Classification Of Hydrogeologic Areas and Hydrogeologic Flow Systems in the Basin and Range Physiographic Province, Southwestern United States

Professional Paper 1702

Ground-Water Resources Program

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By David W. Anning *and* A.D. Konieczki

GROUND-WATER RESOURCES PROGRAM

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Conversion Factors

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Classification of Hydrogeologic Areas and Hydrogeologic Flow Systems in the Basin and Range Physiographic Province, Southwestern United States

By David W. Anning *and* A.D. Konieczki

Abstract

The hydrogeology of the Basin and Range Physiographic Province in parts of Arizona, California, New Mexico, Utah, and most of Nevada was classified at basin and larger scales to facilitate information transfer and to provide a synthesis of results from many previous hydrologic investigations. A conceptual model for the spatial hierarchy of the hydrogeology was developed for the Basin and Range Physiographic Province and consists, in order of increasing spatial scale, of hydrogeologic components, hydrogeologic areas, hydrogeologic flow systems, and hydrogeologic regions. This hierarchy formed a framework for hydrogeologic classification.

Hydrogeologic areas consist of coincident ground-water and surface-water basins and were delineated on the basis of existing sets of basin boundaries that were used in past investigations by State and Federal government agencies. Within the study area, 344 hydrogeologic areas were identified and delineated. This set of basins not only provides a framework for the classification developed in this report, but also has value for regional and subregional purposes of inventory, study, analysis, and planning throughout the Basin and Range Physiographic Province. The fact that nearly all of the province is delineated by the hydrogeologic areas makes this set well suited to support regional-scale investigations.

Hydrogeologic areas are conceptualized as a control volume consisting of three hydrogeologic components: the soils and streams, basin fill, and consolidated rocks. The soils and streams hydrogeologic component consists of all surface-water bodies and soils extending to the bottom of the plant root zone. The basin-fill hydrogeologic component consists of unconsolidated and semiconsolidated sediment deposited in the structural basin. The consolidated-rocks hydrogeologic component consists of the crystalline and sedimentary rocks that form the mountain blocks and basement rock of the structural basin.

Hydrogeologic areas were classified into 19 groups through a cluster analysis of 8 characteristics of each area's hydrologic system. Six characteristics represented the inflows and outflows of water through the soils and streams, basin fill, and consolidated rocks, and can be used to determine the hydrogeologic area's position in a hydrogeologic flow system. Source-, link-, and sink-type hydrogeologic areas have outflow but not inflow, inflow and outflow, and inflow but not outflow, respectively, through one or more of the three hydrogeologic components. Isolated hydrogeologic areas have no inflow or outflow through any of the three hydrogeologic components. The remaining two characteristics are indexes that represent natural recharge and discharge processes and anthropogenic recharge and discharge processes occurring in the hydrogeologic area.

Of the 19 groups of hydrogeologic areas, 1 consisted of predominantly isolated-type hydrogeologic areas, 7 consisted of source-type hydrogeologic areas, 9 consisted of link-type hydrogeologic areas, and 2 consisted of sink-type hydrogeologic areas. Groups comprising the source-, link-, and sink-type hydrogeologic areas can be distinguished between each other on the basis of the hydrogeologic component(s) through which interbasin flow occurs, as well as typical values for the two indexes. Conceptual models of the hydrologic systems of a representative hydrogeologic area for each group were developed to help distinguish groups and to synthesize the variation in hydrogeologic systems in the Basin and Range Physiographic Province.

Hydrogeologic flow systems consist of either a single isolated hydrogeologic area or a series of multiple hydrogeologic areas that are hydraulically connected through interbasin flows. A total of 54 hydrogeologic flow systems were identified and classified into 9 groups. One group consisted of single isolated hydrogeologic areas. The remaining eight groups consisted of multiple hydrogeologic areas and were distinguished on the basis of (1) whether all water is removed from the system through evapotranspiration (terminally closed) or whether some water is removed as outflow into another downgradient system (terminally open), and (2) the predominant hydrogeologic component(s) that hydraulically connected the hydrogeologic areas into hydrogeologic flow systems.

The northern, middle, and southern Basin and Range Physiographic Province hydrogeologic regions were identified through a spatial analysis of the distribution of hydrogeologic flow systems. The northern Basin and Range hydrogeologic region contains mostly terminally closed, multiple-area hydrogeologic flow systems that have hydrogeologic areas that are hydraulically connected predominantly through the soils and streams and the basin fill. The middle Basin and Range hydrogeologic region contains hydrogeologic areas that, in most cases, are topographically closed. As a result, most of the hydrogeologic flow systems either are single-area hydrogeologic flow systems, which have no interbasin flows, or are terminally closed, multiple-area hydrogeologic flow systems that have hydrogeologic areas hydraulically connected by interbasin flows, mostly through the basin fill and (or) consolidated rocks. The southern Basin and Range hydrogeologic region mostly contains terminally open, multiple-area hydrogeologic flow systems that delineate the Colorado River and Rio Grande drainages. Most hydrogeologic areas in this region are hydraulically connected predominantly through soils and streams and through basin fill.

Introduction

The Basin and Range Physiographic Province is an extensive area in the Southwestern United States and northern Mexico that is distinguished by its many isolated and roughly parallel mountain ranges that are separated by desert basins (**fig. 1**; Fenneman, 1931). The province is drained by the Rio Grande and Colorado River systems, as well as by many internal river systems, such as the Humboldt, that drain into saline lakes rather than the ocean. Runoff is generally low because of the arid to semi-arid climate, and it does not always flow through an entire river system, but rather could be lost to infiltration or evapotranspiration.

Most of the province is sparsely populated with small ranching, agricultural, and mining communities; however, a small portion of the province is densely populated in the metropolitan areas of Albuquerque, New Mexico; Phoenix and Tucson, Arizona; Las Vegas and Reno, Nevada; and Salt Lake City, Utah. Large or small, the communities and cities need adequate and reliable water supplies to sustain economic activities. As a result, hundreds of basin-scale hydrologic investigations have been conducted throughout the province by the U.S. Geological Survey (USGS) and other Federal, State, local, and private agencies during the last century. Knowledge learned in these investigations is used by natural-resource managers to make informed decisions on the use, conservation, and protection of water resources. In each basin, initial investigation objectives are to establish a conceptual model for the hydrogeologic system of the basin. This conceptual model describes the occurrence and relation between (1) geologic media, geologic structures, and geomorphic features, and (2) hydrologic processes that involve the transmission and storage of surface and subsurface water. Subsequent investigations commonly involve refining the knowledge of the hydrologic system and are achieved through additional observation and monitoring of geologic features and hydrologic processes. When sufficient hydrogeologic information is known, numerical models are developed that simulate the flow processes in the basin and that can be used to assess and predict positive and negative consequences of possible future water-resources development scenarios.

Investigations have also been made at larger spatial scales to gain a regional synthesis and understanding of water-resources information for the province. As part of an appraisal for the Nation's ground-water resources, the availability and replenishment of ground-water resources were investigated by the USGS for the California region (Thomas and Phoenix, 1976), the Great Basin region (Eakin and others, 1976), the lower Colorado region (Davidson, 1979), and the Rio Grande region (West and Broadhurst, 1975). At a regional scale, hydrogeologic environments of the Basin and Range Physiographic Province were characterized to provide information for selecting areas to store high-level radioactive waste (Bedinger and others, 1989). Aquifer-systems in the Great Basin (Harrill and Prudic, 1998), in the alluvial basins of southern Arizona and adjacent States (Anderson, 1995), and in the alluvial basins of New Mexico and adjacent States (Wilkins, 1986) were studied intensively as part of the USGS's Regional Aquifer Systems Analysis program. This program was a systematic effort to study many of the Nation's most important aquifer systems in which geologic, hydrologic, and geochemical information were assembled and interpreted to develop an understanding of the systems, and to develop predictive capabilities that will contribute to the effective management of the systems.

