient thickness for construction of the repository and for buffer zones above and below the repository, and be in a climatic environment in which potential evaporation greatly exceeds precipitation. Percolation of water through the repository zone would ideally be minimized by a zone of large interstitial pore spaces and minimal permeability above the repository zone or by a very slow recharge rate. Drainage of water which may reach the repository could be facilitated by diversion drains and wells constructed in the respository chambers, and the waste could be further isolated from moisture by engineered capillary barriers (Winograd, 1981).

[1]Idaho Department of Water Resources.

DEPTH OF THE REPOSITORY

A deep, mined repository ideally must be located at a depth sufficient to prevent surficial processes from exposing the waste for an extremely long time and to limit the possibility of human intrusion. The depth of the repository ideally should be great enough to preclude a temperature increase at the land surface caused by the heat dissipating from the waste. If the repository is so engineered to impose a maximum temperature of 100–150 °C in the chamber, studies indicate that a repository depth as shallow as 25 m would cause no more than a 2–3 °C increase in near-surface temperature (D.W. Pollack, U.S. Geological Survey, oral commun., 1983). The minimum depth requirements also need to be analyzed for a given geologic setting with consideration of such factors as the effects of uplift, downcutting, stream piracy, scarp retreat, and increased precipitation. In some deeply dissected environments, a depth of 300 m may be required, whereas in a subsiding and aggrading basin, depths of as little as 100 m may suffice.

There is no generally applicable guideline for maximum depth of a repository. The ambient temperature at the repository depth needs to be considered, because it can affect the heat dissipation and the density of waste implacement. Considerations determining the maximum depth, such as mining and stability problems, and costs of excavation and construction are beyond the scope of this study. However, 1,000 m was adopted provisionally as the general guideline for maximum depth in screening potential host rocks.

CHARACTERISTICS OF REPOSITORY MEDIA

Thickness.—In the saturated zone, a minimum thickness of 100 m of host rock would be sufficient for repository excavations and buffer zones above and below. Below the water table, buffer zones serve as barriers to flow of water to and from the repository.

For disposal above the water table, the thickness of the unsaturated zone ideally must be sufficient to include a buffer zone above the repository, a zone for repository excavations, and a buffer zone between the repository and the water table. The zone above the repository provides isolation from the land surface and a barrier to exhumation by erosion. The thickness of rock between the water table and the repository provides a zone within which the water level may rise relative to the repository without saturating the repository, and it may provide media for delay or sorption of radionuclides during their downward migration to the saturated zone. The probable maximum magnitude of water-level rise relative to the repository needs to be determined for each unsaturated environment considered. The mechanisms by which the water level might rise relative to the repository include climatic changes, which affect the hydrologic system, and tectonic events, which could cause subsidence of the block in which the repository is located. Environments where the depth to water is greater than 150 m are considered as having potential for further evaluation.

Lateral extent.—The host rock ideally should be continuous throughout the area of the repository and should include a lateral buffer zone. It is estimated that the operations area probably will require a minimum area of about 8 km^2. The buffer zone probably will need to extend at least 2 km beyond all sides of the operations area.

Strength, mineability, and thermal conductivity.—Because of variability in the physical and engineering properties of rocks, it is not possible to predict these properties at depth with any degree of certainty. However certain rocks generally are believed to possess undesirable physical properties for mining at depth; for example, certain shales may deform plastically, or thin multiple basalt flows may be extensively fractured and thereby subject to caving. Furthermore, certain characteristics observed in surface exposures, such as zones of shearing and other structural complications, and the presence of chemically altered rock, may indicate potential mining problems. Thermal conductivity of the host rock needs to be considered in the design of the repository to preclude adverse affects to the integrity of the waste form, repository, and host rock acting as barriers to radionuclide migration. It is generally known that dense saturated rocks with little porosity, such as salt, dense basalt, densely welded tuff, and granite, have greater thermal conductivities than unconsolidated or consolidated but porous or extensively fractured media, such as alluvium, sandstone, and brecciated lava flows.

REGIONAL GEOLOGIC STUDIES

Geologic characterization of the Basin and Range province started with compilation of outcrop maps of selected rock types and of lithologic descriptions of stratigraphic sections. Outcrop maps of rock types considered as potential host media were compiled at 1:500,000 scale from various State geologic maps. These outcrops maps are published separate from this report and are referenced in the following table. Outcrop patterns were locally revised to reflect more recent mapping. The rock types mapped include, in general terms, granitic rocks, argillaceous rocks, ash-flow tuff, and basaltic rocks. This was followed by preparation of geologic sections which portray subsurface geology, mainly structural framework and lithology. The geologic information was used to define the hydrogeologic framework for analysis of ground-water traveltime and geochemical environments.

Rock-outcrop maps.—Shale and other fine-grained argillaceous rocks are shown where outcrop thicknesses are about equal to or greater than 150 m. The ages of argillaceous sequences and their thicknesses, vary greatly, and the relationships of argillaceous material to interbedded limestone, siltstone, and locally gypsum are variable and complex. In many areas of the Basin and Range province, shale bodies may have been thrust into their present position, resulting in the thinning or thickening of some shale units.

Granitic rocks include mostly silicic to intermediate and some mafic coarse-grained intrusive rocks. Most of the coarse-grained intrusive rocks are quartz monzonite or granodiorite. Rocks of dioritic to gabbroic composition are rare in most of the regions. Many small exposures of such rock types were included in the map compilation because they may indicate large plutons at depth.

Ash-flow tuff is widespread in the Basin and Range province; thicknesses greater than 100 m are found in every State in the province. Pyroclastic flows with aggregate thicknesses of 1,000–3,000 m are found in or near calderas and volcano-tectonic troughs in the province, primarily in southern and central Nevada. Most of the ash-flow tuff in the province is rhyolitic to dacitic in composition and was extruded in Tertiary time, although ash flows as old as Jurassic are known in Arizona and Nevada and as young as Quaternary in California. Many areas have large numbers of pyroclastic flows intercalated with lavas, air-fall tuff, and reworked tuff. Also included are laharic breccia flows. These laharic flows commonly occur in sequences 300 m or more in thickness and are composed of a mixture of volcaniclastic debris in a fine-grained groundmass. The rock generally is dense and massive and may have excellent excavation properties. The composition of the rock is andesitic to dacitic. Deposits generally are formed on the flanks of shield volcanoes and stratovolcanoes. Laharic breccia is widespread in southwestern New Mexico but occurs in smaller areas in other province States. Most of the laharic breccias noted in the Basin and Range province are of Oligocene and Miocene age.

Basaltic rocks shown as potential host media are not limited to mafic extrusive rocks. They include a considerable range of mafic to intermediate flows and a few intrusive equivalents such as diabase. Basaltic andesite, andesitic basalt, and trachyte are common lithologic types. Although distribution in the province is widespread, nearly all outcrop areas shown represent thicknesses less than 100 m and thus need careful evaluation as a host media. The vast majority of basaltic rocks occur as sequences of discrete lava flows. Individual flows generally are less than 15 m thick with their own sets of cooling joints and frequently separated from overlying and underlying flows by soils, scoria, or basalt breccia. Rarely individual flows may be thicker locally, and breaks between flows may be difficult to distinguish. Most of the basaltic flows in the province, which have host-media potential, are of mid-Tertiary age. Cretaceous to lower Tertiary basalts and massive dense Precambrian diabase occur locally.

The rock-unit maps have been published in the U.S. Geological Survey Water-Resources Investigation series as follows:

Geographic area	Rock unit	Reference
Arizona	Granitic rocks.	Johnson and Scarborough, 1984a.
	Argillaceous sedimentary and metasedimentary rocks.	Johnson, 1984a.
	Pre-Quaternary ash-flow tuff and laharic breccia.	Jenness, Lopez, and LaFortune, 1984.
	Pre-Quaternary basaltic rocks.	Johnson and Scarborough, 1984b.
Southern California	Granitic and shallow silicic intrusive rocks.	Hills, 1984.
	Pre-Quaternary ash-flow tuff.	Jenness and Lopez, 1984.
	Pre-Quaternary basaltic rocks.	Roggensack and Lopez, 1984.
Nevada	Granitic rocks.	Sargent and Roggensack, 1984a.
	Pre-Quaternary ash-flow tuff.	Sargent and Roggensack, 1984b.
	Pre-Quaternary basaltic rocks.	Roggensack and Sargent, 1984.
New Mexico	Granitic and shallow silicic intrusive rocks.	Hills and Sargent, 1984.
	Argillaceous rocks.	Johnson, 1984b.
	Pre-Quaternary ash-flow tuff and laharic breccia.	Jenness, Roggensack, and Lopez, 1984.
	Pre-Quaternary basaltic rocks.	Johnson, 1984c.
Texas	Granitic rocks.	Henry and Fisher, 1984a.
	Pre-Quaternary ash-flow tuff.	Henry and Fisher, 1984b.
	Pre-Quaternary basaltic rocks.	Henry and Fisher, 1984c.
Utah	Granitic rocks.	Jenness, 1984a.
	Argillaceous sedimentary and metasedimentary rocks.	Johnson, 1984d.
	Pre-Quaternary ash-flow tuff and laharic breccia.	Roggensack and Jenness, 1984.
	Pre-Quaternary basaltic rocks.	Jenness, 1984b.

Geologic sections.—Geologic sections of each region were constructed transverse to the long dimension of the structural basins on spacings ranging from about 15 to 30 km. In addition, a geologic section was constructed near the center of each basin parallel to the long dimension of the basin. Stratigraphic sections and lithologic descriptions also were compiled for the regions. The geologic sections were compiled using current structural principles mainly from published geologic maps, unpublished file data, structural and stratigraphic sections, and subsurface information from test drilling and geophysical surveys. Because of the limited available subsurface information, the geologic sections are mainly interpretive.

The locations of geologic sections prepared for characterization of the regions are shown in plate 1 (in pocket). Geologic sections were prepared by, in close coordination with, or under the direction of the various State agencies of the Province Working Group members. The geologic sections for each State are available in open-file releases or from the following agencies:

State	Geologic sections prepared by	Address
Arizona	Robert Scarborough	Arizona Bureau of Geology and Mineral Technology 845 North Park Avenue Tucson, AZ 85719
California	G.I. Smith and T.L.T. Grose.	Department of Conservation, California Division of Mines and Geology 2815 O Street Sacramento, CA 95816
Nevada	T.L.T. Grose	Nevada Bureau of Mines and Geology University of Nevada, Reno Reno, NV 89557-0088
New Mexico	J.W. Hawley, W. Stone, and F.E. Kottlowski.	New Mexico Bureau of Mines and Mineral Resources Campus Station Socorro, NM 87801
Texas	C.D. Henry	Texas Bureau of Economic Geology University of Texas at Austin University Station, Box X Austin, TX 78712
Utah	D.R. Mabey and K. Budding	Utah Geological and Mineral Survey 606 Black Hawk Way Salt Lake City, UT 84108

Geologic sections were prepared following accepted geologic procedures with commonly used stratigraphic units. In general, crystalline rock units included silicic to mafic coarse-grained intrusive bodies; they are treated as lithodemic units. A lithodemic unit is a body of predominantly intrusive, substantially deformed, and (or) highly metamorphosed rock lacking primary depositional structures (North American Commission on Stratigraphic Nomenclature, 1983).

Metamorphic rocks depicted in the geologic sections generally include gneiss, schist, and other high-grade metamorphic types; they too are treated as lithodemic units. Locally, small bodies of metamorphic rocks are included with silicic coarse-grained intrusive masses. Low-grade metamorphic rocks were commonly grouped with their unmetamorphosed equivalents and treated as lithostratigraphic units.

Coarse clastic sedimentary rocks depicted in geologic sections include sandstone and conglomerate and may include minor carbonate and argillaceous strata; these are grouped as lithostratigraphic units. Fine-grained clastic sedimentary rocks primarily include shale, claystone, mudstone, argillite, and siltstone, but may also have minor carbonate rock and coarser grained clastic strata. Fine-grained clastic rocks are also treated as lithostratigraphic units.

Lavas such as basalt, andesite, dacite, rhyolite, and trachyte are distinquished in the geologic sections from ash-flow tuff where possible. Locally, where the two may be composed of complex interbedded lithologies or for other reasons could not be depicted separately in the geologic sections, the lavas are identified as undifferentiated volcanic rocks. Extrusive flows are treated as lithostratigraphic units.

Carbonate rocks include undivided limestone and dolomite. These units include minor fine-grained and, locally, some coarse-grained clastic rocks. Locally, they also may contain considerable thicknesses of gypsiferous strata. They are lithostratigraphic units.

Basin-fill and alluvium were not divided in most of the geologic sections because the scale and vertical exaggeration were not suitable for a detailed portrayal of their lithologic character. These deposits include unconsolidated fine- to coarse-grained clastic sediments, evaporites, and freshwater limestones. Many of the basins formed in middle to late Cenozoic time, and contain volcanic flows and air-fall tuff interbedded with the sediments.

QUATERNARY TECTONIC CONDITIONS

A waste-isolation environment ideally should be located where future tectonic processes or events will not cause radionuclide releases to the accessible environment. Historical seismicity, heat flow, and geologic evidence of faults, volcanism, uplift, and tectonic extension during the Quaternary (from about 2 m.y. to the present) are considered the most useful means to assess the probability of tectonic activity in the future (U.S. Department of Energy, 1983; U.S. Nuclear Regulatory Commission, 1983). Also of concern are areas aligned with earthquake epicenters, Quaternary faults, and volcanism. Areas of relative quietude, such as large areas lacking mapped Quaternary faulting, may be due to lack of data rather than lack of Quaternary activity; such areas may need further investigation.

The general approach needed to evaluate tectonic conditions is to consider the probability of tectonic events of an area as well as to analyze the consequences of tectonic events in a specific hydrogeologic environment in a comprehensive, multi-discipline analysis. Such an analysis would provide a means to ensure that the risks are acceptably small and to identify possible favorable tectonic changes. The U.S. Department of Energy (1983) proposes that the risk should be less than 1 in 10,000 during the first 10,000 yr of a tectonic event resulting in releases of radionuclides to the accessible environment.

SEISMICITY AND FAULTING

Operational considerations and engineering and construction costs would favor locating a repository away from areas of major seismic activity. However, engineering design can compensate for potential damage to structures caused by a certain degree of seismic activity. A fault or earthquake near a repository cannot be considered to be a "failure" of the system, and it need not result in a degradation of the isolation system (Trask, 1982). In some ground-water regimes, movement along faults may have no effect on the existing ground-water flow system (Davis, 1980). In other ground-water regimes, however, ruptures may change ground-water flow patterns by creating permeable zones or zones with minimal permeability that result in new flow paths.

Most repository-breaching and risk-assessment alternatives reported in the literature (for example, Nuclear Energy Agency, 1980) are for repositories in the zone of saturation. If the repository were in the unsaturated zone, where drainage from the repository is desirable, a rupture near or in the repository after closure might be of minimal significance. A hydrogeologic setting in the unsaturated zone in which nearby faulting and associated subsidence and alluviation enhance waste isolation is described by Winograd (1981). Under the existing stress field, future faulting would continue to be along the preexisting zone of weakness, and through geologic time alluviation would increase the depth of burial of the waste.

QUATERNARY VOLCANISM

Unacceptable risk of volcanic activity at the repository and in the ground-water flow paths from the repository to the accessible environment needs to be avoided. An assessment of volcanic risk was made for a site in southern Nevada on the basis of studies characterizing the geology, chronology of eruptions, and tectonic setting of Pliocene and Quaternary volcanism in the region and of probability calculations and consequence analysis (Crowe and Carr, 1981; Crowe and others, 1983).

HEAT FLOW

Areas with greater than normal heat flow and thermal springs need to be evaluated not only for the possibility of relatively shallow igneous activity, but also with respect to the significance of discharge from deep ground-water flow systems, the ambient temperatures at repository depth, and the effects of heat transfer from waste to host rock. Another consideration is that areas with significant heat flow may be subject to subsurface exploration for geothermal energy, thereby providing a potential for human intrusion into the repository area.