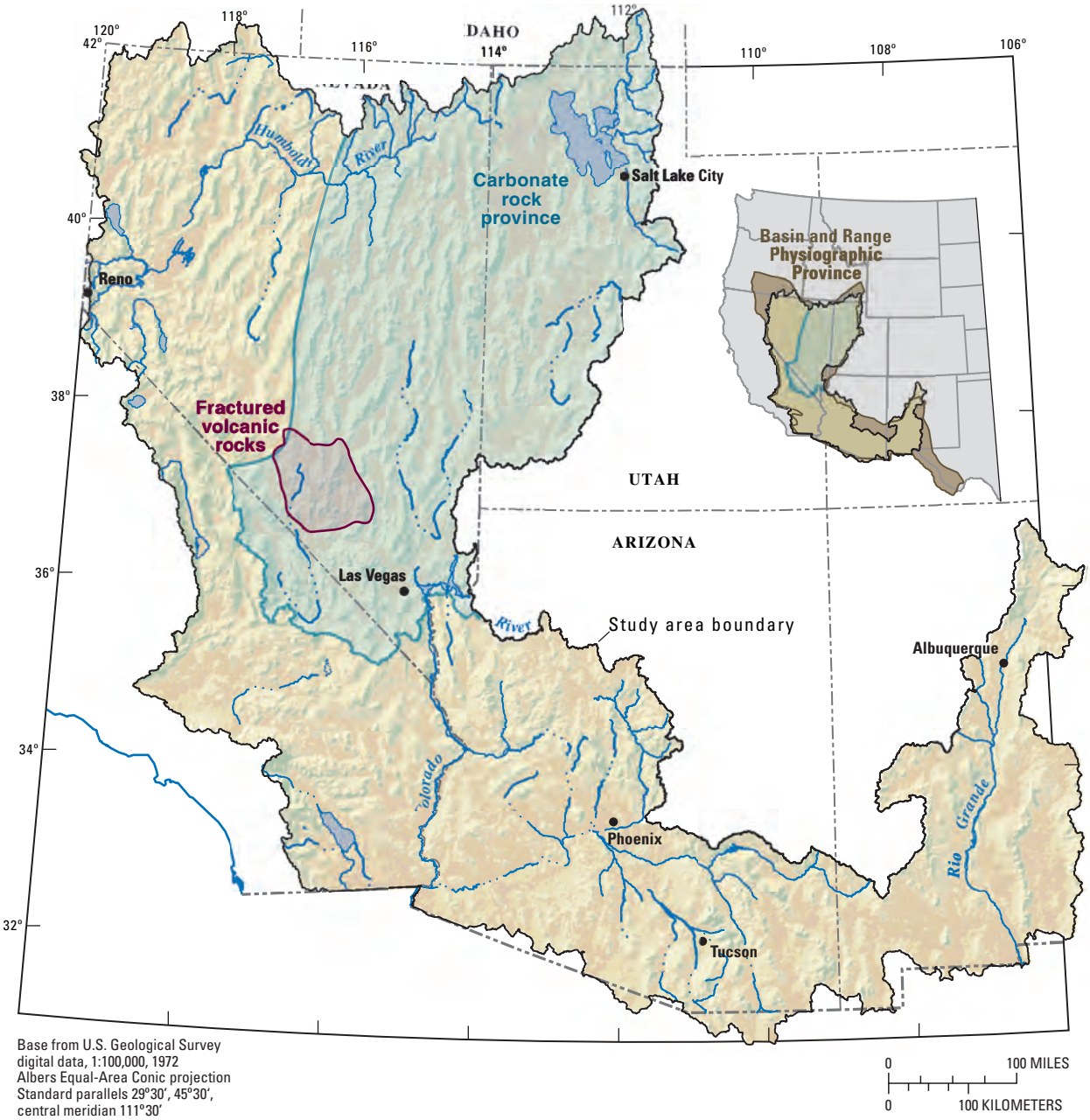

Figure 1. Study area and the carbonate rock province within the Basin and Range Physiographic Province.

There is a monetary cost associated with the information learned from each investigation; therefore, it is economically desirable to transfer information learned from one area to another area where possible. Information transfer, however, can only be done between areas having similar hydrologic conditions. Consequently, identification of these areas is an essential step in the information-transfer process.

Although some previous investigations have identified similar basins in subregions of the Basin and Range Physiographic Province through classification, such investigations have not encompassed the entire part of the province that lies within the United States, nor have any investigations classified regional-scale flow systems. Eakin and others (1976) identified similar basins in the Great Basin region by using a classification system that was originally proposed by Snyder (1962). This classification grouped basins on the basis of (1) the topographic nature of the basin's surface drainage—for example, open or closed; (2) the degree of ground-water drainage of the regional aquifer to an adjacent basin—for example, drained, partly drained, or undrained; and (3) the permanence of flow in the primary stream(s) of the basin. Eakin and others (1976) and Harrill and Prudic (1998) identified regional-scale flow systems for aquifers in the Great Basin region; however, the systems are not classified. Anderson and others (1992) grouped basins in southern Arizona and adjacent States on the basis of two factors that influence the response of an aquifer to development stresses: (1) the geohydrologic properties of the aquifer material and (2) the annual amount of downvalley ground-water flow, which was measured as the sum of stream base flow and subsurface flow. Anderson and others (1992) determined that these basins are interconnected by ground-water and surface-water flow and are aligned in a dendritic pattern that forms a regional-scale flow system. Sargent and Bedinger (1985) identified ground-water flow units, which are analogous to ground-water basins, and large regional ground-water flow systems formed by the units. The units and flow systems, however, were not classified.

Purpose and Scope

The purpose of this report is to present groups of similar basins and similar regional-scale flow systems of the Basin and Range Physiographic Province. Similar basins and similar flow systems have potential for information transfer and, therefore, subsequent investigators can use results from this study to assist their search for information transfer opportunities. In addition, results from this investigation define a stratified sampling design that could be used by future regional hydrologic investigations. Stratified sampling designs allow for gaining information economically by studying in detail only a few objects from a group of several similar objects, and then using the results to extrapolate information to the other objects in the group.

Approach

The desert basins study area used by the Southwest Ground-Water Resources Project (Leake and others, 2000) was adopted for this investigation and includes parts of Arizona, California, New Mexico, Utah, and most of Nevada (**fig. 1**). Most of the Basin and Range Physiographic Province within the United States is included in the study area, except for small parts of the province in northeastern California and western Texas.

A conceptual model for the spatial hierarchy of the hydrogeology of the Basin and Range Physiographic Province was developed and consists of, in order of increasing spatial scale, hydrogeologic components, hydrogeologic areas, hydrogeologic flow systems, and hydrogeologic regions. Hydrogeologic areas were identified within the study area on the basis of surface-drainage and ground-water flow paths. The hydrogeologic areas were classified into groups by using a cluster analysis of eight hydrologic-system characteristics that capture the area's fundamental surface- and subsurface-flow processes and the hydrogeology. Hydrogeologic areas in the same group have similar hydrologic-system characteristics and, therefore, have a potential for information transfer. Hydrogeologic flow systems were identified and classified on the basis of interbasin flows that hydraulically connect hydrogeologic areas. The areal distribution of the types of hydrogeologic flow systems was used to divide the Basin and Range Physiographic Province into three hydrogeologic regions.

Acknowledgments

Personnel from the USGS Office of Ground Water conceived the idea of a regional synthesis of data through a hydrogeologic classification system in the Basin and Range Physiographic Province that would facilitate information transfer. Jim Harrill, Thomas Winter, Frank D'Agnese, Grady O'Brien, Donald Sweetkind, and Stan Leake provided valuable comments on classification of the hydrogeologic areas. Jim Monical and Julian Heilman digitally delineated hydrogeologic-area boundaries and assisted in other geographic information system activities. John Callahan and Sid Alwin assisted in the graphical presentation of results. Numerous hydrologists and hydrologic technicians have conducted hydrologic investigations at basin and regional scales, without which this investigation could not have been completed.

Conceptual Model for the Spatial Hierarchy of the Hydrogeology of the Basin and Range Physiographic Province

Earth scientists view the Basin and Range Physiographic Province as a network or an aggregation of many basins; however, the nature of the basins varies by discipline. Geologists define basins largely on the basis of normal faults—basins are the down-dropped grabens and are separated by the uplifted horsts, which are the ranges. Surface-water hydrologists define basins on the basis of surface drainages and consider basins to be separated by drainage divides. Ground-water hydrologists define basins as having an aquifer or system of aquifers that have well-defined structural boundaries and areas of recharge and discharge. The normal faulting responsible for creating the horsts and grabens that characterize the Basin and Range Physiographic Province has resulted in many coincident geologic, surface-water, and ground-water basins.