QUATERNARY VERTICAL CRUSTAL MOVEMENT

Quaternary vertical crustal movements are important factors where relatively shallow repository environments (150–300 m) are to be evaluated. Vertical movements are of significance because of the potential for exhumation or decrease in depth of burial of waste by erosion and, conversely, the possible benefit of increased burial depth by aggradation. Factors such as tectonic stability, rates of scarp retreat, and denudation or aggradation need to be considered in evaluation of repository environments. These factors are addressed in the "Climatic Change, Geomorphic Processes, and Tectonism" section of this report.

Tectonic conditions of the regions are characterized principally on the basis of maps of the Basin and Range province compiled for characterization of the province. The principal sources of tectonic data used are as follows:

Type of data	Reference
Seismicity	Algermissen and others, 1983; Askew and Algermissen, 1983.
Heat flow	Sass and others, 1976.
Late Cenozoic volcanic centers.	Luedke and Smith, 1978a, b, 1981, 1982.
Quaternary faults	Nakata and others, 1982.
Quaternary vertical crustal movement.	Gable and Hatton, 1983.

Characterizations of tectonic conditions also incorporate published data from detailed studies conducted in the regions.

GROUND-WATER HYDROLOGY

Major barriers to radionuclide migration ideally should be present in the ground-water flow path from the repository to the accessible environment. Factors that present major barriers to radionuclide transport include: (1) Those which result in long ground-water traveltimes—long flow paths, low hydraulic gradients, minimal hydraulic conductivity of geologic units in the flow paths, and substantial effective porosity; and (2) those which decrease the concentration of radionuclides in solution—sorption, minimal solubility, dispersion, diffusion, and dilution of radionuclides. A minimum requirement of a ground-water flow system specified in revisions to the draft of a proposed rule by the U.S. Nuclear Regulatory Commission (1981) is that the waste be completely contained in the waste package for 1,000 yr after closure and that the flow time, before waste emplacement, from the repository to the limit of the controlled area be at least 1,000 yr. A flow time of water (or of a conservative, nonreactive ion) of 10,000 yr from the repository to the accessible environment as defined for this study is adopted as a minimum goal for this study (Bedinger, Sargent, and Reed, 1984). The U.S. Department of Energy (1983) has specified that the nature and rates of hydrologic and geochemical processes operating during the Quaternary Period should not adversely affect the ability of the hydrogeologic environment to isolate wastes during the next 100,000 yr.

Containment of waste in the repository for 1,000 yr provides for a decrease of several orders of magnitude in the short-lived fission products as shown by the inventory of radionuclides of high-level waste through time (fig. 3), during which strontium-90 and cesium-137 decay to harmless levels. Flow time of 10,000 yr from the repository to the accessible environment, if accompanied by significant sorptive capacity of the flow system, may effectively isolate plutonium-239 and americium-243. Precipitation of minerals containing radionuclides, particularly for nonoxygenated (reducing) ground water, can further retard rates of movement of some dissolved radionuclides by several orders of magnitude. Rocks composed of clays or zeolitic minerals are

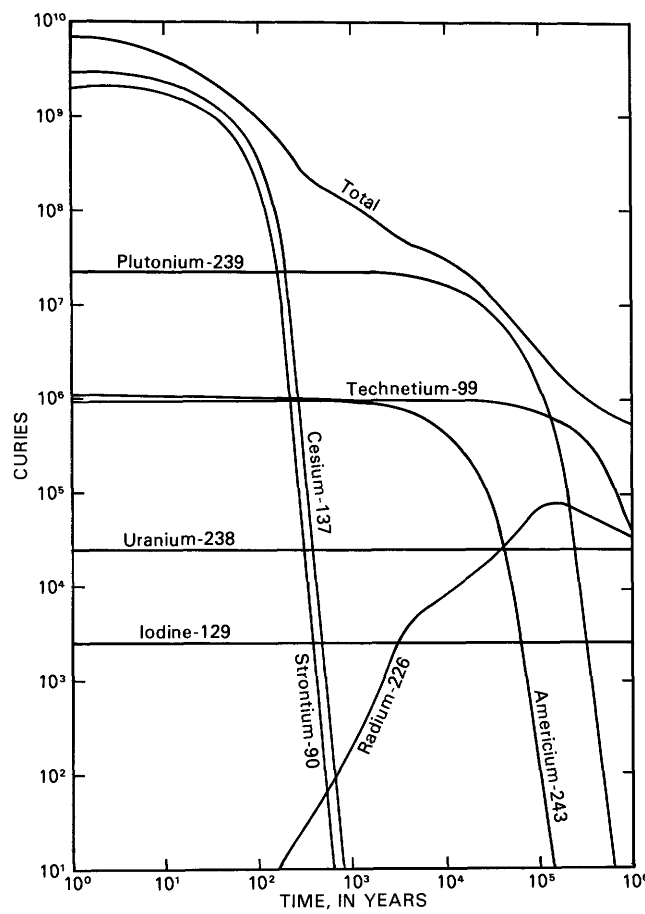


FIGURE 3.—Repository nuclide inventories at various times after closure (modified from Cloninger and others, 1980). The inventory used in the analysis is one-fifth of the total for spent unreprocessed fuel (no-recycle case) estimated to be accumulated in the United States through 2050.

notable for their sorptive properties and are effective in retarding transport of radionuclides. In some environments, oxides of iron and manganese appear to be more sorptive for uranium and thorium than are clays and zeolites. Chemical retardation of transport in ground water is addressed in the "Geochemistry" section of this report. The longer lived transuranic isotopes, such as uranium-238, neptunium-237, and their daughters in the decay chain, such as radium-226, and long-lived isotopes such as technetium-99 and iodine-129, persist for millions of years—times that are well beyond credible predictability for the ground-water flow system.

Decay and sorption of technetium-99 and iodine-129 are not important factors in decreasing their content. Although the technetium-99 and iodine-129 contents of the waste are reported as relatively small fractions of the total curie content of the waste (Gera, 1975; Clonginger and others, 1980), factors other than sorption will determine the hazard presented by the radionuclides. These factors may also be significant in decreasing the hazard of long-lived, sorbed radionuclides. The engineered barrier system of the repository and the relative insolubility of the waste form and of some of the nuclides will undoubtedly greatly limit the nuclide concentration in the water. Significant decreases in radionuclide concentrations can be effected by volumetric dilution and dilution by hydrodynamic dispersion. Both types of dilution occur where the flow path from a repository enters a large regional aquifer or, in some situations, a major stream; volumetric dilution can decrease the concentration of a radionuclide by as much as several orders of magnitude. Hydrodynamic dispersion occurs in most flow media, occurring to a greater extent in permeable rocks that are extensively fractured and jointed. Determination of the fate of long-lived radionuclides will need extensive site-specific studies to consider all the listed factors.

For additional information on the radionuclide content of high-level waste, the reader is referred to Gera (1975), American Physical Society (1978), and Cloninger and others (1980); for information on the ingestion hazard of high-level waste, the reader is referred to Parker (1981) and Cohen (1982).

Downward or lateral flow of water at the repository depth would eliminate the risk of upward leakage of radionuclides through poorly sealed shafts or boreholes. However, upward movement through the repository might be acceptable if flow was into an aquifer containing water of nonusable quality and having a long travel-time to the accessible environment.

The possibility of future intrusion of the repository by drilling would be minimized by the following conditions: (1) The potential host rock unit underlain by and immediately overlain by water of nonusable quality; (2) a great depth to a source of usable quality water; or (3) rocks with little water-yielding ability above and below the potential host rock.

Data on ground-water hydrology were compiled from published reports and file data of the U.S. Geological Survey. Data included ground-water level elevation, depth to water below land surface, flow and temperature of springs, ground-water withdrawal, and information on areas of natural ground-water discharge by evapotranspiration and seepage to streams. Hydrologic reports for each State included in the regional studies are as follows:

Geographic area	Hydrologic information	Reference
Arizona	Ground-water units and withdrawal.	Bedinger, Anderson, and Langer, 1984.
	Ground-water levels, springs, and depth to ground water.	Langer, Mulvihill, and Anderson, 1984.
Southern California	Ground-water units and withdrawal.	Bedinger, Langer, and Moyle, 1984.
	Ground-water levels, springs, and depth to ground water.	Langer, Moyle, and others, 1984.
Nevada	Ground-water units and withdrawal.	Bedinger, Harrill, and Thomas, 1984.
	Ground-water levels, springs, and depth to ground water.	Bedinger, Harrill, Langer, and others, 1984.
New Mexico	Ground-water units and withdrawal.	Brady, Bedinger, and Hart, 1984.
	Ground-water levels, springs, and depth to ground water.	Brady, Mulvihill, and others, 1984.
Texas	Ground-water units and withdrawal.	Brady, Bedinger, Mulvihill, and others, 1984a.
	Ground-water levels, springs, and depth to ground water.	Brady, Bedinger, Mulvihill, and others, 1984b.
Utah	Ground-water units and withdrawal.	Bedinger, Gates, and Stark, 1984.
	Ground-water levels, springs, and depth to ground water.	Bedinger, Mason, and others, 1984.

GROUND-WATER TRAVELTIME

Ground-water flow paths and relative traveltimes along flow paths were estimated within the hydrogeologic framework from data obtained from geologic sections, rock-outcrop maps, and geologic literature for the regions. Hydraulic properties of rocks in a region of study cannot be predicted without site-specific, in-situ or laboratory tests. It is not practicable at this stage to determine site-specific values of hydraulic properties for estimating traveltimes in all the regions. A considerable amount of data exists in the literature containing measurements of hydraulic conductivity and porosity. The literature has been searched for data from the Basin and Range province and data from rocks of similar characteristics elsewhere. These data are reviewed and synthesized in the "Hydraulic Properties of Rocks" section of this report in order to derive values and ranges of values for hydraulic conductivity and porosity applicable to rocks in the Basin and Range province. Because site-specific data on hydraulic properties of rocks in the regions are not available, traveltimes are reported as relative traveltimes.

Ground-water traveltimes in the regions were estimated at or near the water table (referred to below as areal analysis), and in geologic sections to depths of several thousand meters along selected flow sections. The relative traveltimes are believed to be useful for comparing traveltimes in different areas; however, ground-water velocities may differ considerably from the average rates in segments of the flow system. Anomalously large or small permeability distributions may exist throughout significantly large areas; for example, extremely permeable rocks may exist in flow systems sustaining thermal springs. Where evidence of anomalous hydraulic properties exists, these conditions are noted on the traveltime maps.

The strength of these analyses lies in the objectivity used to make a relative comparison for the entire region under consideration. The analyses of ground-water flow systems—areally and in cross section—can be used to characterize regions, and to assist in selecting potential areas for further study.

Areal analysis.—The first step in the areal flow-system analysis was to prepare a subcrop map delineating the rock type that occurs at the water table. This was accomplished through the use of the geologic sections referred to previously, well and test-hole data, geophysical data, and geologic maps. The maps of the rock units at the water table are shown in the chapters of this report series describing the individual regions.

The second step in areal-flow analysis was to assign values of hydraulic conductivity and effective porosity to the rock units mapped at the water table. Where less permeable, saturated materials along the flow path overlie more permeable, saturated materials within several tens of meters of the water table, the flow times were estimated for the more permeable material. Hydrologic properties in a given region were selected on the basis of hydraulic properties (table 1) with weight given to the geologic and hydrologic descriptions available for the rocks in the specific region. The hydraulic-gradient distribution was estimated for the region using available hydraulic-head data and knowledge of the geology, topography, and general ground-water conditions. Selected flow paths were drawn on the water-table subcrop map following the measured or presumed steepest hydraulic gradient from the ground-water divides to the discharge areas.

The velocity, v, of a water particle or nonreactive constituent in water is given by

$$v=\frac{K}{\phi}\,\frac{dh}{dl}\ ,$$

where K is the hydraulic conductivity, ϕ is the effective porosity, and dh/dl is the hydraulic gradient. The traveltime, t, along a given flow path length, L, is given by

$$t=\int_0^L \frac{dl}{v}\ .$$

For a constant velocity,

$$t=\frac{L}{v}\ \text{or,}\ t=\frac{L}{K/\phi\ dh/dl}\,.$$

The map of relative traveltimes was prepared first and used with other geologic and hydrologic information to determine which areas merited more detailed, two-dimensional, cross-sectional modeling. The two-dimensional, cross-sectional models afford the opportunity to verify or refine the values of hydraulic properties of hydrogeologic units, using information on hydraulic gradients and ground-water flow volumes. In areas where the hydraulic properties were revised for the region during the cross-sectional analysis (described elsewhere in this section), the areal-flow analysis was revised using the verified values. The maps of relative traveltime at the water table are shown in the chapters of this report series describing the individual regions.

Cross-sectional analysis.—The first step in the cross-sectional analysis of ground-water flow was to prepare a hydrogeologic section along selected flow paths. The hydrogeologic sections were constructed to extend to a depth of several thousand meters or more to where the rocks are known or inferred to be crystalline with relatively minimal permeability. The second step in the cross-sectional analysis was to assign values of hydraulic conductivity and effective porosity to the rock units portrayed in the geohydrologic sections. The hydraulic conductivity and effective porosity were estimated using the values from table 1 with consideration given to hydraulic properties reported for the region and to geologic and hydrologic descriptions in the literature available for the rock units in the area. The recharge distribution was estimated and the resulting hydraulic-head distribution at the upper boundary from the cross-sectional model analysis (described below) was compared to the actual water-level distribution. The mathematical model used in analysis of cross-sectional flow is described in a later section of this report. From the cross-sectional model analysis, sets of flow paths and traveltimes were drawn on the hydrogeologic sections.

GEOCHEMISTRY

There are numerous chemical and physical processes in a ground-water system that affect the movement of radionuclides. Dispersion of a nuclide as it moves in a porous medium will tend to decrease its concentration while increasing the area of contamination. Diffusion of a nuclide will also tend to decrease its concentration.

Radioactive decay is a time-dependent property of a nuclide, and is, therefore, important to consider in nuclide migration. Such decay will decrease the concentration of a radionuclide with time, and thus decrease its concentration with distance along a flow path. However, the decay of some radionuclides will produce long-lived radioactive daughter products.

Among the chemical reactions associated with radionuclides are those between the nuclides and the native ground water, and those between the nuclides and the rock matrix. The ground-water chemistry will dictate the chemical form of a nuclide, thereby affecting its reactivity both with other solutes and with the solid phase. The native solutes also may complex the nuclide and render it mobile, or they may form an insoluble precipitate and thereby decrease its concentration in solution.

Chemical reaction between a nuclide and the solid phase tend to decrease the concentration of radionuclide in solution. The important reactions are adsorption and ion exchange. Such nuclide-solid reactions are considered by most workers to be more important in nuclide retardation than nuclide-solute interactions. The retardation of nuclide migration by adsorption and ion exchange with the solid phase of the flow system is expressed by the distribution coefficient, K_d. K_d is the measure of the sorption capacity of a given media (sorbent) for a specific element as defined by

$$K_d = \frac{\text{quantity of nuclides in solid phase/mass of solid}}{\text{quantity of nuclides in liquid phase/volume of liquid}}.$$

Traveltimes estimated in the settings refer to the traveltime of a water molecule or of a nonreactive chemical constituent. The following equation relates traveltime of water (t_w) to effective porosity (ϕ), length of flow path (L), hydraulic conductivity (K), and hydraulic gradient (I):

$$t_w = \frac{\phi L}{KI}.$$

Retardation refers to the sorption of radionuclides by natural earth materials in the flow path from repository to discharge area. The radionuclides technetium-99, strontium-90, americium-243, and plutonium-239 were selected to illustrate the retardation effects of sorption radionuclides having half-lives ranging from 29 to 24,000 yr. Calculations of retardation of these radionuclides in the discharge area are based on radionuclide half-life, retardation factors for the radioncuIides of the flow-system media, and water-particle traveltime. The traveltime of a radionuclide, t_n, is the product of the traveltime of the water, t_w, and the retardation factor, K_f, or:

$$t_n = t_w K_f.$$

The retardation factor, K_f, is the ratio of water velocity to nuclide velocity (Cloninger and others, 1980):

$$K_f = 1 + rK_d ,$$

where r is the ratio of bulk-rock density to effective porosity, and K_d is the distribution coefficient.