Hydrogeologic areas are conceptualized as basins that generally have coincident ground-water and surface-water basin boundaries, and because of this coincidence, they are useful for multidiscipline hydrologic investigations. Hydrogeologic-area boundaries generally surround and contain flow paths of surface-water and ground-water from areas of replenishment to areas of discharge. Ground water and surface water generally flow away from much of their boundaries rather than across them, and in many cases smaller-scale flow paths merge into a larger-scale flow field—for ground water this is the regional aquifer, and for surface-water this is a higher-order stream. Short segments of the boundary do have inflow or outflow across them; however, in optimally delineated boundaries the length of these segments is minimized. Replenishment of water to the hydrogeologic area is either by precipitation or by inflow across the boundary, and removal of water is either by evapotranspiration or by outflow across the boundary. Although the hydrogeologic-area boundaries contain coincident ground-water and surface-water basin boundaries, surface water and ground water do not necessarily have parallel flow paths through the hydrologic system.

Hydrogeologic areas are considered control volumes that consist of three hydrogeologic components—soils and streams, basin fill, and consolidated rocks (**fig. 2**). The soils and streams component is spatially continuous and forms the top layer of the hydrogeologic area, overlying the basin-fill component in the middle of the hydrogeologic area and the consolidated-rocks component along margins of the hydrogeologic area. Hydrogeologic-area boundaries are considered to extend from the land surface vertically downward through all three hydrogeologic components. The atmosphere is not considered a part of the hydrogeologic area; however, it lies above and interacts hydrologically with the soils and streams.

The soils and streams hydrogeologic component consists of (1) all soils, unconsolidated and consolidated sediments, and crystalline or volcanic rock occurring within the root zone of plants, and (2) all surface-water bodies and features, including streams and their channels, lakes, reservoirs, and playa surfaces. Thickness of the soils and streams component varies from fractions of less than 1 foot to about 30 feet and is small compared to the thickness of the basin-fill and consolidated-rocks components.

The basin-fill hydrogeologic component consists of the materials that fill the structural basin and varies from unconsolidated to well-consolidated deposits of cobble, gravel, sand, silt, and clay. Basin fill can also contain evaporite deposits or Quaternary basalt flows. Deposits in the basin fill are hydraulically connected and store large volumes of water. The coarser-grained clastic deposits (sand and gravel) readily yield water to wells; thus, these deposits form the principal aquifer in the hydrogeologic area. The aquifer is unconfined in most areas, but can be confined locally. Basin-fill thickness increases with distance away from the mountains and may be more than 10,000 feet in the middle of some hydrogeologic areas.

The consolidated-rocks hydrogeologic component forms the mountain ranges and basement rocks of the structural basins and consists of plutonic, volcanic, metamorphic, and indurated sedimentary rocks. Throughout much of the Basin and Range Physiographic Province, the consolidated rocks do not transmit significant amounts of water and, therefore, are not considered aquifers in most places. Two notable exceptions are the limestones and dolomites in the carbonate-rock province of eastern Nevada and western Utah and the fractured volcanic rocks of southern Nevada (**fig. 1**; Harrill and Prudic, 1998). Where the consolidated rocks form aquifers, hydraulic conditions can be confined locally and at depth.

Flow occurs within and between hydrogeologic components in a hydrogeologic area (**fig. 3**). Flow within the basin fill and within the consolidated rocks is driven by gravity, whereas flow within the soils and streams component can be driven by gravity and (or) by solar energy that results in evapotranspiration. Flows from soils and streams to saturated zones in either basin fill or consolidated rocks are considered ground-water recharge processes and include infiltration from precipitation, lakes and reservoirs, and losing streams.

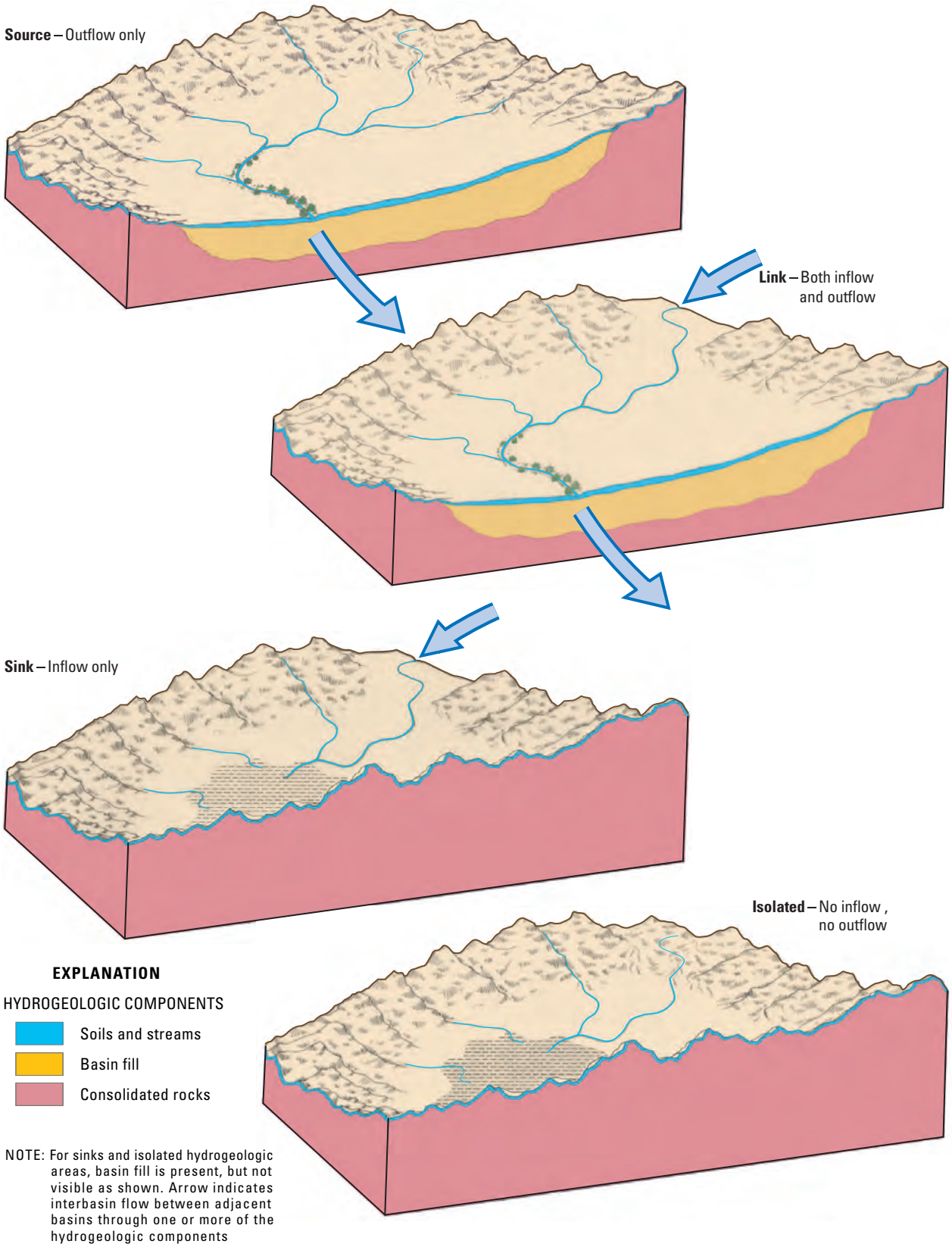

Figure 2. Diagram showing conceptual model of hydrogeologic components in a hydrogeologic area and types of hydrogeologic areas in a hydrogeologic flow system.