Maps for each State in the Basin and Range province were prepared showing the distribution of water-quality type and dissolved-solids concentration for regions within the province. These maps, coupled with geologic information on rock types at the water table and in selected geologic sections provide the basic information used to describe the geochemical environments and characterize nuclide retardation in the different environments. The water-quality data for the regions are found in the following reports:

State	Reference
Arizona	Thompson, Nuter, and Anderson, 1984.
California	Thompson, Nuter, Moyle, and Woolfenden, 1984.
Nevada	Thompson and Chappell, 1984.
New Mexico	Thompson, Chappell, and Hart, 1984.
Texas	Thompson and Nuter, 1984a.
Utah	Thompson and Nuter, 1984b.

MINERAL AND ENERGY RESOURCES

Guidelines discussed previously were concerned primarily with natural conditions relating to containment and isolation of high-level radioactive waste. Nongeologic factors are not addressed, as such, in this study. However, the problem of human intrusion in the quest for metallic and nonmetallic minerals, hydrocarbon resources, geothermal resources, and water supplies overlaps the areas of hydrogeologic and nonhydrogeologic factors. Exploration for resources could result in inadvertent human intrusion into the waste repository or into flow paths of waste migration (Cameron, 1981). Two concepts have been advanced to minimize the chances of the future human intrusion: (1) Society can attempt to prevent intrusion by institutional control of the affected area; and (2) the repository site can be selected in an area believed to have minimal mineral and energy potential. Beyond institutional control, documentation of the repository for the benefit of future societies is considered necessary (Kaplan, 1982). Assessments of natural resources need to be made to provide society with the mineral potential and the knowledge necessary to make decisions about whether or not to dedicate a volume of earth, and the contained mineral and water resources, to the permanent isolation of waste.

The characterization of mineral and energy resources of the regions was based largely on data from the following publications:

Resource	Reference
Mineral Resources	
Arizona	Keith and others, 1984.
California	Wong, 1983b.
Nevada	Wong, 1983c.
New Mexico	Frodey-Hutchins, 1983.
Texas	Henry and others, 1983.
Utah	Wong, 1983a.
Coal, Oil, and Gas Resources	
Basin and Range province.	Brady, 1984.
Geothermal Resources	
Arizona	Witcher and others, 1982.
California	California Department of Conservation, 1980.
Nevada	Trexler, Koenig, and Flynn, 1979.
	Trexler, Flynn, and Koenig, 1979.
New Mexico	Swanberg, 1980.
Texas	Henry, 1979.
	Woodruff and others, 1982.
Utah	Utah Geological and Mineral Survey, 1980.

The characterization of mineral and energy resources in each region is intended to provide a generalized summary of the geologic characteristics and relative importance of known mineralized areas and geothermal and fuel occurrences within the study areas. It does not include all occurrences or areas of potential. The term resource, is used throughout this discussion to denote "* * * a concentration of naturally occurring solid, liquid or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible" (U.S. Bureau of Mines and U.S. Geological Survey, 1980). The classification of a resource requires an adequate description of the physical and chemical characteristics of the commodity and an economic assessment within a specific time period.

The nature and distribution of mineral resources are important factors relative to regional characterization, evaluation, and the disposition of high-level radioactive waste. Mineralized areas commonly contain numerous drill holes and workings, and are the loci of pervasive rock alteration and intense structural deformation. These factors could disrupt local and potentially regional ground-water flow patterns, and promote premature discharge of radionuclides to the accessible environment. Furthermore, the classification and potential of a resource are functions of existing economic conditions and industrial or technological developments. Exploration activities, both in historically productive areas and in frontier geologic provinces, may lead to new discoveries and promote mineral-related development. No attempt is made herein to formally classify or evaluate the potential mineral, energy, or fuel resources within the study area.

HYDRAULIC PROPERTIES OF ROCKS IN THE BASIN AND RANGE PROVINCE

By M.S. Bedinger, William H. Langer, and J.E. Reed

The hydraulic conductivity, K, of a rock is a function of the density of the water, ρ; the dynamic viscosity of the water, μ, in the rock matrix; the acceleration of gravity, g; and the intrinsic permeability of the rock, k:

$$K=\rho gk/\mu.$$

The hydraulic conductivity is thus a function of the field of gravity, of the properties of the rock, and of the water.

In porous media consisting of grains of mean diameter, d, the intrinsic permeability is given by:

$$k=Cd^2,$$

where C is a constant that depends on the distribution of grain sizes, the sphericity and roundness of grains, and the nature of their packing (Hubbert, 1940). The diameter, d, of the mean grain size is proportional to the size of the typical pore. This relationship has been demonstrated theoretically for spheres of uniform packing by Slichter (1899). The relationship has been found (Bedinger, 1961) to hold also for natural granular materials that are relatively well sorted and well rounded. The lack of a similar grain size–permeability relationship for clays has been attributed by Olsen (1962, p. 131) to unequal pore sizes due to grouping arrangements of particles.

Equations for permeability, k, and porosity, ϕ, for fractures that separate a dense medium into uniform cubes were given by Snow (1968, p. 80):

$$k=\frac{d^3}{6\Delta} \text{ and}$$

$$\phi=\frac{3d}{\Delta},$$

where d is the aperture of the fractures, and Δ is the spacing of the fractures. Equations have been derived for other uniform fracture geometrics that also show the increase in hydraulic conductivity as a power function of the fracture aperture and the direct relation between fracture aperture and porosity. In nature, fracture geometry and aperture are quite variable resulting in marked anisotropy of fractured rocks. The great variability in fracture distribution creates problems in scale of measuring hydraulic properties and mapping areal distribution of hydraulic properties in fractured rocks.

Hydraulic properties of rocks in a region cannot be predicted without site-specific, in-situ or laboratory tests. However, it was not practicable at the region phase of the study to determine site-specific values of hydraulic properties for traveltimes. A considerable amount of data exists in the literature containing measurements of hydraulic conductivity and porosity. The literature has been searched for data not only from the Basin and Range province but also for rocks of similar characteristics elsewhere. These data were reviewed and synthesized, and values and ranges of values were derived for hydraulic conductivity and porosity applicable to rocks in the Basin and Range province (Bedinger, Langer and Reed, 1986). The following generalizations from the report by Bedinger, Langer and Reed (1986) were followed in synthesizing the data from the literature on hydraulic conductivity and porosity:

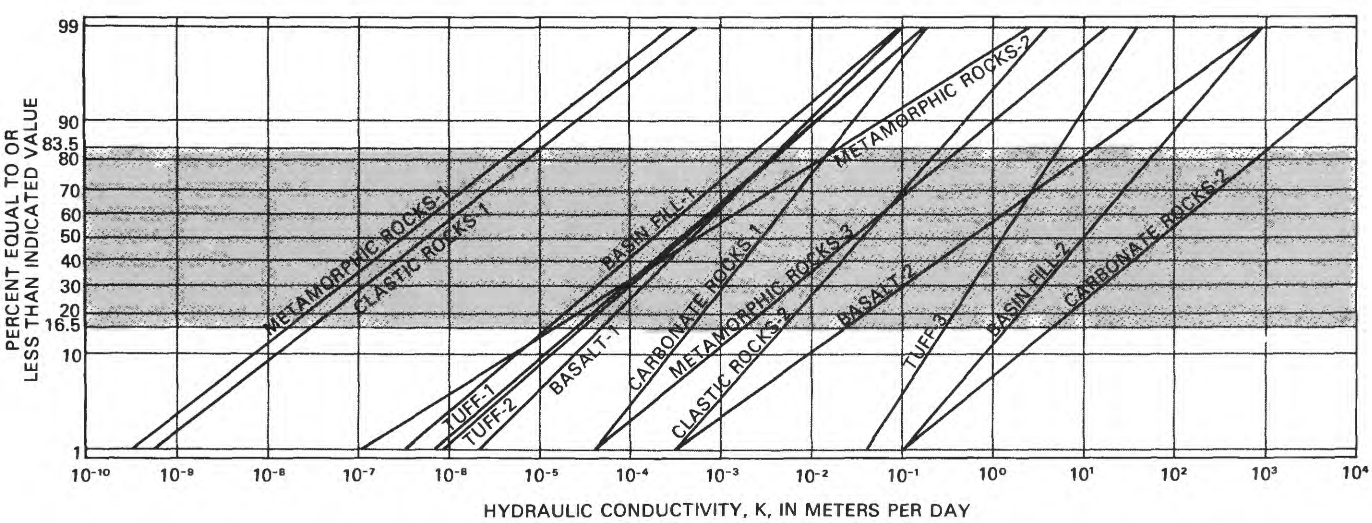
1. Field and laboratory hydraulic-conductivity measurements for many rock types having granular and fracture permeability, predominantly have a log-normal probability distribution.
2. Porosity values for granular materials tend to be normally distributed and vary from a few percent to several tens of percent. For granular material that is well sorted and uniformly packed, the porosity is high and varies within a narrow range, and the permeability is a function of the square of the median grain size. For well-graded, granular, and argillaceous material the porosity varies from a few percent to several tens of percent; permeability may be an exponential function of the porosity.
3. For fractured crystalline rock that is greatly weathered, with fracture and intergranular porosity, the porosity has a normal distribution; but for a fractured crystalline rock that is relatively unweathered, the porosity probably has a log-normal distribution. For fractured, unweathered crystalline rock, the permeability is an exponential function of the porosity if the fracture density and geometry is uniform.
4. Beneath the zone of weathering, average bulk-rock intrinsic permeability of crystalline rock decreases with depth due to overburden pressure. Commonly, a systematic or uniform decrease with depth is not obvious from data from a single test hole. However, larger data sets from several localities in the world, at depths to less than 1,000 m, show a decrease in permeability with depth. The decrease in permeability appears to be greater for depths less than 300 m than for greater

depths. The occurrences of zones of significant permeability tend to decrease with depth, but localized zones of significant permeability have been detected at depths as great as a few thousand meters.

A generalized log-normal plot of hydraulic conductivity for the 13 rock classes using the previously described generalizations and a great deal of judgment is presented in figure 4, after Bedinger and others (1987). The hydraulic conductivities are depicted as a log-normal distribution by plotting the distribution as a straight-line on log-probability coordinates. The distribution for a rock type, for which there were many reported values of hydraulic conductivity, was drawn using the spread from 1 to 99 percentiles for the range of values reported in the literature. The approximate mean of the majority of the values of hydraulic conductivity was placed at the 50-percentile value, and the majority of the values were included within about one standard deviation on either side of the mean (16.5–83.5 percentiles).

Porosity values were estimated, wherever possible, by using paired values of porosity and hydraulic conductivity from individual samples. Lacking paired values of porosity and hydraulic conductivity, porosities were estimated from the relations between porosity and hydraulic conductivity expressed in the preceeding paragraphs. The values of hydraulic conductivity and its associated porosity for the mean and for the 16.5 and 83.5 percentiles for each rock class are presented in table 1.

The K/ϕ value for each pair of porosity and hydraulic conductivity values also is included in table 1. K/ϕ is a measure of the relative velocity of ground-water flow. Strictly interpreted, the K/ϕ value is the ground-water velocity under a hydraulic gradient of 1.



EXPLANATION

BASALT
- 1-Moderately dense to dense lava flows
- 2-Fractured cavernous basalt

BASIN FILL
- 1-Fine-grained basin fill
- 2-Coarse-grained basin fill

CARBONATE ROCKS
- 1-Dense to moderately dense carbonate rocks
- 2-Fractured, karstic carbonate rocks

CLASTIC ROCKS
- 1-Fine-grained clastic rocks
- 2-Coarse-grained clastic rocks

METAMORPHIC ROCKS
- 1-Unweathered metamorphic and intrusive rocks with fracture permeability, greater than 300 meters below land surface
- 2-Unweathered metamorphic and intrusive rocks with fracture permeability, less than 300 meters below land surface
- 3-Weathered metamorphic and intrusive rocks

TUFF
- 1-Nonwelded to partially welded, bedded tuff
- 2-Welded, moderately fractured to dense tuff
- 3-Fractured, welded tuff

FIGURE 4.—Hydraulic-conductivity distributions estimated for rock units (after Bedinger, Langer, and Reed, 1985).

TABLE 1.—*Hydraulic properties of rock types*
[m/d, meters per day]

Rock type	Description	16.5 percentile			Mean			83.5 percentile			References (see list below)
		Hydraulic conductivity (K) (m/d)	Effective porosity (ϕ)	K/ϕ (m/d)	Hydraulic conductivity (K) (m/d)	Effective porosity (ϕ)	K/ϕ (m/d)	Hydraulic conductivity (K) (m/d)	Effective porosity (ϕ)	K/ϕ (m/d)	
Metamorphic rocks; felsic and mafic intrusive rocks.	Weathered	2×10^{-3}	0.03	6×10^{-1}	3×10^{-2}	0.05	6×10^{-1}	4×10^{-1}	0.07	6×10^{-0}	1, 4, 6, 9, 10, 14, 18, 20, 21, 22.
	Fracture permeability; depth less than 300 m.	1×10^{-5}	.002	5×10^{-3}	5×10^{-4}	.003	2×10^{-1}	2×10^{-2}	.005	4×10^{-0}	
	Fracture permeability; depth more than 300 m.	2×10^{-8}	.00004	5×10^{-4}	3×10^{-7}	.0001	3×10^{-3}	6×10^{-6}	.0003	2×10^{-2}	
Lava flows; including basalt, rhyolite, and trachyte.	Fractured and cavernous.	2×10^{-2}	.11	2×10^{-1}	5×10^{-1}	.15	3×10^{-0}	1×10^{-1}	.19	5×10^{-1}	3, 6, 8, 12, 14, 22.
	Moderately dense to dense.	5×10^{-5}	.004	1×10^{-2}	4×10^{-4}	.01	4×10^{-2}	4×10^{-3}	.03	1×10^{-1}	
Tuff	Welded and fractured	3×10^{-1}	.02	2×10^{-1}	1×10^{-0}	.03	3×10^{-1}	5×10^{-0}	.04	1×10^{-2}	4, 10, 12, 16, 18, 20, 21, 22.
	Welded and moderately fractured to dense.	3×10^{-5}	.0004	8×10^{-2}	4×10^{-4}	.001	4×10^{-1}	5×10^{-3}	.003	2×10^{-0}	
	Nonwelded, partially welded, friable, pumiceous, zeolitized, and bedded friable.	2×10^{-5}	.33	6×10^{-5}	4×10^{-5}	.35	1×10^{-3}	5×10^{-3}	.37	1×10^{-1}	
Clastic sedimentary rocks (consolidated).	Coarse-grained (sandstone and conglomerate).	5×10^{-3}	.12	4×10^{-2}	3×10^{-2}	.18	2×10^{-1}	3×10^{-1}	.23	1×10^{-0}	2, 3, 6, 7, 11, 13, 23.
	Fine-grained (argillite and shale).	3×10^{-8}	.10	3×10^{-7}	5×10^{-7}	.22	2×10^{-6}	1×10^{-5}	.30	3×10^{-5}	
Carbonate rocks; including limestone, dolomite, and marble.	Fractured, karstic, cavernous.	4×10^{-0}	.09	4×10^{-1}	6×10^{-1}	.12	5×10^{-2}	1×10^{-2}	.16	6×10^{-3}	4, 6, 14, 15, 17, 21, 22.
	Dense to moderately dense.	5×10^{-4}	.005	1×10^{-1}	3×10^{-3}	.01	3×10^{-1}	2×10^{-2}	.02	1×10^{-0}	
Basin fill (unconsolidated).	Coarse-grained (sand and gravel).	1×10^{-0}	.12	8×10^{-0}	1×10^{-1}	.18	6×10^{-1}	7×10^{-1}	.23	3×10^{-2}	3, 5, 19.
	Fine-grained (clay and silt).	1×10^{-5}	.29	3×10^{-5}	2×10^{-4}	.32	6×10^{-4}	2×10^{-3}	.36	6×10^{-3}	

Number	Reference(s)	Number	Reference(s)
1	Brace, 1980.	13	Muskat, 1937.
2	Brown and Silvey, 1973.	14	Rasmussen, 1964.
3	Davis, 1969.	15	Rove, 1947.
4	Davis, 1980.	16	Rush, Thordarson, and Bruckheimer, 1983.
5	Davis and DeWiest, 1966.	17	Sanyal, Kvenvolden, and Marsden, 1971.
6	Freeze and Cherry, 1979.	18	Thordarson, 1965.
7	Gondouin and Scala, 1958.	19	Trauger, 1972.
8	Isherwood, 1981.	20	Winograd, 1971.
9	Jamieson and Freeze, 1983.	21	Winograd and Thordarson, 1975.
10	Keller, 1960.	22	Wolff, 1982.
11	Lin, 1978.	23	Wyckoff and others, 1934.
12	Morris and Johnson, 1967.		

MATHEMATICAL MODEL FOR SIMULATING GROUND-WATER AND HEAT FLOW

By J.E. Reed

Cross-sectional, ground-water traveltimes were determined by a computer model of ground-water flow. Basic input to the model consists of geometric distribution of lithologies within the geologic section, the hydraulic conductivity for each lithologic type, the water level at recharge or discharge sites such as lakes or streams, and recharge from infiltration of precipitation. The computer code consists of a block-centered, finite-difference approximation of three-dimensional, steady-state, ground-water flow with interblock transmissivity calculated as the harmonic means of the transmissivities of the two adjacent blocks. The code includes a heat-flow model, which is block centered, finite difference, steady state, and uniform head conductivity, and which uses backward weighting for convective heat flow. The two flow models are interdependent because hydraulic conductivity in the ground-water model is a function of temperature and convective flow in the heat model is a function of ground-water flow. An earlier version of this computer model was discussed in Bedinger and others (1979).

The finite-difference method considers the space of interest to be represented by a finite number of blocks. The average value for the variable of interest, hydraulic head or temperature, is assigned to a position within the block called the node. Two methods of node assignment, face-centered or block-centered, commonly are used. Block-centered means that the node is always centered between adjacent block faces. In face-centered models each block face is centered between adjacent nodes. For models having uniform spacing in all directions, block-centered and face-centered models are equivalent. If block size (therefore node spacing) is variable, the nodes in a face-centered model will not be in the center of all blocks. In general, a face-centered grid with a minimum number of nodes cannot be designed because the block faces will not always coincide with natural boundaries in the modeled space. However, a block-centered grid can always be designed to match natural boundaries.

The notation used here in referencing a quantity to its position in the finite-difference network is by subscript. Integer subscripts refer to the adjacent block numbers, whereas fractional subscripts refer to block faces. Variables with no subscript are associated with the block being considered. For example, in reference to block i,j,k, where i,j, and k, are integer block numbers, the hydraulic head at block i,j,k is denoted by h, the hydraulic head at the adjacent block in the i-increasing direction is h_{i+1}, the hydraulic head at the block face in the i-increasing direction is $h_{i+\frac{1}{2}}$, and so forth.

The equation of steady-state ground-water flow may be written for isotropic conditions as

$$\sum_{i=1,2,3} \frac{\partial}{\partial x_i} K \frac{\partial h}{\partial x_i} + W_s = 0 ,$$

where x_1, x_2, and x_3 represent the coordinate system axes, h is the hydraulic head, K is the hydraulic conductivity of the aquifer, and W_s is the rate of recharge per unit depth. A finite-difference approximation of the above equation can be written for the block numbered i, j, k as:

$$\sum_{m=i,j,k} K_{m+\frac{1}{2}} \left(\frac{h_{m+1}-h}{\frac{1}{2}(\Delta x_{m+1}+\Delta x_m)} \right) - K_{m-\frac{1}{2}} \left(\frac{h-h_{m-1}}{\frac{1}{2}(\Delta x_m+\Delta x_{m-1})} \right) + W_s = 0 ,$$

where i, j, and k represent integer block numbering in the three coordinate directions, and x is the dimension of the block in the direction x. K, h, and W_s are defined above, and $m \pm \frac{1}{2}$ represent previous and succeeding interblock positions. The above finite-difference approximation applied to a region of interest results in a system of n (number of blocks) linear equations in n unknown hydraulic heads. The interblock hydraulic conductivities are calculated as

$$K_{m+\frac{1}{2}} = \frac{K_m K_{m+1}(\Delta x_m + \Delta x_{m+1})}{K_m \Delta x_{m+1} + K_{m+1} \Delta x_m}$$

and similarly for $K_{m-\frac{1}{2}}$,

$$K_{m-\frac{1}{2}} = \frac{K_m K_{m-1}(\Delta x_m + \Delta x_{m-1})}{K_m \Delta x_{m-1} + K_{m-1} \Delta x}$$

The equation of steady-state heat flow for conditions of uniform conductivity and specific heat may be written as:

$$\sum_{i=1,2,3} K_t \frac{\partial^2 t}{\partial xi^2} + S_t \frac{\partial q}{\partial xi} + H_t = 0$$

where x_1, x_2, and x_3 are the coordinate axes, t is the temperature, K_t is the thermal conductivity for rock saturated with water, S_t is the volumetric specific heat for water, q is the specific discharge of ground water at a point, and H_t is the geothermal heat flow per unit depth. A finite-difference approximation of the above equation can be written for a block numbered i, j, and k as

$$\sum_{m=i,j,k} \frac{K_t}{\Delta x_m} \left(\frac{(t_{m+1}-t)}{½(\Delta x_{m+1}+\Delta x_m)} - \frac{(t-t_{m-1})}{½(\Delta x_m+\Delta x_{m-1})} \right) + S_t \left(\frac{q_{m+½}t_{m+½}-q_{m-½}t_{m-½}}{\Delta x_m} \right) + H_t=0 \,,$$

where i, j, k, x, $m\pm1$, and $m\pm½$ are as defined previously, and t, K_t, S_t, q, and H_t are as defined above. The backward weighting determines the effective temperature for convective flow as

$$t_{m+½}= \begin{cases} t_m & \text{if } q_{m+½}>0 \\ t_{m+1} & \text{if } q_{m+½}<0 \end{cases} \quad \text{and}$$

$$t_{m-½}= \begin{cases} t_{m-1} & \text{if } q_{m-½}>0 \\ t_m & \text{if } q_{m-½}<0 \end{cases}$$

The specific discharge is calculated as

$$q_{m+½}=K_{m+½} \left(\frac{h-h_{m+1}}{½(\Delta x_{m+1}+\Delta x_m)} \right)$$

and similarly for $q_{m-½}$,

$$q_{m-½}=K_{m-½} \left(\frac{h_{m-1}-h}{½(\Delta x_{m-1}+\Delta x_m)} \right).$$

The finite-difference equations for a block are multiplied by the volume of the block, and then become balance equations, each term representing a flow into or out of the block, with the requirement that total inflow to the block must equal total outflow. A discussion of finite-difference methods as applied to ground-water flow is given in Bennett (1976).

Backward weighting for convective-heat transport assigns face temperature to the "upgradient" node. Central weighting computes face temperature as an average for the two adjacent nodes. Central weighting has less error for small grid spacing but may result in an unstable solution for large grid spacing. Backward weighting, on the other hand, has a stable solution for large grid spacing.

The computer code numbers the balance equations such that the equation matrix has the form shown in Larson (1978, fig. 2); Gauss-Doolittle elimination of variables results in an upper triangular equation matrix with the nth (last) variable known. Successive back substitution computes values for the other variables. The water and heat equations are solved alternately, with hydraulic conductivities updated after solution of the heat equation, and water flux through the block faces updated after solution of the water equation. The computer code also may be used as an isothermal model, and only the ground-water flow equation solved.

Traveltime is computed by the code by moving a particle of water through the model. The velocity at a block face

$$v_{m+½}=\frac{q_{m+½}}{\phi}$$

and similarly for $v_{m-½}$

$$v_{m-½}=\frac{q_{m-½}}{\phi}$$

where $m=i$, j, and k are the integer block numbers, v is the velocity, q is the specific discharge, and ϕ is the porosity. The velocity in a given direction within the block is estimated as a linear function of the velocity at the two opposing faces

$$v=a+bx_m$$

where a and b are constants defining the linear function. The time, t_m, that it would take to travel to a block face in direction m is given by

$$\Delta t_m=\int_{x_{mo}}^{x_{mf}} \frac{dx_m}{a+bx_m} = \frac{1}{b} \ln\left(\frac{a+bx_{mf}}{a+bx_{mo}}\right) \,,$$

where x_{mo} is the starting position, and x_{mf} is on the block face in the direction of movement for direction m. The time to travel to any block face is given by the minimum of the traveltimes for the three directions. The total traveltime is the sum of the block traveltimes.

CLIMATIC CHANGE, GEOMORPHIC PROCESSES, AND TECTONISM

By M.S. Bedinger

Climatic change and geomorphic processes that modify the hydrologic system and affect rates of erosion and aggradation are of concern in evaluating the changes in the environment and consequently the integrity of a high-level radioactive waste repository. Environmental factors of concern in repository design that are related to changes in climatic and geomorphic conditions during long-term postclosure time include: (1) The depth of a repository below land surface, (2) thermal perturbations of earth temperature at land surface, (3) change from an unsaturated to a saturated environment or vice versa, and (4) changes that would accelerate the transport or contact of radionuclides with the accessible environment or would increase the chance of human intrusion.

CLIMATIC CHANGE

Biological processes and surface- and ground-water systems are greatly affected by climatic change accompanying the expansion and recession of ice sheets. Geomorphic and hydrologic processes that are affected include runoff, erosion, aggradation, and ground-water recharge. Variations of climate during the late Pleistocene Epoch indicate that a significant change in climate may occur within the next 10,000–20,000 yr. Such time spans are well within the period of concern in the evaluation of waste-isolation environments. In this section, the information on the magnitude of climatic change is reviewed and consideration is given to the effect of climatic changes on geomorphic and hydrologic processes.

Knowledge of climates during the past 2 m.y., the Quaternary Period, comes from a combination of historical, archaeological, geological, and biological records. A broad overview of the roles and methods of Earth science in climate research during the Quaternary Period and longer is given in Smith (1976). Substantial changes in climate have occurred in the past 1,000 yr. Within the past 15,000 yr, the transition from the last major continental glaciation into the current postglacial condition has occurred. The past 150,000 yr includes the last glacial stage and the preceding interglacial stage. Multiple advances and retreats of continental sheet margins occurred during this period. Repeated glacial and interglacial cycles occurred during the past 1 m.y.

The astronomical theory of the glacial-interglacial climate procession holds that variations in eccentricity, precession, and obliquity of the Earth's orbital geometry affect climate by changing seasonal and latitudinal distribution of incoming solar radiation. Because these changes can be calculated with great precision for the past several million years, it is possible, in principle, to test the theory by comparing the record of Pleistocene climate with a predicted pattern of climate changes. Imbrie and Imbrie (1980) have prepared a model driven by the Earth's orbital variations that compares favorably with the record of Quaternary northern-latitude, continental glacial record from deep sea cores. The model has been used to predict the climate for the next 100,000 yr in the absence of anthropogenic or other sources of variation (Imbrie and Imbrie, 1980). The model was designed to achieve the closest correspondence with the expansion and contraction of glacial ice using the enrichment of oxygen-18 in deep-sea cores as an index of the volume of continental ice. The model predicts that a long-term cooling trend which began about 6,000 yr ago will continue for the next 23,000 yr.

LATE PLEISTOCENE FULL-GLACIAL CLIMATE

Reconstructions of the last full-glacial climate in the southwestern United States by various investigators from various geologic, hydrologic, and fossil-plant studies, compiled by Spaulding (1984), are given in table 2. A summary of estimates of late Quaternary climate for the Nevada Test Site and vicinity by Spaulding (1984) from analysis of fossil plant macrofossils from packrat (*Neotoma* sp.) middens is given in table 3.

Investigators concur that, in the Basin and Range province, there was more water available for runoff and vegetal growth during full-glacial climates than there is now. This greater availability of water is hypothesized to have been derived through either one of two principal mechanisms. The first mechanism was an increase in precipitation and a decrease in temperature, which consequently meant there was a decrease in evaporation. The second mechanism was a decrease in temperature, with no increase in precipitation or with even a slight decrease in precipitation. The first, "mild-wet climate," was advocated by Reeves (1966, 1973) and Van Devender and Spaulding (1979), and the second, "cold-dry climate," was advocated by Galloway (1970, 1983) and Brakenridge (1978).

During the late Pleistocene, more than 100 lakes existed in closed basins of the Basin and Range province (Williams and Bedinger, 1984; Smith and Street-Perrott, 1984). Most investigators who have reconstructed the

TABLE 2.—*Paleoclimatic reconstructions for the full glacial of the American Southwest*

[Modified from Spaulding (1983); ΔT_a, change, in degrees Celsius, in annual temperature; ΔT_s, change, in degrees Celsius, in summer temperature; ΔT_w, change, in degrees Celsius, in winter temperature; ΔP, change, in centimeters, in annual precipitation; percent *MP*, percent of change from modern precipitation; percent *ME*, percent of change from modern evapotranspiration]

Author	Data base	Location	ΔT_a	ΔT_s	ΔT_w	ΔP	Percent *MP*	Percent *ME*
Antevs (1952)	Hydrologic budgets	Lake Lahontan, west-central Nevada.	-2.5 to -3.0	---	---	+8 to +16	50 to 100	-30
Antevs (1954)	Relict snowlines	North-central New Mexico.	---	-5.6	---	+23	---	---
Bachhuber and McClellan (1977).	Foraminifer distributions.	Lake Estancia, Torrance Co., New Mexico.	---	-9.7	---	---	---	---
Brakenridge (1978).	Relict cirques and cryogenic deposits.	Montana to Arizona (lat 45° 40′N. to 33° 20′N.).	[1]-7.0	---	---	0	0	---
Broecker and Orr (1958).	Hydrologic budgets	Lake Lahontan, west-central Nevada.	-5.0	---	---	+20	80	---
Galloway (1970)	?Solifluction deposits.	Sacramento Mountains, south-central New Mexico.	-10.5	---	---	-4.6	---	---
Leopold (1951)	Hydrologic budgets and snowline changes.	Lake Estancia, Torrance Co., New Mexico.	-6.6	-9.0	-2.8	+18 to +25	+50 to +70	-23 to -50
Mifflin and Wheat (1979).	Hydrologic budgets	Nevada, statewide.	-2.8	---	---	+8.4 to -24	[2]68	-10
Reeves (1966)	Hydrologic budgets	Llano Estacado, western Texas.	-5.0	-8.0	---	+39	89	-27
Snyder and Langbein (1962).	Hydrologic budgets	Lake Spring, east-central Nevada.	[3]-5.0	[4]-7.2	---	+20	67	-30
Van Devender (1973).	Packrat middens	Western Arizona	-2.2 to -3.9	---	---	+12.3 to +22.0	---	---
Spaulding (1983).	Packrat middens	Southern Nevada[5]	-6.0 to -7.0	-7.0 to -8.0	[1]-6	---	10 to 20	---

[1]Minimum estimate.
[2]State-wide average.
[3]Extrapolated by Morrison (1965), Schumm (1965), and Mifflin and Wheat (1979).
[4]Extrapolated by Schumm (1965) and Brakenridge (1978).
[5]18,000 years before present.

glacial climate from Pleistocene lakes (Leopold, 1951; Snyder and Langbein, 1962; Reeves, 1966, 1973; Mifflin and Wheat, 1979) have concluded that the full-glacial climate was characterized by increased precipitation and a decrease in temperature. As shown by table 2, the projected changes in annual temperature and annual precipitation vary considerably between studies. The estimates of some of these investigators approach the climate of the "cold-dry" hypothesis. Galloway (1970, 1983) proposed that glacial climates were 10–11 °C colder than at the present time and that annual precipitation was about 80 percent of the modern rate.