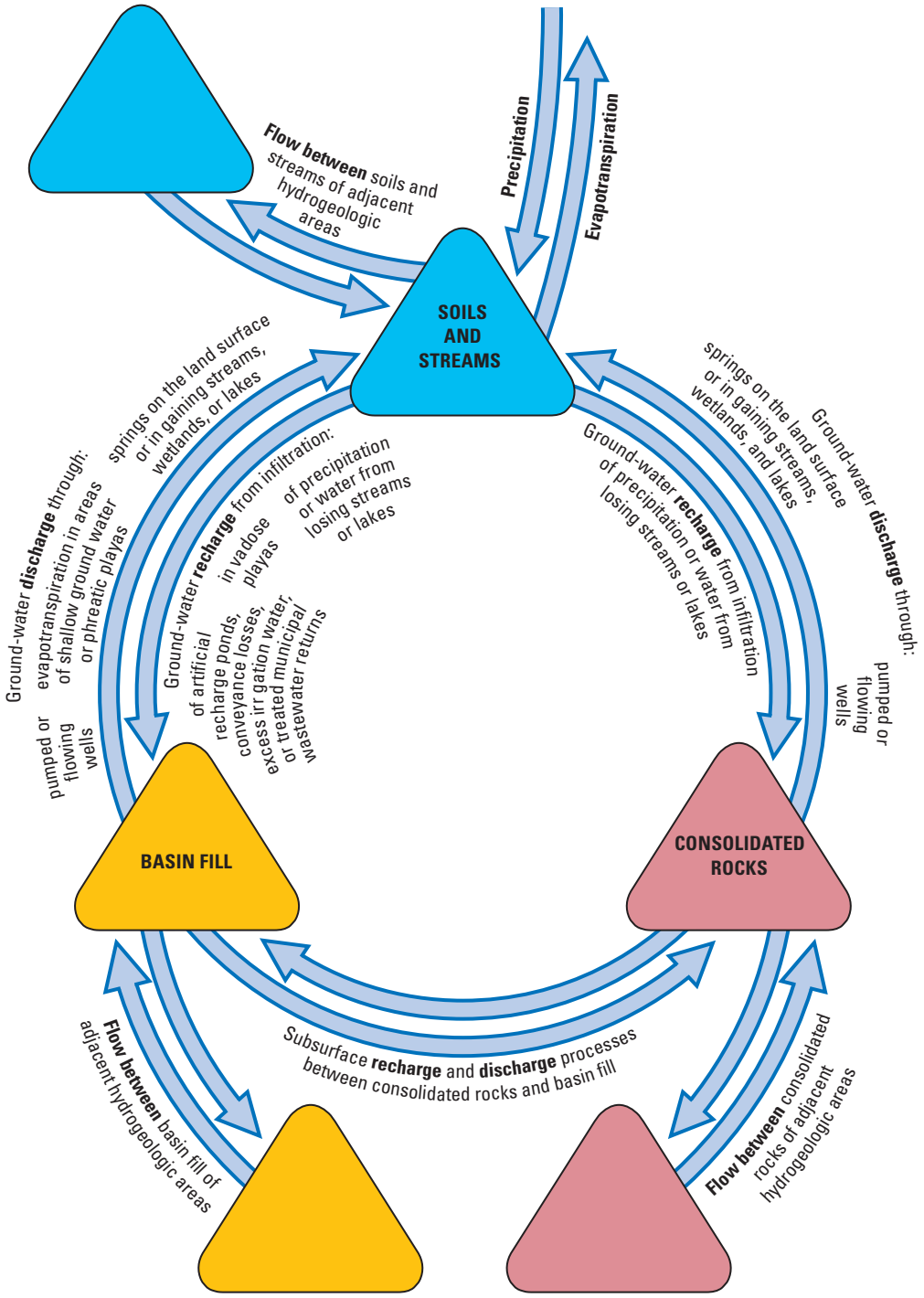

Figure 3. Conceptual model of flow processes within and between hydrogeologic areas.

In the basin fill, additional ground-water recharge processes include intermittent infiltration below vadose playas[1] and infiltration that results from human activities, such as infiltration from conveyance losses, irrigation seepage below crop roots, infiltration of agricultural or municipal wastewater, and infiltration below artificial recharge ponds. Flow from basin fill or consolidated rocks to soils and streams is considered a ground-water discharge process and includes discharge of ground water to springs, gaining stream reaches, wetlands, and lakes and reservoirs. Ground water discharged to the soils and streams in this manner may be removed from the hydrogeologic area through (1) evapotranspiration from vegetation or open water bodies, or (2) outflow to an adjacent hydrogeologic area. In addition, ground water in the basin fill can be removed from the hydrogeologic area through the soils and streams by evapotranspiration in phreatic playas. Ground water can also be discharged from the basin fill or consolidated rocks to the soils and streams by pumping or by artesian flowing wells. Within a hydrogeologic area, ground-water flow processes can also occur between the basin fill and the consolidated rocks. For example, mountain block recharge water in the consolidated rocks eventually flows into the basin fill. Conversely, ground water in the regional aquifer of the basin fill can recharge adjacent consolidated rocks, provided that the consolidated rocks are transmissive.

Flow commonly occurs between adjacent hydrogeologic areas through one or more of the hydrogeologic components (**fig. 3**) and results from flow of surface water or ground water downgradient to the end of a long flow path. These interbasin flows hydraulically connect adjacent hydrogeologic areas into a hydrogeologic flow system. Hydrogeologic flow systems are similar to hydrogeologic areas in that they contain flow paths that define ground-water and surface-water flow systems; however, for hydrogeologic flow systems, a larger portion of the boundary does not have flow. In fact, in many hydrogeologic flow systems, all flow paths are contained, and there is no flow across the boundary. Some flow paths are exceptionally long, however, and warrant delineation by multiple hydrogeologic systems rather than one exceedingly large system. In this case, hydrogeologic flow systems along the flow path are optimally divided where all inflow (or outflow) of the three hydrogeologic components must pass through a single, exceptionally narrow constriction in the boundary.

Hydrogeologic flow systems generally consist of multiple hydrogeologic areas, but can also consist of a single isolated hydrogeologic area with no interbasin flow (fig. 4). Three general types of hydrogeologic areas form multiple-area hydrogeologic flow systems, which include “sources,” which have outflow but no inflow; “links,” which have both inflow and outflow; or “sinks,” which have inflow, but no outflow (**figs. 2** and **4**). In a multiple-area hydrogeologic flow system, interbasin flow can occur through one or more of the three hydrogeologic components. Where flow paths are delineated by only one hydrogeologic flow system, the system is terminally closed and ends in a sink-type hydrogeologic area (fig. 4). In these systems, all water must be removed from the system by evapotranspiration. In contrast, where exceptionally long flow paths are delineated by several hydrogeologic flow systems, each system is terminally open and ends in a link-type hydrogeologic area (fig. 4). In these systems, some water is removed from the system by evapotranspiration along the flow path, and the remaining water flows out to the next down-gradient system. This conceptual model of hydrogeologic areas in the context of hydrogeologic flow systems forms a framework for classification of both hydrogeologic areas and hydrogeologic flow systems and will be built upon in following sections.

Delineation of Hydrogeologic Areas and Hydrogeologic Flow Systems

Three criteria were required for delineating hydrogeologic areas. First, the hydrogeologic areas must be contiguous. Second, the boundaries must maximize the coincidence of surface-water and ground-water basins where possible because the hydrogeologic areas are to be characterized and classified on the basis of hydrologic flow processes that involve surface water, ground water, and their interactions. Third, the hydrogeologic areas must be sufficiently comparable to basins used in past studies to facilitate information transfer.

In complying with the second criterion, much of the length of the hydrogeologic area boundary must represent a surface drainage divide and a physical barrier to ground-water flow, a ground-water divide, or an area of parallel ground-water flow. Many hydrogeologic areas are hydraulically connected and, therefore, part of the boundary must have surface-water and (or) ground-water flow across it; however, the length of this part of the boundary is minimized in optimally delineated boundaries.

[1]Playas are described as “phreatic” if the water table is sufficiently close to the land surface to allow evapotranspiration of shallow ground water, or are described as “vadose” if the depth to water is too deep for such ground-water discharge.