TABLE 3.—*Summary of estimates of late Quaternary climate for the Nevada Test Site and vicinity*

[Modified from Spaulding (1984); yr B.P., year before present; ΔT_w, estimated change, in degrees Celsius, of average winter temperature; ΔT_s, estimated change, in degrees Celsius, of average summer temperature; ΔT_a, estimated change, in degrees Celsius, of average annual temperature; percent P_s, estimated percent change in average summer precipitation relative to current quantities; percent P_w, estimated percent change in average winter precipitation relative to current quantities; percent P_a, estimated percent change in average annual precipitation relative to current quantities]

Time (yr B.P.)	ΔT_w	ΔT_s	ΔT_a	Percent P_s	Percent P_w	Percent P_a
45,000	-2 to -3	---	-1 to -3	[1]-60	+20	0
38,700	---	---	-1 to -2	-40	+25 to +50	+10 to +20
37,800	---	---	-5	---	---	+20
30,000	---	---	-3 to -6	---	---	+10 to +25
18,000	[1]-6	-7 to -8	-6 to -7	-40 to -50	+60 to +70	+30 to +40
10,000	-1 to -2	+1 to +2	0	[2]+50	0	+10 to +20

[1]Minimum estimate.
[2]Maximum estimate.

Brakenridge (1978), in reviewing hydrologic budgets of Pleistocene lakes, relict snowlines and cryogenic deposits, and displacement of vegetation in the southwestern United States, concluded that there is no evidence for increased precipitation and that an annual temperature of 7–8 °C lower than at the present time would account for the observed relict Pleistocene phenomena.

Studies of plant macrofossils indicate that full-glacial climate displaced vegetation communities in the southwestern United States to lower elevation ranges (Brakenridge, 1978; Spaulding, 1983; Spaulding and others, 1984) compared to modern vegetation distributions. The lower desert shrub community was displaced about 700 m; timberline was displaced about 1,000 m (Brakenridge, 1978). Fossil-vegetation studies of the Pleistocene full-glacial period show that the increase in water availability was distributed throughout the vertical section of the topography. Because of the large size of the Basin and Range province, and its differences in latitude, elevation, distance to the ocean, and relation to storm tracks, it is to be expected that a range of differences in vegetation types similar to those seen today occurred within the Basin and Range province during full-glacial epochs.

Fossil vegetation and animal remains provide a basis for inferring geographic and seasonal differences in the full-glacial climate. Spaulding (1983), on the basis of plant macrofossils from the Nevada Test Site and vicinity in southern Nevada, characterizes the Wisconsin maximum, about 19,000 yr B.P., as a cold, continental climate with winter temperatures 6–7 °C less than modern and a distinct lack of summer rain but with winter precipitation as much as 70 percent greater than current values. The average annual precipitation was as much as 40 percent greater than modern quantities.

The full-glacial climate to the south and southeast of Nevada in southern Arizona, southern New Mexico, and Trans-Pecos Texas apparently was marked by milder temperatures and greater precipitation (Van Devender, 1973, as referred to in Spaulding, 1983; Van Devender and Spaulding, 1979; Wells, 1979; Van Devender and Toolin, 1983). The work by Van Devender and Toolin (1983) shows that *Pinus ponderosa* in late Wisconsin time was at an elevation 950–1,000 m below its present stand on Salinas Peak in the San Andres Mountains of New Mexico. The expansion of forest plants to lower elevation is attributed to cooler summer temperatures, and the presence of mesic and riparian plants indicate that annual precipitation was much greater than at present. Although milder temperatures may have prevailed in southern Arizona, southern New Mexico, and Trans-Pecos Texas, Spaulding (1983) noted that colder winter temperatures during the late Wisconsin full-glacial stage of at least 5 °C less than at present at the latitude of Tucson, Ariz., may be inferred from the modern and late Wisconsin occurrences of the chuckwalla (*Sauromalus obesus*) and the desert tortoise (*Gopherus agassizi*). A winter temperature decrease of 5 °C also would explain the absence from the fossil record of many frost-sensitive plants that characterize the modern southwestern Basin and Range province (Spaulding, 1983).

EFFECTS OF CLIMATIC CHANGE ON GROUND-WATER RECHARGE

In many areas of the Basin and Range province, a principal mechanism of ground-water recharge recognized by many ground-water hydrologists is infiltration in or near the mountain fronts as runoff from the consolidated rocks of the ranges debouches on the more permeable fill of the basins (Gates and others, 1980; Gates and Kruer, 1981; Rush, 1964; Harrill, 1971; Anderson, 1972). Where the geologic terrane in the mountain ranges is permeable by virtue of fractures or intergranular openings and where soil-moisture demands are minimal, significant recharge occurs to indurated rock of the mountains if a supply of moisture is available (Mifflin, 1968; Winograd and Riggs, 1984; Winograd and Thordarson, 1975; Feth, 1964; Cooley, 1968).

Winter precipitation results in a greater moisture availability for runoff and recharge than does summer precipitation. Winograd and Riggs (1984) have found that virtually all ground-water recharge in the Spring Mountains of southern Nevada has stable-isotope signatures of winter precipitation; summer convective rain storms do not provide water for recharge in excess of demands by evaporation and plant transpiration. Simpson and others (1970), using the stable deuterium isotope, found evidence to support the conclusion that water in wells sampled in the Tucson Basin, Ariz., was derived from winter precipitation in the Santa Catalina Mountains. Similarly, Gallaher (1979) concluded from study of oxygen-18 analyses that recharge to the Tucson Basin was derived primarily from winter precipitation in the adjacent mountains.

A full-glacial climate with increased winter rather than summer precipitation and decreased annual temperature, as postulated by Spaulding (1983) for southern Nevada, would result in greater water availability for both surface runoff and ground-water recharge compared to a climatic regime with mild temperatures and increased summer precipitation.

Recharge in the Basin and Range province has been estimated for large areas using a water-budget technique developed by Maxey and Eakin (1949). By this method, the recharge component of the water budget is calculated as the quantity required to balance the mass balance equation for a basin. The recharge component is integrated throughout the basin as a percentage of the precipitation in isohyetal bands approximately in proportion to the water excess in each band. The procedure is empirical with no implication as to the geographic location where recharge takes place. Using multiple regression techniques, Watson and others (1976) were unable to improve the Maxey-Eakin technique or develop a reliable regression relating recharge to precipitation using hydrologic-budget data from 63 basins in Nevada.

The isohyetal bands and corresponding percentage of recharge estimated by Maxey and Eakin (1949) are given in the following table:

Annual precipitation (millimeters)	Recharge as a percent of precipitation
More than 508	25
381–508	15
305–381	7
204–305	3
Less than 204	0

The effect on recharge rates of the change to pluvial conditions is difficult, if not impossible, to estimate because the pluvial climate probably varied geographically and because the characteristics of the pluvial climate are not only incompletely known, but are subject to disagreement among investigators. Furthermore, recharge is poorly known even under modern climatic conditions that are well known. However, an approach can be made to estimate the response of recharge to change in climate based on two techniques: (1) The Maxey-Eakin technique, and (2) a general estimate of change in water availability from the precipitation-runoff-temperature relation of Langbein and others (1949). Examination of the changes in recharge by the Maxey-Eakin technique from the preceding table indicates that recharge increases about three-fold with an increase in precipitation of 35 percent, from 255 to 343 mm, and about nine-fold with an increase in precipitation of 74 percent, from 255 to 444 mm. These estimates should be considered only as possible changes in magnitude because of the empirical nature of the Maxey-Eakin technique.

Changes in water availability are shown by the relation between precipitation, runoff, and mean annual temperature (fig. 5). A decrease of 6 °C in annual temperature and a 35 percent increase in precipitation may effect as much as a 5- to 10-fold increase in runoff. This increase in runoff includes water available for recharge because runoff includes ground-water recharge as the ground-water component of stream flow (Langbein and Iseri, 1960).

In southern Nevada, with the full-glacial climatic conditions postulated by Spaulding (1983), it appears plausible that ground-water recharge may increase 3 to 10 or more times the modern rate. In the southern and southwestern parts of the province under a "mild-wet" climate, the increase in recharge could conceivably be less than that in southern Nevada. Under a "cold-dry" climate in which precipitation occurs mostly in the winter, recharge in the southern and southwestern parts of the province could equal that in southern Nevada. Lacking confidence in estimating pluvial climatic conditions or recharge rates, it would seem prudent to use conservative (large) estimates of change in recharge in performance assessments.

EROSION AND AGGRADATION

The late Cenozoic geologic history of the Basin and Range province provides ample evidence that vertical crustal movements, erosion, and aggradation have shaped most of the present surface features in the province. Aggradation of the basinal troughs and erosion of the mountain ranges are almost equal forces tending to level the topography, whereas vertical crustal movements, which are manifested by range-front faults, maintain many closed basins and areas of high relief in the province.

RATES OF SEDIMENT YIELD

Many factors can affect a basin's sediment yield, but climate and tectonic events are the most important in controlling erosional and depositional processes. Sediment yields have been related primarily to precipitation by Langbein and Schumm (1958), who also show that other factors may cause a 30-percent standard deviation in sediment yield for basins having the same effective precipitation. One factor of significance which causes variations in the sediment yield under a given effective precipitation is the topographic relief of a drainage basin. Schumm and Hadley (1961) show that the sediment-yield rate can be expressed as an exponential function of the relief-to-length ratio of basins.

The two principal factors, precipitation and topographic relief as shown by Langbein and Schumm (1958) and by Schumm and Hadley (1961), respectively, can be used to estimate approximate rates of erosion and also to illustrate the gross areal distribution and variations in rates of erosion and deposition in the Basin and Range province. Other factors such as intensity of and seasonal variations in rainfall, vegetation, temperature, and land use, and variations due to different rock types and tectonic events also affect rates of erosion and deposition. Several of these factors are interrelated, however. Vegetation is reflected in part in precipitation; temperature is reflected in part in the "effective mean annual precipitation" as defined by Langbein and others (1949); and tectonic events are reflected in part in the topographic relief.

Effective precipitation is defined as the quantity of precipitation at a given mean annual temperature required to produce a known quantity of runoff. The relation between effective mean annual precipitation and mean annual runoff is given in figure 5 from Langbein and others (1949). This graph illustrates the effect of temperature on the relation between annual runoff and precipitation for several reference temperatures. In the basins and other areas of lower elevation, which have a relatively warm climate, a given quantity of precipitation produces less runoff than in the cooler climate of the mountain ranges. This relation between temperature and precipitation reflects the greater water loss by evapotranspiration in the warmer climate of the basins.

The relation between effective mean annual precipitation and sediment yield for a mean annual temperature of 10 °C as determined from records at sediment stations is shown in figure 6. The same relation (effective mean annual precipitation to sediment yield at a mean annual temperature of 10 °C) but determined from reservoir surveys is shown in figure 7. Both illustrations show that sediment yield is at a maximum at about 25–30 cm of precipitation and decreases abruptly on both sides of this maximum. The sediment yield for less than 25 cm of precipitation decreases because there is a deficiency of runoff; and the sediment yield for greater than 30 cm of precipitation decreases because there is increased density of vegetation. The sediment stations used in preparation of figure 6 have an average drainage-basin area of 579 km^2; the reservoirs used in preparation of figure 7 have an average drainage-basin area of 12 km^2. The greater sediment yield from the smaller basins is attributed in part, to greater topographic relief in the smaller basins. Because of the effect of temperature on mean annual runoff, the

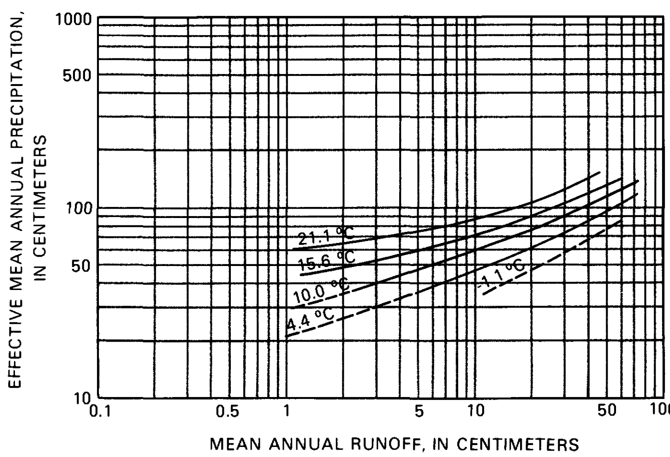


FIGURE 5.—Effect of temperature, in degrees Celsius (°C), on the relation between mean annual runoff and mean annual precipitation (modified from Langbein and others, 1949).

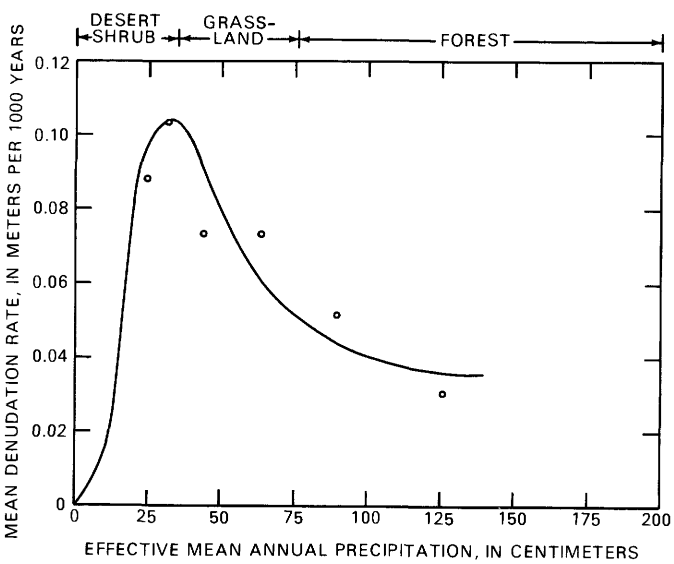


FIGURE 6.—Climatic variation of yield of sediment as determined from records at sediment stations throughout the United States (modified from Langbein and Schumm, 1958).

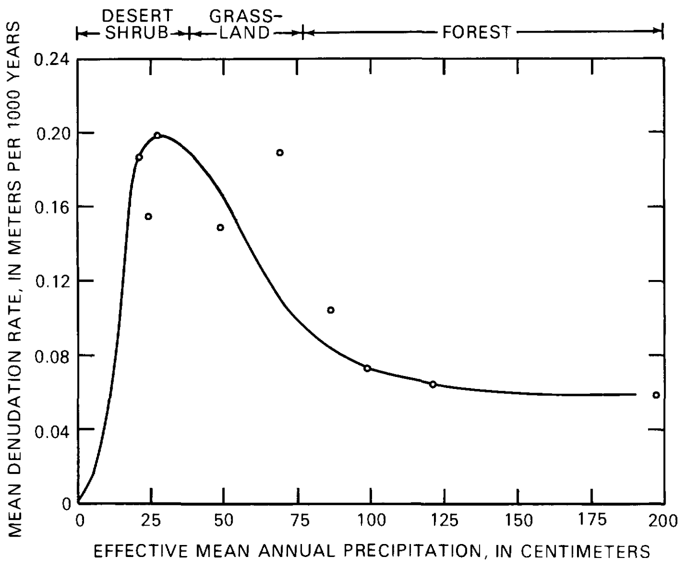


FIGURE 7.—Climatic variation of yield of sediment as determined from reservoir surveys throughout the United States (modified from Langbein and Schumm, 1958).

curves in figures 6 and 7 are shifted to the right for higher temperatures and to the left for lower temperatures (Schumm, 1965).

The average annual runoff in the Basin and Range province is shown in figure 8. The annual-runoff data can be used with figure 5 to estimate the effective annual precipitation which in turn can be used to estimate the sediment yield. The effective annual precipitation of 25–30 cm/yr, producing the greatest sediment yield, appears to occur in the intermediate elevations of the higher basin areas and the lower parts of the mountain ranges.

The annual runoff in the basin areas of the province generally is 0.5 cm/yr or less, corresponding to an effective annual precipitation of less than 25 cm/yr. This, combined with the smaller relief-to-length ratio of the basins, means that the basins have less capability to yield sediment than the ranges. Thus, based on the relation between sediment yield and effective precipitation and relief-to-length ratio, it is concluded that not only closed basins are aggrading, but also so are basins with open drainage, except in the vicinity of major arroyos.

RELATION OF EROSION TO VERTICAL CRUSTAL MOVEMENT

The history of late Cenozoic vertical movement of the basins and ranges is recorded in deposits filling the basins; some of these deposits are as thick as 3,000 m. The rates of vertical crustal movements are greater than aggradation or erosion as evidenced by the continued existence of ranges and closed basins.

Average rates of vertical crustal movements in the Basin and Range province during the past 10 m.y. were synthesized from many sources by Gable and Hatton (1983). Vertical movements are detected and measured by vertical displacement of faults, uplift of positive areas, and downwarp or subsidence of negative areas, and are based on data derived from geology, geomorphology geophysics, paleobotany, radiocarbon dating, geodetic leveling, and sea-level measurements (tide-gage data). The slowest average rate of vertical movement during the past 10 m.y. in the Basin and Range province (fig. 9) is about 1–2 m/10^4 yr in the eastern part of the province in Texas, New Mexico (except for the Rio Grande Rift), Arizona, and most of Utah. The range in average vertical movement during the past 10 m.y. in the western part of the province is between 2 and 4 m/10^4 yr, with the more rapid rates in northeastern Nevada, Oregon, northern California, and the strip parallel to the Sierra Nevada in western Nevada and southern California. For comparison, Langbein and Schumm (1958) and Schumm (1963) show the maximum rate of denudation for drainage basins in the United States having effective precipitation similar to the Basin and Range province (figs. 6 and 7) as 1–2 m/10^4 yr for large basins (average area, 3,900 km^2) and 2 m/10^4 yr for small basins (average area, 80 km^2).

The maximum rates of erosion in the mountain ranges or aggradation in the basin areas may nearly equal the slowest (1–2 m/10^4 yr) of the long-term rates of vertical crustal movement in the eastern part of the province. Where long-term rates of vertical crustal movement are greater than 1–2 m/10^4 yr, corresponding rates of erosion and aggradation could be used as a maximum potential rate in evaluation of exhumation or burial of a repository.

Spatial distribution of erosion and deposition are dependent on geomorphic setting and may differ greatly within a basin. The average rate of deposition or erosion in a basin may be unimportant, whereas the local geomorphic processes, such as scarp retreat, stream entrenchment, stream aggradation, basin filling, or hillslope erosion may predominate in affecting the geomorphic environment of a given repository. Rates of channel entrenchment compiled for the Colorado Plateau and the Basin and Range province range from about 0.08–2.3 m/10^4 yr (table 4). Scarp-retreat rates compiled in the same areas (table 5) range from 1.8–8.0 m/10^4 yr.

Many lines of evidence support the conclusion that rates of tectonic activity are episodic. Such evidence includes occurrences of faulting (Trask, 1982), earthquakes, and rapid vertical changes documented by successive leveling surveys. Schumm (1963) cited successive terrace levels of streams as evidence of intermittent isostatic adjustment after epeirogenic movements. Because tectonic activity is episodic, the average rates of vertical movement and erosion during long periods

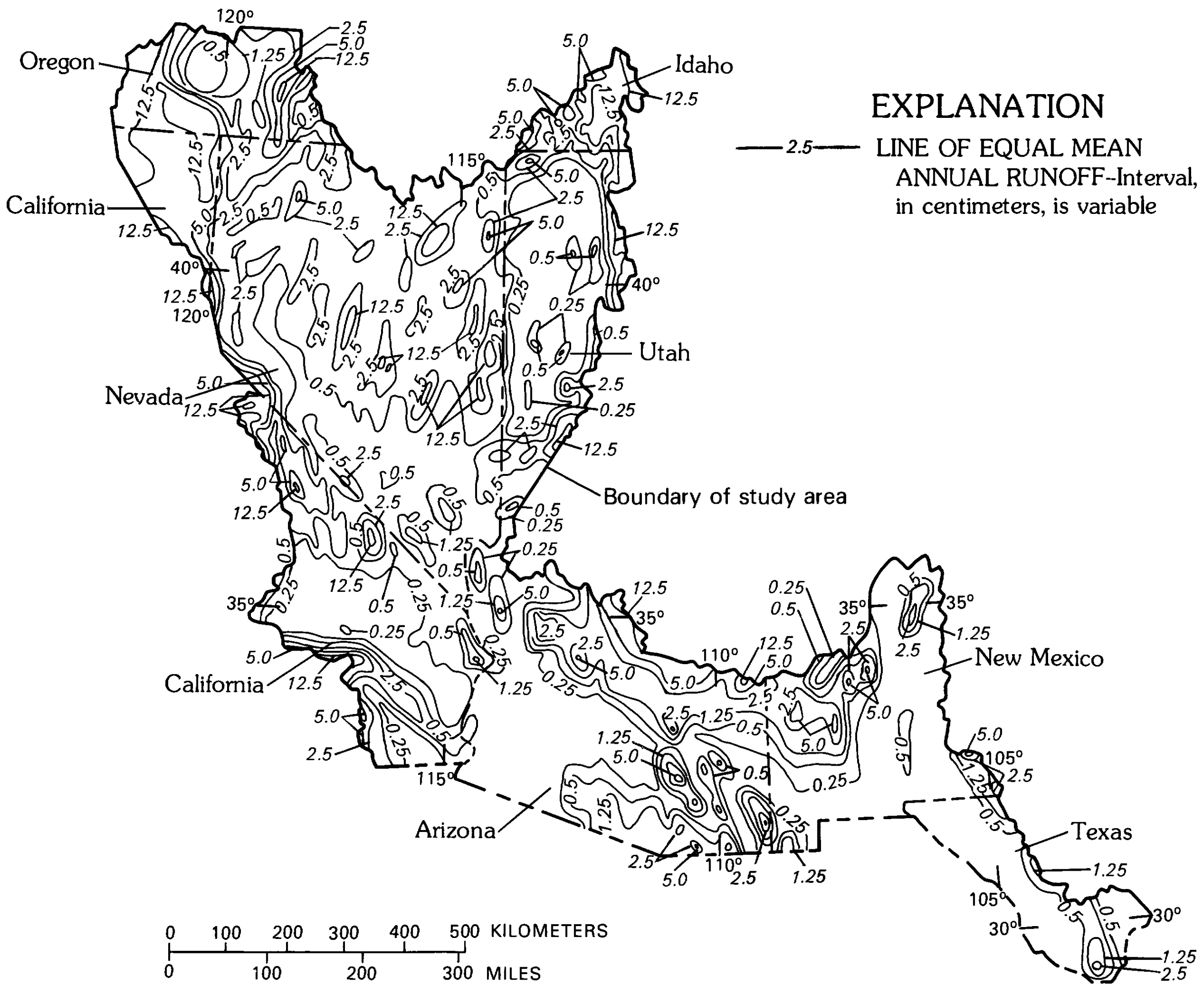


FIGURE 8.—Mean annual runoff (modified from Busby, 1966).

may be greater or lesser than the short-term rates. Short-term rates of vertical movement determined from geodetic-leveling data are shown in figure 9. These movements range from 2–20 mm/yr and include isostatic rebound from the release of pressure at ancient lakes Bonneville and Lahontan and at areas possibly affected by magmatic activity at depth (Socorro, N. Mex., and Owens Valley, Calif.).

SUMMARY

Reconstructions of the last full-glacial climate indicate that there was greater water availability for runoff and vegetal growth than now exists. Based on the increase in water availability and depending upon the seasonal distribution of precipitation, the soil characteristics, the topography, and other characteristics, it is estimated that ground-water recharge during the full-glacial climate could have been 2 to 5 or more times the modern rate. During the full-glacial climate, more than 100 lakes occupied closed basins in the province. Increase in ground-water recharge and refilling of Pleistocene lakes will tend to decrease the ground-water traveltime. The thickness of the unsaturated zone, considered a host media where the thickness is greater than 150 m, will be decreased by these changes. In contrast, aggradation of basin areas, incision of streams and other tectonic or climatically induced changes that

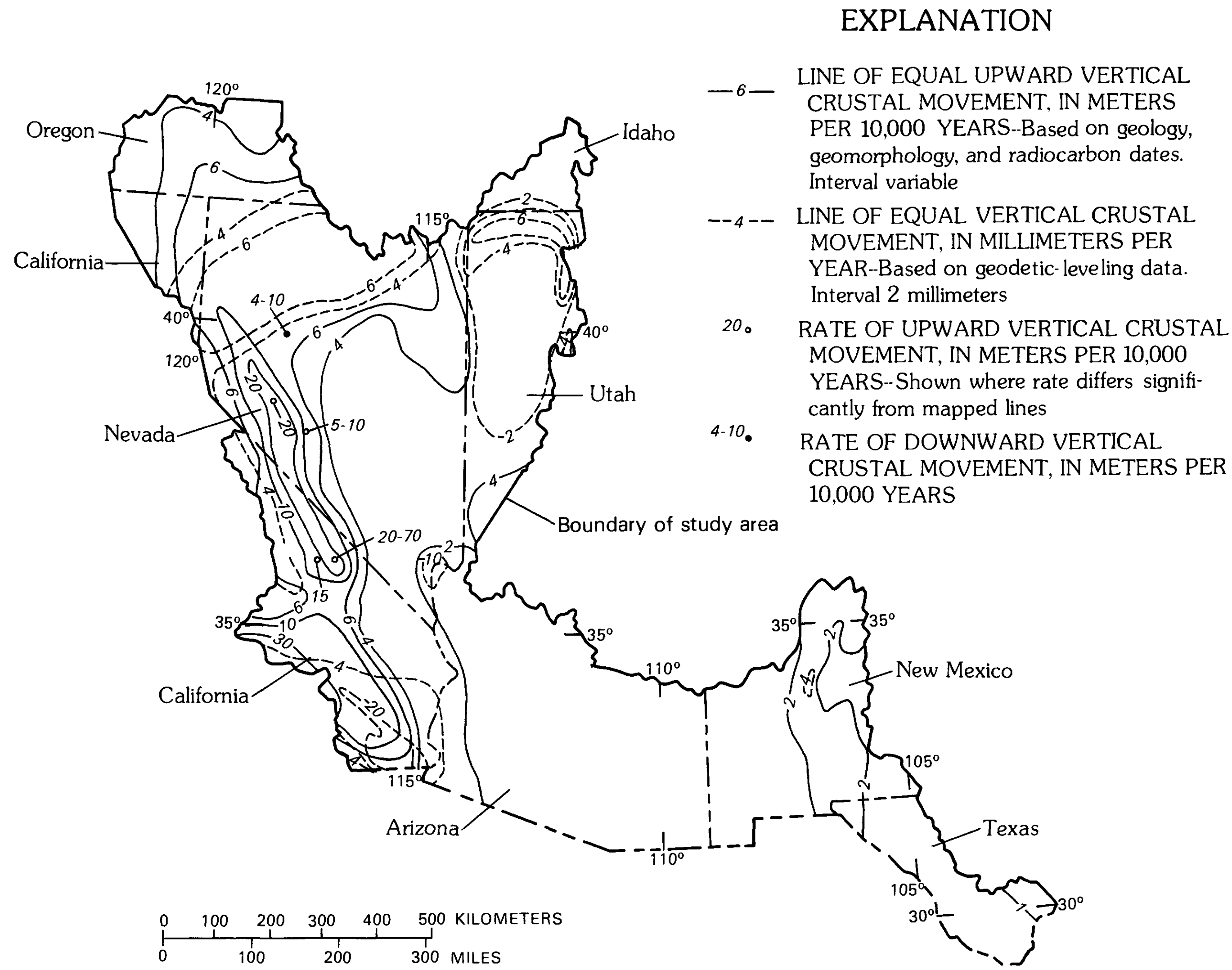


FIGURE 9.—Rates of vertical crustal movement (modified from Gable and Hatton, 1983).

lower the ground-water discharge level will tend to increase the thickness of the unsaturated zone.

The late Cenozoic history of the Basin and Range province records that continued vertical crustal movements have maintained mountain ranges and closed basins, although aggradation of the basins and erosion of the mountain ranges have tended to level the topography. Maximum rates of denudation for small basins in areas climatically similar to the Basin and Range are about 2 m/10^4 yr. Geologic evidence shows maximum average rates of stream entrenchment in the Basin and Range province of about 2 m/10^4 yr. A conservative estimate of erosion affecting long-term changes in depth of burial of a high-level waste repository would appear to be 2 m/10^4 yr or greater, to equal the long-term rate of vertical crustal movement.

Effects of long-term climatic and tectonic changes on the hydrologic and geomorphic conditions of a deep, mined repository differ from area to area, and rates of change of geomorphic and hydrologic changes may vary significantly. Site-specific studies are essential in assessing the long-term integrity of deep, mined repositories.

TABLE 4.—*Rates of channel entrenchment*

Area	Depth of entrenchment (meters)	Estimated time (10^6 years)	Rates of entrenchment (meters per 10^4 years)	Reference
Colorado River System, Utah and Arizona	240–460	2.2	1.2–2.3	Cooley, 1962.
LaSal Mountains, Utah	300	2.0	1.5	Hunt, 1969, as referred to in Woodward-Clyde Consultants, 1983.
Chaco River at San Juan River, New Mexico	150	2.2	0.7	Hunt, 1969, as referred to in Woodward-Clyde Consultants, 1983.
Virgin River at St. George, Utah	210	2.2	1.0	Hamblin and others, 1975 as referred to in Woodward-Clyde Consultants, 1983.
Rio Grande in Seldon Canyon, New Mexico	100	0.5	2.0	Seager and Clemons, 1975; Seager and others, 1984.
Rio Puerco west of Prieta, Albuquerque basin, New Mexico.	350	2.0	1.8	Bachman and Mehnert, 1978.
Rio Puerco tributaries, New Mexico	23–209	2.6–3.0	0.08–0.8	Grimm, 1982.
Rio Grande in Presidio Bolson, Texas	76	0.5	1.5	J.W. Hawley, New Mexico Bureau of Mines and Mineral Resources, oral commun., 1984.

TABLE 5.—*Rates of scarp retreat*

Area	Scarp retreat (meters)	Estimated time (10^6 years)	Rate of scarp retreat (meters per 10^4 years)	Reference
Virgin River at St. George, Utah	670	2.2	3.0	Hamblin and others, 1975, as referred to in Woodward-Clyde Consultants, 1983.
Colorado River at Green River, Utah	1,600	3.0	5.3	Hunt, 1969, as referred to in Woodward-Clyde Consultants, 1983.
Grand Canyon, Arizona	---	0.013 (average)	1.8–7.2	Cole and Mayer, 1982.
Mogollon Rim, Arizona	---	---	4.0–8.0	Mayer, 1979, as referred to in Cole and Mayer, 1982.

RESPONSE OF GROUND WATER TO CHANGES IN BOUNDARY CONDITIONS

By J.E. REED and M.S. BEDINGER

The effect of changes in boundary conditions, including changes in stream level, lake level, and recharge, on ground water is discussed in two parts: (1) The principles and effects of boundary-condition changes under steady-state and nonsteady-state conditions, and (2) ground-water changes in response to changes in boundary conditions in the Basin and Range province.

Changes in hydraulic head and ground-water flux along the hydrologic boundaries of flow systems may occur in response to tectonism and changes in climate. Changes in boundary conditions due to climatic changes may include changes in recharge to the aquifer, changes in hydraulic head along aquifer boundaries, and development of additional boundaries, such as springs and evapotranspiration areas due to rising ground-water levels. Changes in hydraulic-boundary conditions may occur due to erosion, including: (1) Entrenchment of streams and lowering of the ground-water discharge level; (2) stream piracy or integration of drainage of closed basins, which would alter the position and possibly the discharge level of aquifer boundaries; and (3) aggradation of closed basins or valley floors and consequent raising of a stream, lake, or marsh discharge level. Large perennial streams in the province are the base levels of ground-water discharge. Most perennial streams in open basins, such as the Colorado River, Rio Grande, Gila River, and Salt River, and probably long reaches of large streams in closed basins, such as the Humboldt River, Walker River, and Owens River, probably were entrenched 20–30 m below present levels during the last full-glacial stage.