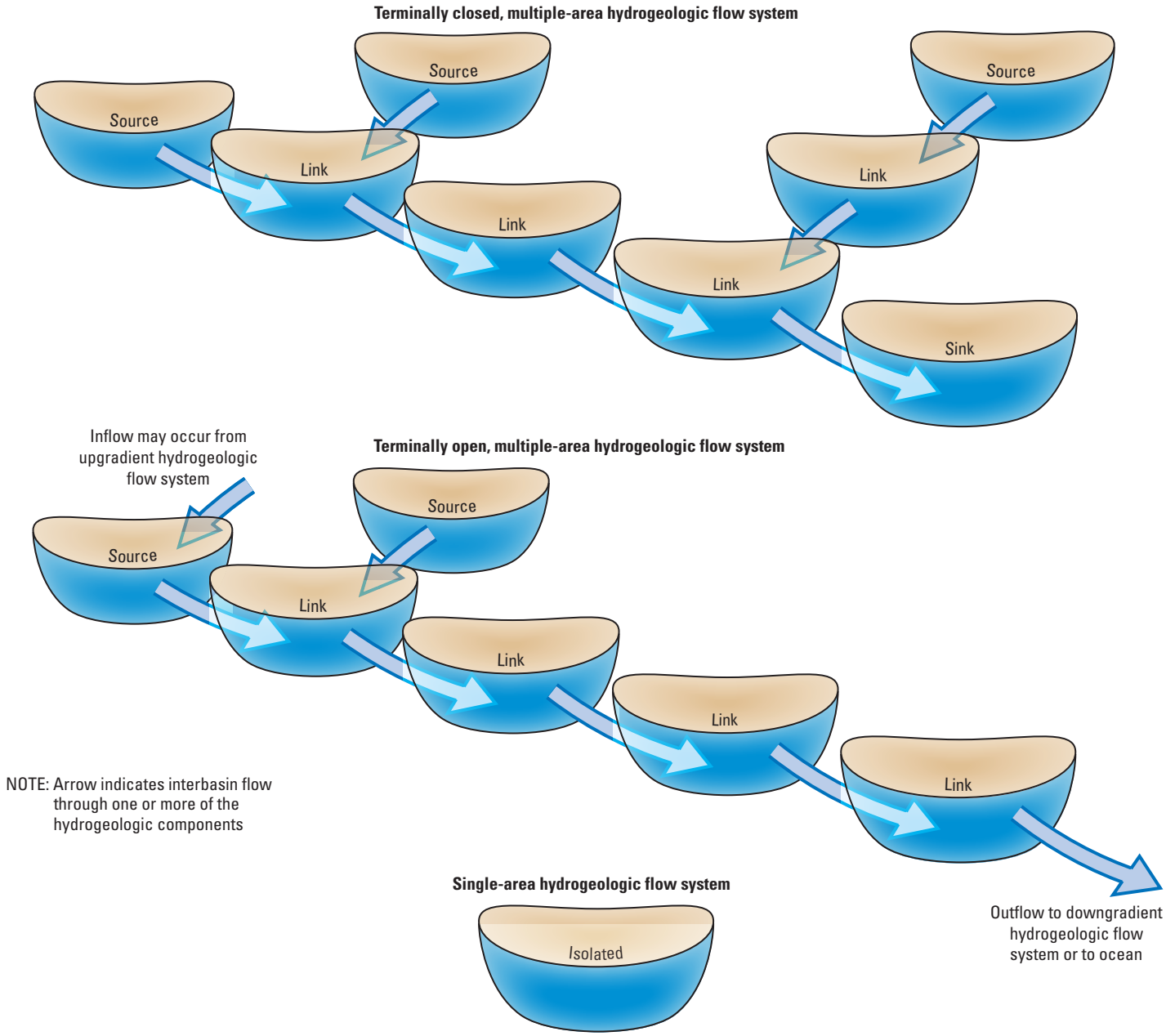

Figure 4. Conceptual models of three types of hydrogeologic flow systems.

To comply with the third criterion, boundaries of existing sets of basins commonly used by previous studies were examined for use. Hydrologic units (Seaber and others, 1987) are the only available basins that are contiguous for the entire study area and have been used in several USGS investigations. These basins, however, were unacceptable for use in this study because they are surface-water basins (Seaber and others, 1987) that, in many cases, do not correspond well to ground-water basins. The lack of correspondence occurs because the surface-drainage outlet (pour point) of the hydrologic units was typically at the confluence of two streams. This location is commonly in the middle of a ground-water basin rather than at the margin of the basin. In these instances, the surface-water and ground-water basins do not encompass the same areas.

Four sets of previously delineated ground-water basins, when combined together, cover the entire study area and include basins used by the USGS Regional Aquifer Analysis Program for Arizona, Nevada and Utah, and New Mexico (Wilkins, 1986; Anderson, 1995; Harrill and Prudic, 1998), and basins used by the California Department of Water Resources (1975). Although the boundaries for these four sets of basins do not precisely correspond to boundaries of surface-water basins, they could be adapted with minor modifications to account for surface-drainage patterns, and the basins generally have been used more frequently than hydrologic units for basin- and regional-scale investigations.

A total of 344 hydrogeologic areas were delineated by modifying the boundaries of the 4 existing sets of ground-water basins (**pl. 1**). For hydrogeologic areas in California and New Mexico, most modifications involved extending the original ground-water basin boundaries from the contact between basin fill and consolidated rocks to the surface-drainage divide in the mountain ranges. For hydrogeologic areas in Arizona, most modifications involved small changes in the original ground-water basin boundaries so that they aligned better with surface-drainage patterns. For hydrogeologic areas in Nevada and Utah, most modifications included combining basins because parts of the basin boundaries were coincident with streams. Some of the hydrogeologic areas in California and Nevada were delineated by combining small adjacent ground-water basins because the flow systems in the basins were much smaller or more localized than others nearby. Combining basins improved the consistency of the delineated hydrogeologic areas. For all hydrogeologic areas, surface-drainage patterns depicted by the National Elevation Dataset (U.S. Geological Survey, 2002a) were used as a guide in delineation. To facilitate information transfer, modification of boundaries was minimized where possible to maintain comparability to the original ground-water basins. In a few hydrogeologic areas in the southern part of the study area, part of the hydrogeologic-area boundary follows political boundaries because data are insufficient to define surface-water and ground-water basin boundaries.

The resulting set of basins not only provides a framework for the classification developed in this report, but also has value for regional and subregional purposes of inventory, study, analysis, and planning throughout the province. The fact that nearly all of the Basin and Range Physiographic Province is delineated by the hydrogeologic areas makes this set well suited to support regional-scale investigations.

A total of 54 hydrogeologic flow systems were delineated on the basis of the hydrogeologic-area boundaries and the presence and absence of interbasin flows between hydrogeologic areas (pl. 1). Determination of interbasin flow is discussed in the following section. Regional ground-water flow systems identified by Harrill and others (1988) for the Great Basin region and those identified by Sargent and Bedinger (1985) for the Basin and Range Physiographic Province were used as a guide for delineating the hydrogeologic flow systems. Several hydrogeologic flow systems were identified in the Colorado River drainage. Boundaries between these systems were delineated where all interbasin flow occurs through a narrow section of the system boundary, and preferably only through the soils and streams.

The network of interbasin flows is quite complex in certain areas, and in some cases flow crosses hydrogeologic flow-system boundaries, particularly in the Great Basin region. The magnitude of these flows, however, is generally considered to be minor compared with the flow of the whole system (Harrill and others, 1988, for those in the Great Basin region). Boundaries of the hydrogeologic flow systems shown in plate 1 are delineated on the basis of existing information about interbasin flows, which varies in degree of uncertainty, and could be refined when additional information is acquired in future hydrologic investigations.

Classification of Hydrogeologic Areas

Eight hydrologic-system characteristics were selected that represent the fundamental surface and subsurface flow processes and hydrogeology for each hydrogeologic area. Hydrogeologic areas were classified into distinct groups on the basis of these eight variables by using cluster-analysis procedures.

Selection of Hydrologic-System Characteristics

Eight characteristics were selected to represent the hydrologic systems of the hydrogeologic areas. Six characteristics represent interbasin flows between adjacent hydrogeologic areas through each of the three hydrogeologic components (**fig. 3**). These six characteristics also implicitly represent hydrogeologic conditions that affect these flows. The other two characteristics represent the natural and anthropogenic recharge and discharge processes in the

hydrogeologic area. The characteristics were determined on the basis of data that were readily available and covered the regional scale required for this investigation.

Characteristics representing inflows and outflows from the hydrogeologic area include inflow and outflow to soils and streams, inflow and outflow to basin fill, and inflow and outflow to consolidated rocks. The six interbasin-flow characteristics were determined to be either "present" or "absent." Water-resources development can change the state of these six characteristics, and because the hydrogeologic areas have undergone varying degrees of development, these characteristics were determined for predevelopment conditions where known. For example, major aqueducts, such as those of the Central Arizona Project and the California Aqueduct, now hydraulically connect several hydrogeologic areas through the soils and streams. These hydrogeologic areas, however, were characterized for predevelopment conditions by disregarding interbasin flows through the aqueducts.

The primary sources of information for inflows and outflows through the basin fill and consolidated rocks were Freethey and Anderson (1986) for hydrogeologic areas in Arizona, Harrill and others (1988) for hydrogeologic areas in Nevada and Utah, Wilkins (1986) for hydrogeologic areas in New Mexico, and California Department of Water Resources (2002) for hydrogeologic areas in California. Throughout the study area, flow through the basin fill of some hydrogeologic areas was determined on the basis of the presence of basin fill at the hydrogeologic-area boundary (U.S. Geological Survey, 2002c) and a ground-water flow gradient across that boundary. Presence of the ground-water flow gradient across the boundary was determined on the basis of regional-scale ground-water level maps (Brady and others, 1984; Langer and others, 1984; Langer, Moyle, and others, 1984; and Thomas and others, 1986).