ANALYTICAL MODELS OF GROUND-WATER RESPONSE TO BOUNDARY CHANGES

STEADY-STATE RESPONSE

The hydraulic-head distribution in an aquifer under steady-state conditions is the result of the rate and distribution of recharge to and discharge from the aquifer, of the transmissivity of the aquifer, and of the nature and configuration of the lateral boundaries of the aquifer. For simplicity, let us assume an aquifer enclosed by boundaries which are impermeable or have fixed values of hydraulic head. Reed and Bedinger (1961) have shown that the hydraulic head in such an aquifer may be separated into two components, if the differences in hydraulic head are small compared to the total thickness of the aquifer and assuming flow in two horizontal dimensions. This condition also requires that transmissivity does not change appreciably for the range of conditions being considered. These components of hydraulic head are shown diagrammatically in figure 10*A*.

The boundary component of hydraulic head is determined by the type and configuration of the lateral hydraulic boundaries of the aquifer and the hydraulic-head distribution on the constant head boundaries.

The accretion component of hydraulic head is determined by the ratio of accretion to the transmissivity and by the areal geometric shape of the aquifer and the nature of the boundaries. Accretion is used here as defined by Stallman (1956) to represent the net rate at which water is gained or lost vertically through the aquifer surface in response to external forces. Infiltration of precipitation, evapotranspiration, and vertical leakage between the aquifer and confining beds are examples of accretion. The accretion component of hydraulic head is zero on the constant head boundaries of the aquifer. If the recharge to an aquifer is multiplied by a constant factor then the accretion component of head also is multiplied by the same constant factor, again assuming no appreciable change in transmissivity.

The partial differential equation for steady-state two-dimensional flow in an isotropic aquifer following the notation of Trescott and others (1976) is given by

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)=-W(x,y)\,,$$

where T is the transmissivity, h is the hydraulic head, and $W\ (x,y)$ is the volumetric flux of recharge or discharge per unit surface area of the aquifer. Incorporating the concept that the hydraulic head is the sum of two components of hydraulic head, the accretion component of head, h_a, can be expressed as the solution of

$$\frac{\partial}{\partial x}\left(T\frac{\partial h_a}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h_a}{\partial y}\right)=-W(x,y)\,,$$

and the boundary component, h_b, can be expressed as the solution of

$$\frac{\partial}{\partial x}\left(T\frac{\partial h_b}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h_b}{\partial y}\right)=0.$$

The accretion component of hydraulic head, h_a, (fig. 10*A*) is proportional to the uniform recharge rate, W, and inversely proportional to the transmissivity, T, of

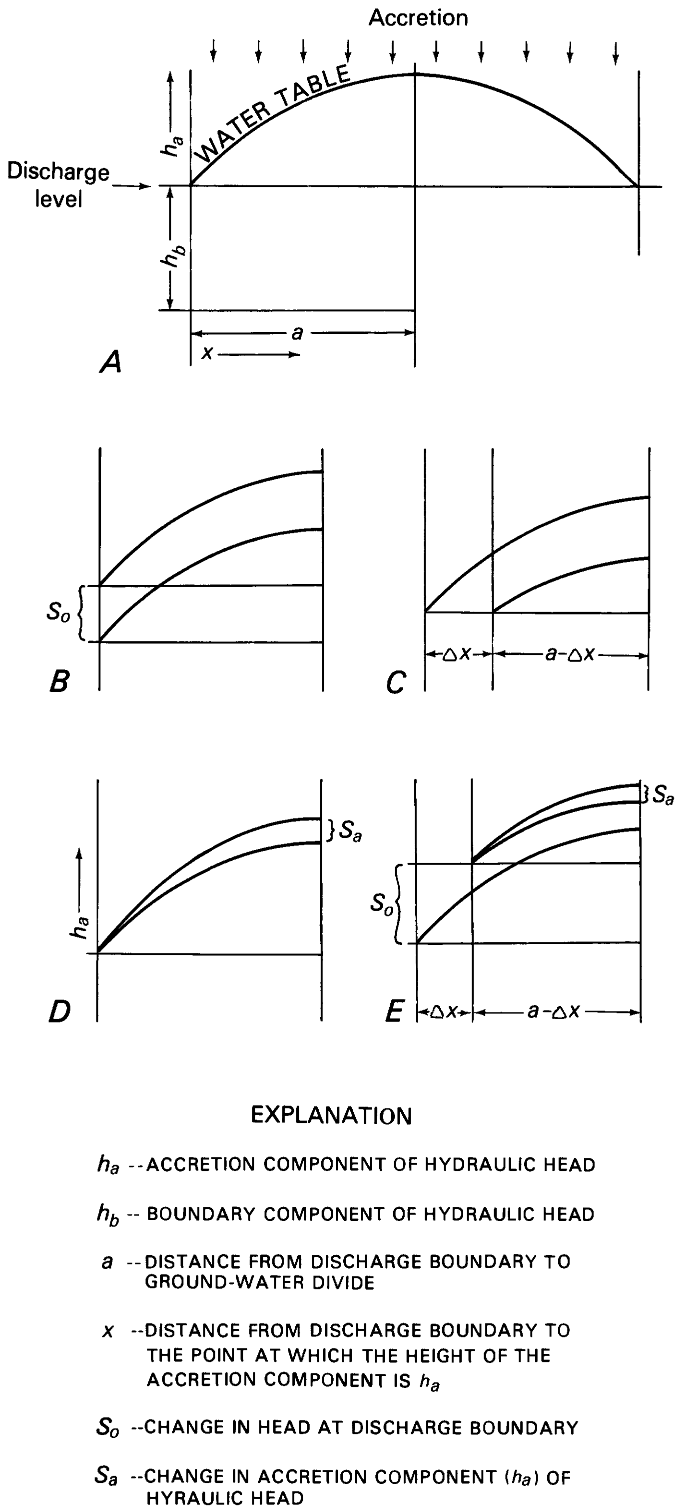


FIGURE 10.—Steady-state effect of changes in discharge and recharge boundaries on ground-water level. *A*, Components of hydraulic head; *B*, Effect of change in head at discharge boundary; *C*, Effect of change in position of discharge boundary to divide; *D*, Effect of increase in accretion; and *E*, Resultant effect of changes in head and position of discharge boundary and accretion on boundary components and accretion component.

the water-bearing rock, as seen from equation 1, which is the analytical expression for the accretion component in an infinite strip aquifer of uniform permeability where the recharge is uniformly distributed (Jacob, 1943).

$$h_a = \frac{W}{T}\left(ax - \frac{x^2}{2}\right), \qquad (1)$$

where h_a is the accretion component of head or the height of the water level above the stream or lake discharge boundary, which is the boundary component; W is the accretion rate; T is the coefficient of transmissivity; a is the distance from the discharge boundary to the ground-water divide; and x is the distance from the discharge boundary to the point at which the height of the accretion component is h_a. Consider now the effect of a change in head, S_o, at the discharge boundary, but no change in recharge, W. After attainment of equilibrium to a rise in the discharge boundary, a change in the boundary component of head will be produced (fig. 10*B*). The change in boundary component of head at the boundary is equal to the change in discharge level. A shift in the position of the discharge boundary, for example, by lateral erosion of the stream, produces an increase or decrease of Δx in a, the distance from the discharge boundary to the divide, as shown in figure 10*C*. The result is an increase or decrease in surface area of the aquifer to receive recharge, a change in the accretion component, h_a, and shorter or longer flow paths of ground water.

The effect of an increase in accretion to the aquifer is shown in figure 10*D*. At equilibrium, the change in thickness of the accretion component is a function of the change in accretion.

Because the boundary and accretion components are linear functions, the resultant effect of a change in boundary component of head and position of the discharge boundary and of a change in accretion component is the algebraic sum of the individual component changes in hydraulic head (fig. 10*E*).

NONSTEADY-STATE RESPONSE TO STEP CHANGES

The time required for a flow system to reach equilibrium with a boundary change of either a change in discharge level or a change in recharge is a function of the dimensions, the transmissivity, and the storage coefficient of the aquifer. We can examine the time required for the ground-water system to reach equilibrium by applying reasonable values of these parameters to analytical models. Then, the estimated times required to reach equilibrium can be compared to geologic evidence of the duration of the pluvial periods.

Consider first the response of water level to a rapid step change in discharge level occurring at time $t=0$. The ratio of the change in boundary component of hydraulic head, s_b, to the change in discharge level, s_o, is given by the following equation modified from Rorabaugh (1960):

$$\frac{s_b}{s_o} = 1 - \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n-1} \exp\left[\frac{-(2n-1)^2\pi^2 Tt}{4a^2 S}\right] \sin\frac{(2n-1)\,\pi\, x}{2a} \tag{2}$$

where x is the distance from the discharge boundary; a is the distance from the discharge point to the water-table divide (fig. 10A); T and S are the transmissivity and coefficient of storage, respectively, of the aquifer; and t is the time since the change in boundary level occurred.

Next, consider the change in water level in response to a change in an otherwise steady rate of recharge occurring at time $t=0$. The ratio of transient change in head, s_a, to the final or steady-state change in head, s_{af}, caused by a step-change in otherwise constant recharge, is given by the following equation from Bedinger, Sargent, and others (1984):

$$\frac{s_a}{s_{af}} = 1 - \frac{32a^2}{\pi^3(2ax-x^2)} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^3} \exp\left[\frac{-(2n-1)^2\pi^2 Tt}{4a^2 S}\right] \sin\frac{(2n-1)\,\pi\, x}{2a} \tag{3}$$

As can be seen from equation 3, the ratio of the transient-head response to the steady-state change in head is independent of the amount of change in recharge rate.

CYCLIC CHANGES

The response of a hydrologic system, consisting of one-dimensional nonsteady flow in an aquifer between two discharge boundaries, to cyclic variations in recharge rate can be determined by convolution using equation 3 as the unit response (Bedinger, Sargent, and others, 1984). As the time interval becomes large, the transient response dies away leaving a steady oscillation of period P and amplitude W; the head, h, is given by:

$$h = \frac{4W}{\pi S} \sum_{n=1}^{\infty} \frac{\sin Cx}{2n-1} \, \frac{C^2 D \sin Bt - B \cos Bt}{C^4 D^2 + B^2}, \tag{4}$$

Where

$B = 2\pi/P$,
$C = (2n-1)\pi/2a$, and
$D = T/S$.

The maximum change in head in an aquifer to a sine wave of recharge is a sine wave of ground-water-level fluctuation whose amplitude, A_o, is given by Jacobs' parabola, equation 1. The amplitude, A, of the response of a given aquifer depends upon the period of the recharge cycle, P; L is the lag of water level behind recharge; diffusivity of the aquifer, $D=T/S$; distance from discharge point to the divide, a; and distance from the discharge point, x. The amplitude ratio, A/A_o, can be computed by the following equation modified from Bedinger, Sargent, and others (1985):

$$\frac{A}{A_o} = \frac{1}{4\pi}\left(\frac{PD}{a^2}\right)^2 \frac{\displaystyle\sum_{n=1}^{\infty} \sin\left(\frac{(2n-1)}{2}\pi\frac{x}{a}\right) \frac{2n-1}{\frac{(2n-1)^4\pi^2}{64}\left(\frac{PD}{a^2}\right)^2+1}}{\left(\frac{x}{a}-\frac{1}{2}\left(\frac{x}{a}\right)^2\right)\cos\frac{2\pi L}{p}}$$

$$= \frac{2}{\pi^2}\left(\frac{PD}{a^2}\right) \frac{\displaystyle\sum_{n=1}^{\infty} \frac{\sin\left(\frac{(2n-1)}{2}\pi\frac{x}{a}\right)}{2n-1} \frac{1}{\frac{(2n-1)^4\pi^2}{64}\left(\frac{PD}{a^2}\right)^2+1}}{\left(\frac{x}{a}-\frac{1}{2}\left(\frac{x}{a}\right)^2\right)\sin\frac{2\pi L}{p}} \tag{5}$$

The maximum response and response for PD/a^2 equal to 2.5 and to 1 are shown in figure 11. For PD/a^2 equal to 2.5, A_1/A_o is 0.6983 and the lag is 0.1310 period. For PD/a^2 equal to 1, A_2/A_o is 0.3587 and the lag is 0.2010 period.

RESPONSE OF AQUIFER SYSTEMS IN THE BASIN AND RANGE PROVINCE

The foregoing analytical models were applied to the Basin and Range province with respect to the general nature and time of response of ground water to changes in climate and geomorphic processes. Of importance in respository site evaluation are: (1) The potential effect on the ground-water system to a change in boundary conditions, (2) the time of response of the ground-water system to a change in boundary conditions, and (3) the

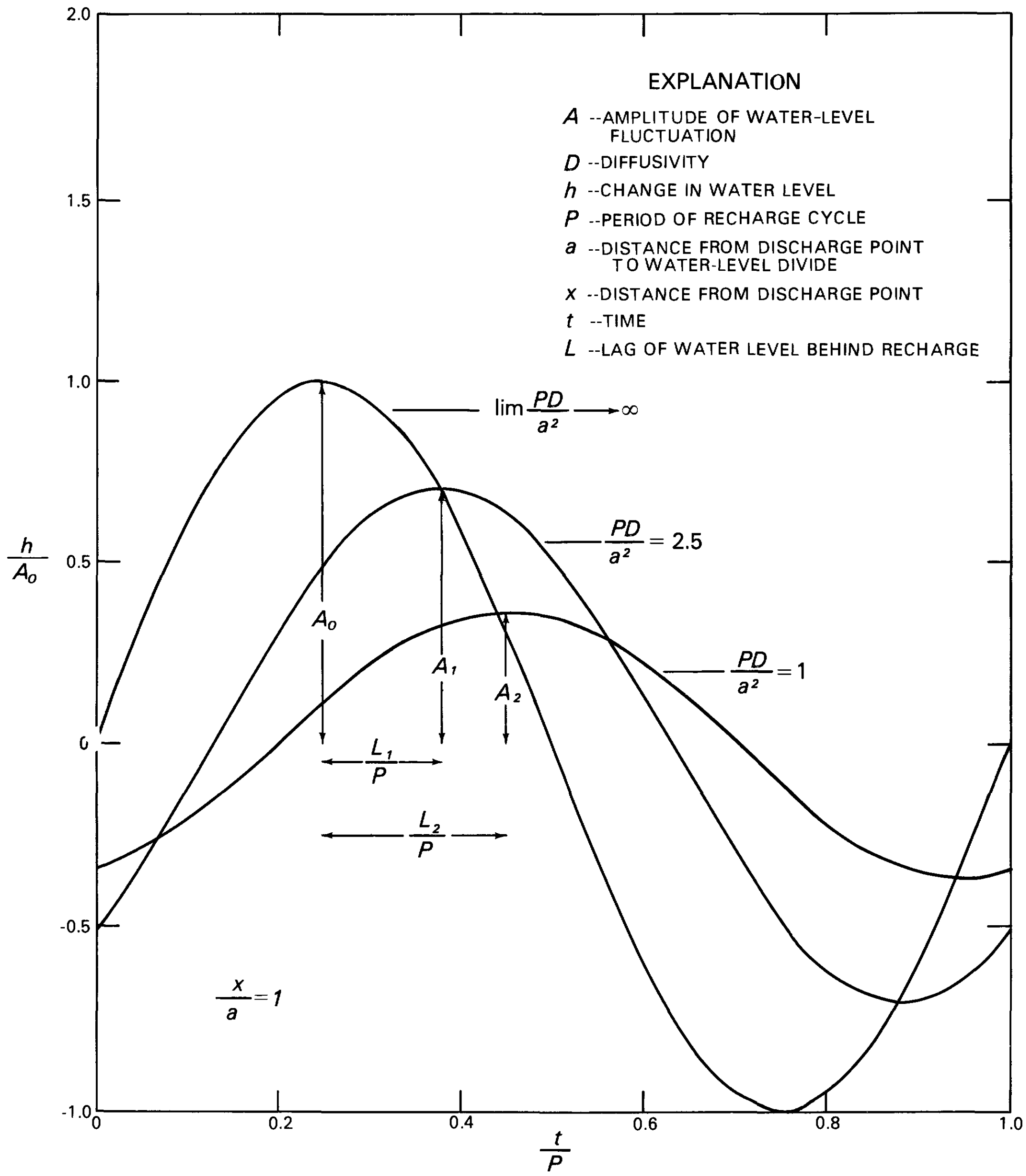


FIGURE 11.—Dimensionless water-level response (h/A_0) versus dimensionless time (t/P) for cyclic recharge.

present state of response of the ground-water system to past changes in boundary conditions.