Inflows and outflows between hydrogeologic areas within soils and streams, basin fill, and consolidated rocks are shown in **plate 1**. For a given hydrogeologic component, the number of hydrogeologic areas with outflows through the component was larger than the number of hydrogeologic areas with inflows through the component. This occurs because some hydrogeologic areas have inflow from more than one hydrogeologic area, but in nearly every case, hydrogeologic areas either have outflow only to one hydrogeologic area or do not have any outflow. There are 201 hydrogeologic areas that have outflow through soils and streams, but there are only 130 hydrogeologic areas that have inflow through this hydrogeologic component. Similarly, there are 185 hydrogeologic areas that have outflow through basin fill but there are only 119 hydrogeologic areas that have inflow through basin fill. There are 86 hydrogeologic areas that have outflow through consolidated rocks, but there are only 76 hydrogeologic areas that have inflow through consolidated rocks.

The six interbasin flows characterize a hydrogeologic area as isolated or as a source-, link-, or sink-type hydrogeologic area in a hydrogeologic flow system (**figs. 3** and **4**) and also reflect sources of the recharge and destinations of discharge to ground-water and surface-water bodies in the hydrogeologic area. Ground-water and surface-water bodies in source-type hydrogeologic areas, for example, ultimately are recharged from precipitation only. In contrast, ground-water and surface-water bodies in link- or sink-type hydrogeologic areas can also be recharged by inflow from an adjacent hydrogeologic area through one or more of the hydrogeologic components. Similarly, ground-water and surface-water bodies in sink-type hydrogeologic areas are discharged only by evapotranspiration. In contrast, ground-water and surface-water bodies in source-type and link-type hydrogeologic areas can also be discharged by outflow to an adjacent hydrogeologic area through one or more of the hydrogeologic components.

The hydrogeology of each area is implicitly reflected through the six characteristics representing interbasin flows. For example, presence of inflows or outflows in the consolidated rocks of a hydrogeologic area indicates that the consolidated rocks are, in places, permeable; whereas the absence of these flows, if there is a flow gradient, indicates that the consolidated rocks are not permeable. Presence of outflow through soils and streams but not through basin fill indicates that the basin outlet is a constriction composed of impermeable consolidated rocks. This implicit characterization also applies analogously for inflows through the basin inlet. Absence of inflow and outflow through the soils and streams indicates that the basin is topographically closed owing to geologic structure(s).

Natural recharge and discharge processes occurring in the hydrogeologic area were represented by the ground-water/surface-water interactions index. This index describes the hydraulic connection between ground water in the regional aquifer of the basin fill and surface water in the predominant surface-drainage feature of the soils and streams. This feature is commonly a stream, lake, or playa in the lowest part of the hydrogeologic area and typically has the largest contributing drainage area of such features in the hydrogeologic area. For values of the index, the regional aquifer of each hydrogeologic area was determined as being either "hydraulically connected," "indirectly and intermittently connected," or "disconnected" to the predominant surface-drainage feature.

The index for hydrogeologic areas was "hydraulically connected" if the ground-water table of the regional aquifer intercepts the land surface, as evident by the presence of perennial flow in the predominant stream or by the presence of a permanent freshwater or saline lake. These features indicate a perennial hydraulic connection through which the regional aquifer can discharge or receive recharge. The regional aquifer can discharge (1) directly through spring flow or seepage in certain reaches of the stream or parts of the lake, or (2) indirectly through evapotranspiration by phreatophytes. The regional aquifer can also receive recharge from streamflow infiltration in losing reaches of the perennial stream.

The index for hydrogeologic areas was "indirectly and intermittently connected" where the ground-water table of the regional aquifer was within the upper 30 feet of the subsurface near the predominant surface-drainage feature. For these

hydrogeologic areas, the regional aquifer typically is not in direct connection with the predominant surface-drainage feature except during and following prolonged and (or) high-discharge runoff when significant recharge occurs from streamflow infiltration. The regional aquifer can discharge indirectly, however, through evapotranspiration by phreatophytes because of the shallow depths to ground water.

The index was "disconnected" for hydrogeologic areas in which depths to the ground-water table of the regional aquifer were greater than 30 feet near the predominant surface-drainage feature. For these hydrogeologic areas, the regional aquifer is neither directly nor indirectly hydraulically connected to the predominant surface-drainage feature; and there is no discharge from the aquifer to the surface-drainage feature. There is, however, a potential for recharge to the aquifer from infiltration of ephemeral streamflow along most of the length or area of the surface-drainage feature because depths to ground water are well below the land surface.

The ground-water/surface-water interactions index was determined on the basis of land-surface data and maps that showed depth to ground water (Brady and others, 1984; Langer, Moyle, and others, 1984; Langer, Mulvihill, and Anderson, 1984; Thomas and others, 1986), areas with shallow ground water (Harrill and others, 1988), and the presence of perennially flowing streams (Freethey and Anderson, 1986; Harrill and others, 1988). In almost all the hydrogeologic areas the index reflects the potential for ground-water/surface-water interaction to occur between the basin fill and the soils and streams. In a few hydrogeologic areas where basin fill was essentially absent, however, the index reflects the potential for ground-water/surface-water interaction between the consolidated rocks and the soils and streams. Like the six variables representing inflows and outflows through the hydrogeologic components to and from adjacent hydrogeologic areas, the ground-water/surface-water interactions index was determined for predevelopment conditions. Of the 344 hydrogeologic areas, the ground-water/surface-water interactions index was "hydraulically connected" in 121 areas, "indirectly and intermittently connected" in 112 areas, and "disconnected" in 111 areas. The spatial distribution of the ground-water/surface-water interactions index is shown in **figure 5**.

In addition to reflecting the potential for ground-water recharge and discharge through the predominant surface-drainage feature, the ground-water/surface-water interactions index also reflects positive and negative consequences of ground-water pumping. In hydrogeologic areas that have had substantial quantities of ground water pumped, some or all of these consequences have already occurred; in less developed hydrogeologic areas, there remains a potential for these consequences. In hydrogeologic areas where ground water in the regional aquifer is "hydraulically connected" to surface water in the predominant surface-drainage feature, substantial lowering of the ground-water table could cause perennial streams or lakes to become intermittent, which likely represents a loss of a surface-water supply, aquatic habitat, and possibly riparian habitat, but a decrease in the depletion of ground water through evaporation and transpiration. For hydrogeologic areas where ground water in the regional aquifer is "indirectly and intermittently connected" to surface water in the predominant surface-drainage feature, substantial lowering of the ground-water table could result in loss of riparian habitat but a decrease in the depletion of ground water through transpiration. For hydrogeologic areas in which ground water in the regional aquifer is "disconnected" to surface water in the predominant surface-drainage feature, there is not a perennial surface-water supply, aquatic habitat, and (or) riparian habitat associated with the feature that can be diminished as a result of a substantial lowering of the ground-water table. For all three cases of the ground-water/surface-water interactions index, lowering of the ground-water table represents a loss in ground-water storage.

The hydraulic connectivity between ground water in the regional aquifer and surface water in the predominant surface-drainage feature provides implications about the hydrogeology that are useful in determining the hydrogeologic area's role in a hydrogeologic flow system. For example, where the regional aquifer and predominant surface-drainage feature are either directly or indirectly hydraulically connected, there is an indication that for some parts of the hydrogeologic area, more ground water is flowing downgradient than the basin fill and (or) consolidated rocks can transmit; therefore, some water must be transmitted as surface flow or removed from the area by evapotranspiration. For the case of sink-type or isolated-type hydrogeologic areas, all inflow from adjacent hydrogeologic areas and recharge from precipitation ultimately must be removed through evapotranspiration. Conversely, if there is some inflow from adjacent hydrogeologic areas or recharge from precipitation to the hydrogeologic area, and the regional aquifer is not hydraulically connected to the predominant surface-drainage feature to allow removal of ground water through surface outflow or through evapotranspiration, then there must be some subsurface outflow through either the basin fill or consolidated rocks. Implied in these deductions is that the regional aquifer is in a steady-state condition with a constant volume of storage over time.

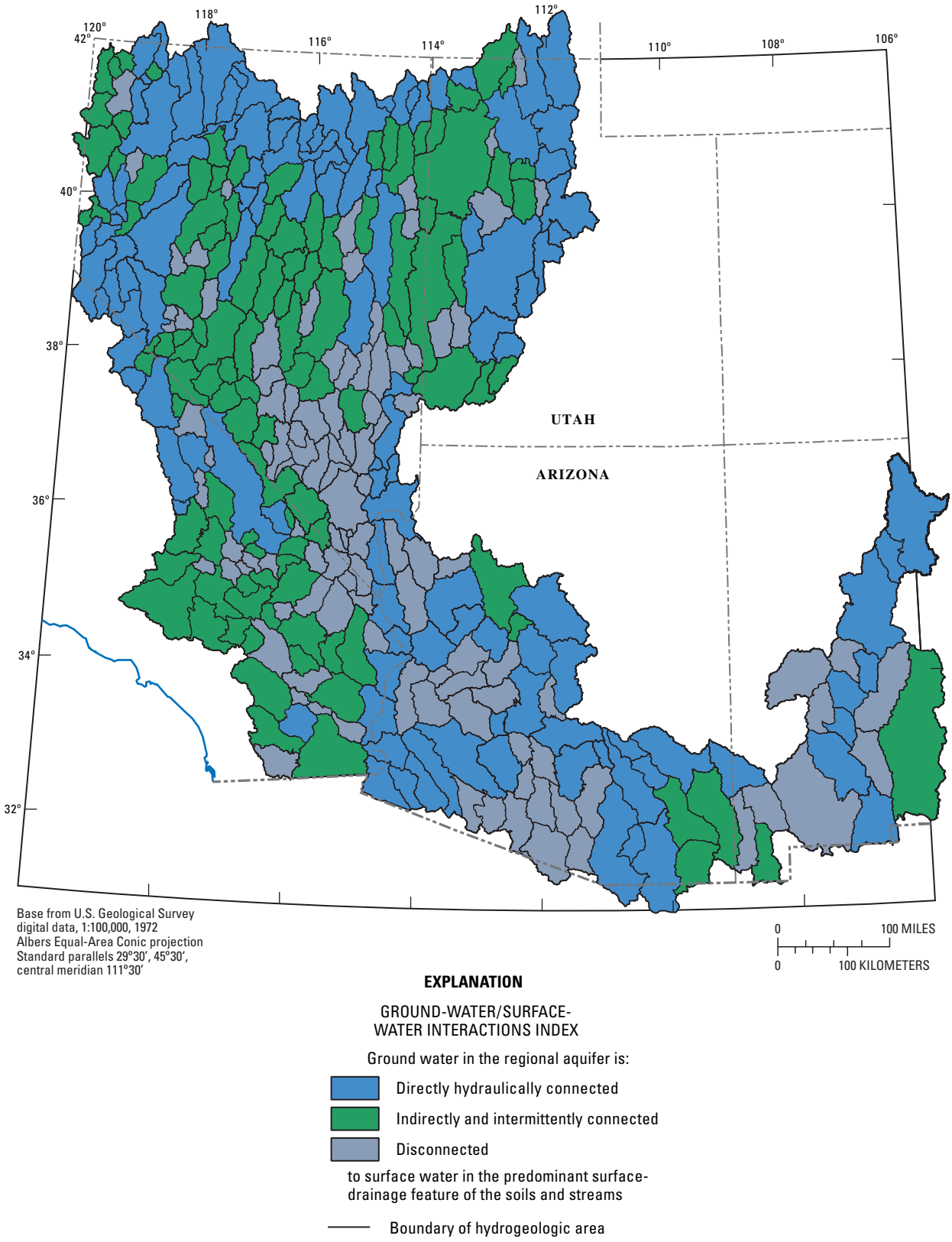

Figure 5. Distribution of the ground-water/surface-water interactions index for predevelopment conditions of hydrogeologic areas in the Basin and Range Physiographic Province.

The variety and magnitude of anthropogenic recharge and discharge processes, such as ground-water pumpage, surface-water diversions, incidental recharge, and artificial recharge, were represented with the water-resources development index. This index was estimated for each hydrogeologic area on the basis of coarse estimates of annual water use for irrigation and municipal purposes. Water used for these two purposes constitutes about 95 percent of the water use in Arizona, California, Nevada, New Mexico, and Utah (Konieczki and Heilman, 2004). The amount of water used for irrigation was estimated by multiplying the irrigated acreage in each hydrogeologic area by an average annual application rate of 3.67 feet per acre. Irrigated acreage reflects conditions in about 1990 determined from the National Land Cover data (U.S. Geological Survey, 2002b), and the application rate is an annual average rate for Arizona, California, Nevada, New Mexico, and Utah in 1995 (Konieczki and Heilman, 2004). The amount of water used for municipal purposes was calculated by multiplying the population of the hydrogeologic area by an average use rate of 197 gallons per person per year. The population for each hydrogeologic area reflects conditions in 2000 determined from U.S. Census Bureau data (2003a, 2003b). The per-capita use rate is also an annual average rate for Arizona, California, Nevada, New Mexico, and Utah in 1995 (Konieczki and Heilman, 2004). The water-resources development index is represented as a continuous variable that is computed as the log of the sum of the annual water used for irrigation and municipal purposes. Values for the degree of water-resources development range from 0.8 to 6.3, representing approximate annual water uses from 6 acre-feet per year to 2 million acre-feet per year (**fig. 6**).

For the water-resources development index, it was assumed that the amount and magnitude of anthropogenic recharge and discharge processes is correlated to the magnitude of water use in a hydrogeologic area. For hydrogeologic areas with a high water-resources development index, there is most likely a substantial amount of ground-water pumpage and, if practicable, surface-water diversions. Some conveyance losses likely occur, and this water could recharge basin-fill aquifers. A portion of the pumped or diverted water will also be returned to the hydrologic system after being used. This could occur as incidental recharge to the basin-fill aquifers from irrigation seepage or from infiltration of treated sewage effluent that is released to a stream or a recharge basin. In a few of the hydrogeologic areas with a high water-resources development index, recharge also occurs intentionally from artificial-recharge projects. For hydrogeologic areas with an intermediate water-resources development index, anthropogenic flow processes are fewer in number and smaller in magnitude than those occurring in hydrogeologic areas with a high index value. For hydrogeologic areas with a low water-resources development index, there are few anthropogenic flow processes, and the magnitude of these flows is small.

Cluster Analysis

A primary objective of this investigation is to enable a comprehensive understanding of all 344 hydrogeologic areas in the Basin and Range Physiographic Province by reducing them into groups with similar hydrologic-system characteristics. A classification scheme that rigidly assigns hydrogeologic areas into different groups with unique hydrologic-system characteristics would be unsatisfactory because the number of groups would be too large for enabling a comprehensive understanding of the hydrogeologic areas. For example, if the water-resources development index was recoded into a binary variable with values of “higher than the mean index value” or “lower than the mean index value,” there would be 384 possible groups (2x2x2x2x2x2x3x2=384) to which the hydrogeologic areas could be assigned. Given the hydrologic-system characteristics for all the hydrogeologic areas, only 92 of these 384 possible groups would be populated; however, this is too many groups to enable a comprehensive understanding of the hydrogeologic areas. The number of groups can be reduced by allowing some nonhomogeneity of the hydrologic-system characteristics within a given group. Eakin and others (1976) and Anderson and others (1992) assigned basins to a small number of groups with similar, but not unique, characteristics by using a manual classification scheme. Their manual classification schemes have the advantage of using the investigator’s hydrologic expertise and insight, but the disadvantage of not enabling repeatable results from different investigators.

For this investigation, cluster analysis was used to classify the hydrogeologic areas into a small number of groups. Cluster analysis uses statistical procedures to identify groups with similar characteristics; it has the advantage of making the study repeatable by other investigators and reduces the possibility of introducing investigator bias, human error, and lack of assignment consistency. Cluster analysis is a statistical procedure through which groups of similar objects are identified by minimizing the within-group variability of object characteristics, and maximizing the between-group variability of object characteristics. Hydrogeologic areas that fall into the same group have similar hydrologic-system characteristics and, therefore, have a potential for information transfer.