Maximum potential change in water level in response to changes in boundary conditions would be the sum of the steady-state effects of: (1) The increase (decrease) in boundary component equal to the stage rise (fall) of the lake or stream level to which the ground water discharges, and (2) the increase (decrease) in accretion component in proportion to the increase (decrease) in recharge. This maximum potential change will be attenuated by the increase (decrease) in transmissivity of the aquifer and by other discharge boundaries of the aquifer that may be created, such as where the rise in water level intersects the land surface. In less permeable rocks, as in the range blocks composed of crystalline rocks of low permeability, the change in head may take place very slowly and never reach equilibrium within a pluvial cycle of a few thousand years.

The time to reach equilibrium with a step change in discharge level or recharge, called the unit aquifer response, is inversely proportional to the hydraulic diffusivity (T/S) of the ground-water-bearing section, and directly proportional to the lateral dimension of the flow system (fig. 10*A*). Transmissivity, T, is the product of the hydraulic conductivity, *k*, and the thickness, *m*, of the water-bearing section. The storage coefficient, *S*, is the quantity of water released from storage in response to a unit decline in hydraulic head throughout a unit area. For ground-water occurrence under water-table conditions, the storage coefficient (specific yield), *S*, is less than the effective porosity. Storage coefficients for artesian aquifers are a function of the compressibility of the aquifer and the water and are commonly several orders of magnitude smaller than the effective porosity. Aquifers taking longer times to reach equilibrium generally will be under water-table conditions with relatively large effective porosities and low transmissivity.

Referring to table 1, rocks with the smallest ratio of hydraulic conductivity to effective porosity, K/ϕ, are the consolidated and unconsolidated fine-grained sedimentary units. These units do not occupy a large part of hydrogeologic sections and would not limit the time of response of the system to a boundary change. Metamorphic and intrusive igneous rocks having fracture permeability have the next smallest K/ϕ. They are extensively exposed in upland areas in the province and probably are the rocks that will limit the response of the flow systems in many mountain ranges to changes in boundary conditions. Hydraulic-property values for metamorphic and intrusive igneous rocks from 16.5 percentile, median, and 83.5 percentile from table 1 were used to obtain conservative values of time.

Because ground-water flow systems are subject to continually changing boundary conditions in response to short-term climatic variations and changes in discharge level, a ground-water flow system never reaches a true steady state or condition of equilibrium. However, in the response to long-term boundary conditions that fluctuate within a relatively narrow range, the average state of the flow system may reach a near-steady state or quasiequilibrium state with the boundary conditions.

The time to reach 95 percent of equilibrium hydraulic head in a block of crystalline fractured rock of 10-km width is 200,000, 30,000, and 4,000 yr for diffusivities of 0.5, 3, and 20 m^2/d, respectively, based on properties of fractured rock at depths of less than 300 m (table 1), and 20,000, 500, and 20 yr for diffusivities of 5, 167, and 4,000 m^2/d, respectively, based on K/ϕ of the 16.5 percentile, median, and 83.5 percentile, respectively, based on properties of fractured rock at depths of more than 300 m (table 1) and a water-bearing thickness of 1,000 m for both cases.

The response to a change in discharge boundary level or change in recharge rate in basin fill probably will be dominated by the coarse-grained basin fill. The time response to reach 95 percent equilibrium in basin fill based on a distance of 5 km from the discharge point to the ground-water divide or a minimal permeable boundary would be about 50, 8, and 1 yr for diffusivities based on K/ϕ of the 16.5 percentile, median, and 83.5 percentile, respectively, and a water-bearing thickness of 200 m.

The most rapid response to boundary-condition and recharge changes will take place in confined (artesian) aquifers for an aquifer of given permeability and thickness. The head response calculated above for basin fill may be more rapid where the fill is confined by fine-grained sediments.

The head response in the large carbonate-rock aquifers is calculated for both the confined and unconfined (water table) condition. For the confined condition, assume a thickness of 1,000 m, a storage coefficient of 10^{-5}, and a permeability for dense to moderately dense carbonate rocks from table 1. The time required to reach 95 percent response at a distance of 64 km to a change of recharge or discharge level would be about 300, 50, and 7 yr for *K* of the 16.5 percentile, median, and 83.5 percentile, respectively, from table 1.

For the unconfined condition in a dense to moderately dense carbonate rock, with a thickness of 1,000 m, the time of 95 percent response at a distance of 64 km to a change in discharge level or recharge would be about 150,000, 50,000, and 15,000 yr for a K/ϕ of 1×10^{-1}, 3×10^{-1}, and 1×10^{0}, respectively from table 1.

The predicted climatic variations of the model of Imbrie and Imbrie (1980) are useful in establishing the frequency of boundary changes in considering the time response of the ground-water flow systems in the Basin and Range province to large changes in boundary condition. The time response of a ground-water system to a forcing wave is not a function of the absolute change in recharge or boundary-head change, but rather of the hydraulic properties and the geometry of the system. Therefore, the absolute effect of the change in climate is not critical and the change in accretion need not be a constant function of the climate index in order to determine the relative time lag and amplitude ratio.

The response of a flow system to cyclic changes in recharge is given by the amplitude ratio, A/A_o, in equation 5. Calculation of A/A_o and L for a period of 20,000 yr indicates that for $D/a^2>10^{-6}$ *d*, A/A_o is greater than 0.94, and for $D/a^2<10^{-8}$ *d*, A/A_o is less than 0.11. This relationship, in terms of the value of T/s and a that produce a good ($A/A_o>0.9$), poor ($A/A_o<0.01$), or intermediate ($0.91\geq A/A_o\geq0.02$) response to a forcing sine wave with period of 20,000 yr, is shown in figure 12. Twenty thousand years was chosen because the two smallest frequencies of the Earth's orbital variations are about 19,000 and 23,000 yr (Imbrie and Imbrie, 1980).

The effect of differences in hydraulic properties of geometric volumes of a flow system is considered below.

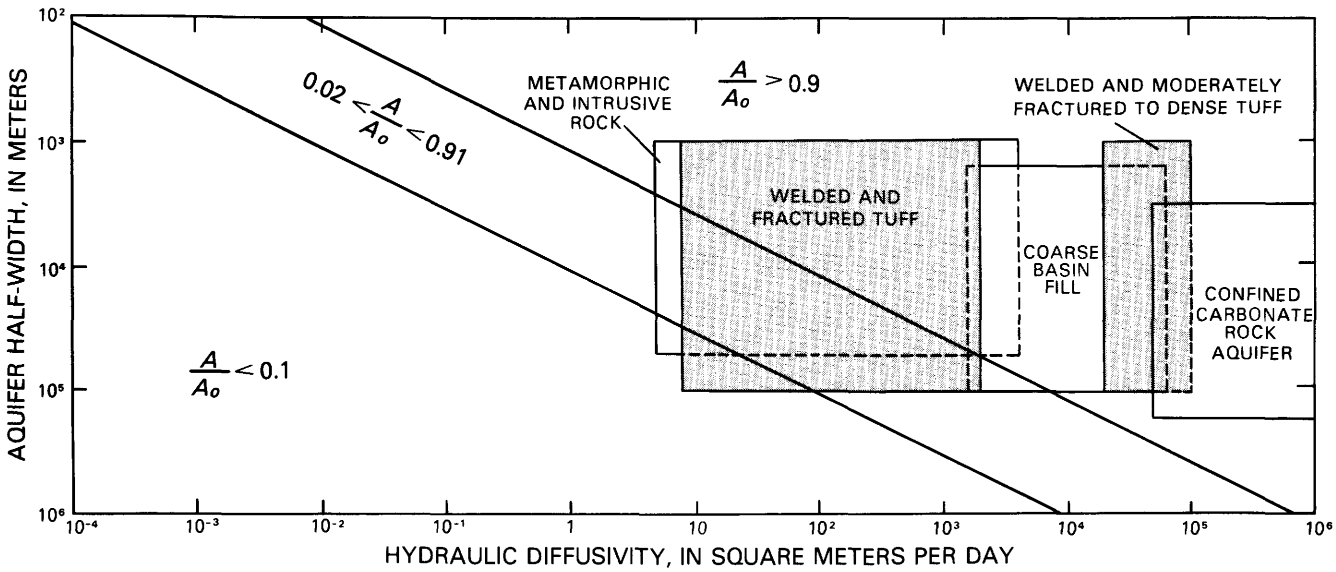


FIGURE 12.—Response of a ground-water flow system to a 20,000-year recharge cycle.

A diagrammatic framework of a flow system composed of discrete volumetric components, A, B, and C, each having uniform hydraulic properties is shown in figure 13. The dimensions A_a, B_a, and C_a refer to lateral distances from the discharge boundary to a ground-water divide or a contact with a much less permeable volume. The subscript b, that is, A_b, B_b, and C_b, refers to the vertical dimension of each volumetric component. In volumetric components A and B, it is the distance from the upper surface of saturation to the lower surface of each elemental volume; in volumetric component C, it is the distance from the upper to lower surface; Δs refers to the change in hydraulic head at the discharge boundary; and ΔW refers to the change in recharge at the surface of the flow system.

Consider a common arrangement of component volumes in which A is basin fill, B is fractured crystalline rock, and C is dense crystalline rock. Time response in basin fill, volume A, will not be significantly affected by volumes B and C where the K/ϕ of B and C are significantly less, by an order of magnitude or more, than that of volume A. The time response in volume B may be considered imposed directly by a change in recharge at the water table and a change in head at the boundary with volume A. Because volume A responds rapidly to changes in discharge level, there is a relatively short time lag of head change at this boundary.

The K/ϕ of volume C is at least an order of magnitude less than that of volumes A and B. Head response in volume C may be considered as that imposed by volumes A and B on the upper surface of C. The values of K for volume C may be assumed from table 1. However, the unit will respond as an artesian unit with an artesian storage coefficient. The specific storage, S', (m^{-1}) is calculated from the following equation:

$$S' = p\, g\, \phi \left(\frac{1}{C_w} + \frac{1}{C_s} \right)$$

where p = mass density of water, 10^3 kg/m^3;
g = gravitational acceleration, 9.8 m/s^2;
ϕ = porosity of dense crystalline rocks, in percent;
C_w = compressibility of water, 2.2×10^9 Pa; and
C_s = compressibility of dense crystalline rock, 4×10^{10} Pa.

Thus, $S'=5\times10^{-6}\phi$, and
$D=K/S'$.

The time lag of head induced in dense crystalline rock by the head change in an overlying volume is shown in the following table:

K (meter per day)	S' (meter^{-1})	D (meters squared per day)	a (meters)	D/a^2 (day^{-1})	t (years)	s_b/s_o
2×10^{-8}	2×10^{-10}	2×10^{2}	10^4	2×10^{-6}	3,500	0.95
3×10^{-7}	5×10^{-10}	6×10^{2}	10^4	6×10^{-6}	600	.95
6×10^{-6}	1.5×10^{-9}	4×10^{3}	10^4	4×10^{-5}	100	.97

CONCLUSIONS

Changes in climate regime and geomorphology affect changes in: (1) Discharge boundary level, that is, a lake, river, or marsh stage; (2) position of a discharge

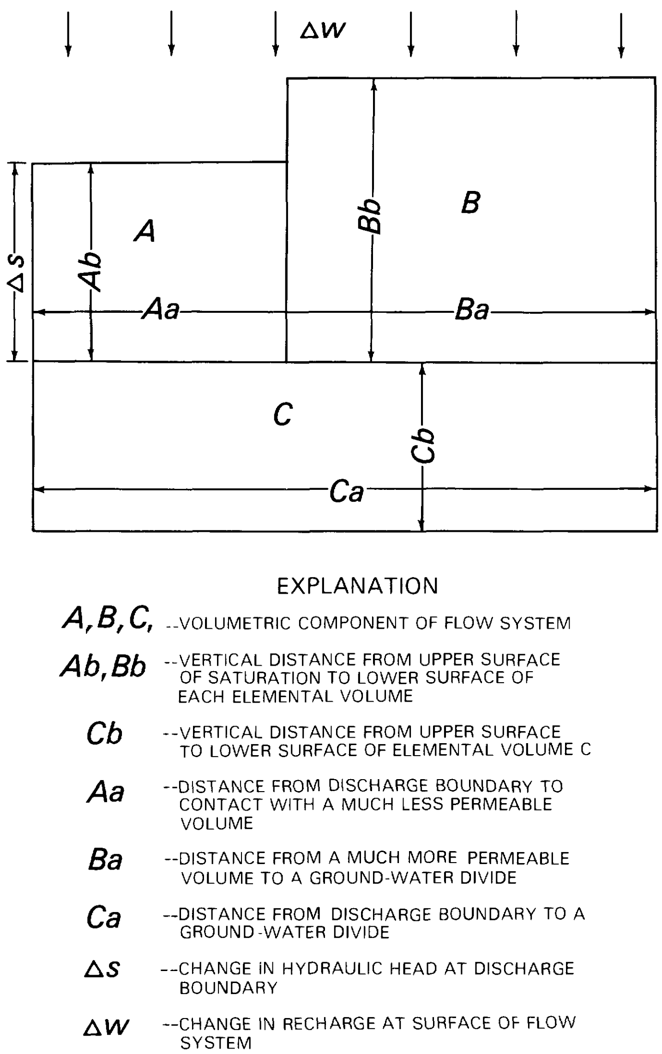


FIGURE 13.—Diagrammatic framework of a flow system composed of discrete volumetric components.

boundary; and (3) recharge rate to the ground-water flow system. The change in water level in response to both change in discharge-boundary head and accretion is the algebraic sum of the induced changes. The time lag and attenuation of change in the aquifer in response to a cyclic boundary change is a function of the hydraulic diffusivity and size of the aquifer. The time lag and attenuation of aquifer response is not a function of the magnitude of change at the boundaries.

Use of analytical models indicates that ground water in many parts of the Basin and Range province responds with small lag and amplitude decreases to boundary-condition changes having a 20,000-yr cycle. Aquifer response in basin fill will be controlled largely by the permeable coarse-grained sections. In the adjacent mountain ranges of igneous and metamorphic rock response will vary from relatively rapid to slow. For example, in crystalline rock having *T/S* less than 5×10^0 and aquifer half-widths 10,000 m or greater, significant magnitude attenuation will occur. Magnitude attenuation will not be great in crystalline rocks at depth compared to water-level changes in overlying aquifers. Extensive (aquifer half-widths of 30,000 m or greater) water-table carbonate and dense tuff aquifers may have significant lag and magnitude attenuation.

In terms of processes, events, and changes that will effect the ground-water conditions at the repository site and in the flow system, climatic change will be the potentially dominant factor in effecting changes in the repository environment during the near term, the next 50,000 yr, by producing changes in ground-water level and flow conditions. During the intermediate term, 50,000–200,000 yr, erosion or aggradation processes and vertical crustal movement, as inferred from the past 10 m.y., in addition to climate, could significantly affect hydraulic-boundary conditions and ground-water flow in the repository environment. During the long term, greater than 200,000 yr, large-scale tectonic forces could dominate processes that determine the depth of burial and other factors of hydrologic and geologic environment of the repository, provided the repository is sited beyond reasonable hazard from local catastrophic volcanic activity such as igneous intrusion or volcanic eruption.

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