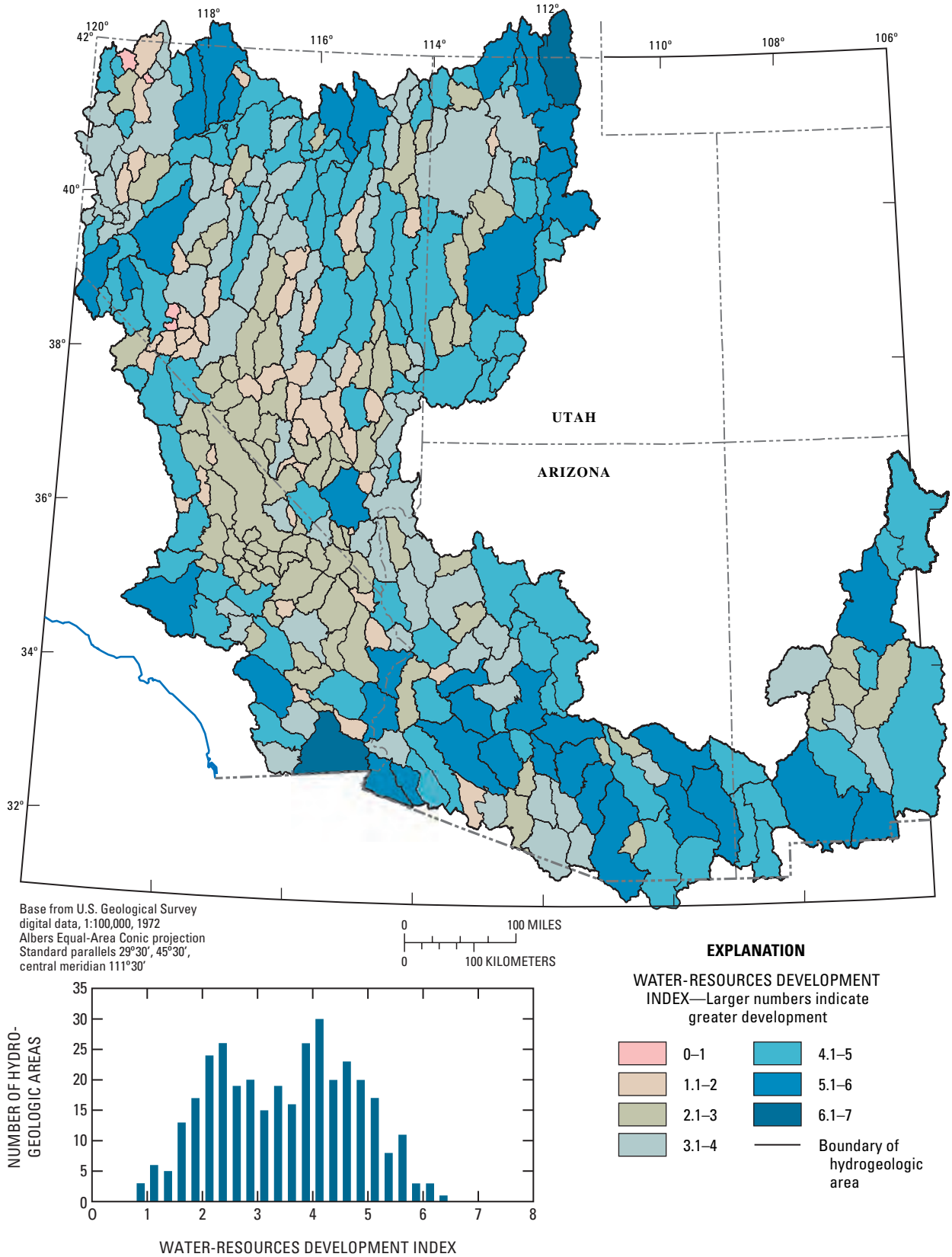

Figure 6. Distribution of the water-resources development index for hydrogeologic areas in the Basin and Range Physiographic Province.

The algorithm for partitioning around medoids was used to perform the cluster analysis (Kaufman and Rousseeuw, 1990). Medoids, a term derived from median and centroid, are representative objects for each group. In this algorithm, the user specifies that *n* objects are to be assigned into *k* groups on the basis of *p* variables. The objective of the algorithm is to assign each object to one of *k* groups such that the variation of the *p* variables for objects within a group is a minimum, and variation of the *p* variables for objects between the *k* groups is a maximum.

Variation of the *p* variables from object to object is measured by their dissimilarity. The dissimilarity between objects *i* and *j* is computed as:

$$d(i,j) = \frac{1}{p}\sum_{f=1}^{p} d_{ij}^{(f)}, \qquad (1)$$

where $d_{ij}^{(f)}$ is the dissimilarity between objects *i* and *j* for the *f*th variable. For binary variables, $d_{ij}^{(f)}$ equals zero if the values for objects are equal, or one if unequal. For ordinal variables $d_{ij}^{(f)}$ is computed as:

$$d_{ij}^{(f)} = \frac{|r_{if} - r_{jf}|}{R_f}, \qquad (2)$$

where r_{if} and r_{jf} are the ranked values of variable *f* for objects *i* and *j,* respectively, and R_f equals the number of values the ordinal variable can be assigned. For continuous variables, $d_{ij}^{(f)}$ is computed in a similar manner:

$$d_{ij}^{(f)} = \frac{|f_i - f_j|}{R_f}, \qquad (3)$$

where f_i and f_j are the values of the *f*th variable for *i* and *j*, and R_f equals the difference between the minimum and maximum value of this variable for the *n* objects in the data set.

The algorithm for partitioning around medoids assigns objects to the *k* groups as follows. An *n*-by-*n* matrix of dissimilarities is computed for all possible combinations of the objects. Next, *k* objects are selected as representative objects for the *k* groups. Each of the *n* minus *k* remaining objects are then assigned as members to the group that has the least dissimilar representative object. The average dissimilarity between each object in a given group and the representative objects for that group are determined. This process is repeated for the different possible sets of *k* representative objects and *n* minus *k* remaining objects. The best clustering of the *n* objects into the *k* groups is that which has the smallest average dissimilarity between each object and the representative object of its group. The representative object for each group is called the medoid for the group, hence the name for the algorithm, partitioning around medoids.

For clustering with the partitioning-around-medoids algorithm, *k* is determined by the user. Silhouette plots are a graphical and numerical means of determining an appropriate value for *k*. The graph consists of the statistic *s(i)* plotted for each of the *n* objects. The value for *s(i)* is determined as follows. First, *a(i)* is determined as the average dissimilarity of object *i* to other objects within group *A*, the group to which object *i* is assigned. Then, for the remaining *k* minus *1* groups to which object *i* is not assigned, the average dissimilarity of object *i* to the objects within each group is determined. Of the *k* minus *1* groups, *B* is the group with the smallest average dissimilarity to object *i*, and the average dissimilarity for group *B* is *b(i)*. Under this definition, group *B* is the next best group for object *i* to belong to because object *i* is least dissimilar to the objects in that group. The statistic *s(i)* is computed as:

$$s(i) = \frac{b(i) - a(i)}{maximum\{a(i), b(i)\}}. \qquad (4)$$

Values for *s(i)* can range from -1 to +1. When *s(i)* is nearly +1, object *i* is well classified because the average dissimilarity of object *i* to other objects in its group, *A*, is much smaller than the average dissimilarity of object *i* to objects in the next best group, *B*. When *s(i)* is nearly zero, object *i* fits about equally well in groups *A* and *B*, so it is not clear to which group object *i* should belong. When *s(i)* is negative, which is uncommon, object *i* is more similar to objects in group *B* than to objects in group *A* and, therefore, appears misclassified.

The average silhouette width, calculated as the mean value of *s(i)* for all *n* objects in the data set, can be used to determine the optimal value for *k*. The value for *k* having the largest average silhouette width typically is chosen as the optimal value for *k*. Kaufman and Rousseeuw (1990) provide some subjective guidance on interpreting average silhouette values. Values from 0.71 to 1.0 indicate that a strong structure underlies the data, values from 0.51 to 0.70 indicate that a reasonable structure underlies the data, values from 0.26 to 0.50 indicate that the structure of the data is weak or artificial, and values less than 0.25 indicate that there is no substantial structure to the data.

The 344 hydrogeologic areas in the Basin and Range Physiographic Province were classified into 19 groups on the basis of results from the cluster analysis (**pl. 2**). The analysis was repeated using different values of *k*, in increments of 1 for *k* between 2 and 40, and in increments of 5 for *k* between 40 and 150. The optimal partitioning of the hydrogeologic areas into *k* groups occurs at *k*=75, as indicated by the

maximum value for the average silhouette width (fig. 7). The average silhouette width decreases for *k* less than 75 as a result of having more variation of hydrologic-system characteristics within a given group. The average silhouette width decreases for *k* greater than 75 as a result of significant overlap in the hydrologic-system characteristics between groups; therefore, some hydrogeologic areas are not well classified because they are very similar to hydrogeologic areas in other groups. The average silhouette width at *k*=75 is 0.64, indicating that there is a reasonable structure to the distribution of the hydrogeologic areas. The large value for the optimal value of *k* indicates that even when coarsely describing the hydrologic system with the eight characteristics chosen in this analysis, each hydrogeologic area is unique. If more variables were chosen that characterized the hydrogeologic systems at a higher resolution than the eight characteristics used in this analysis, the distinctions between the hydrogeologic areas would be greater.

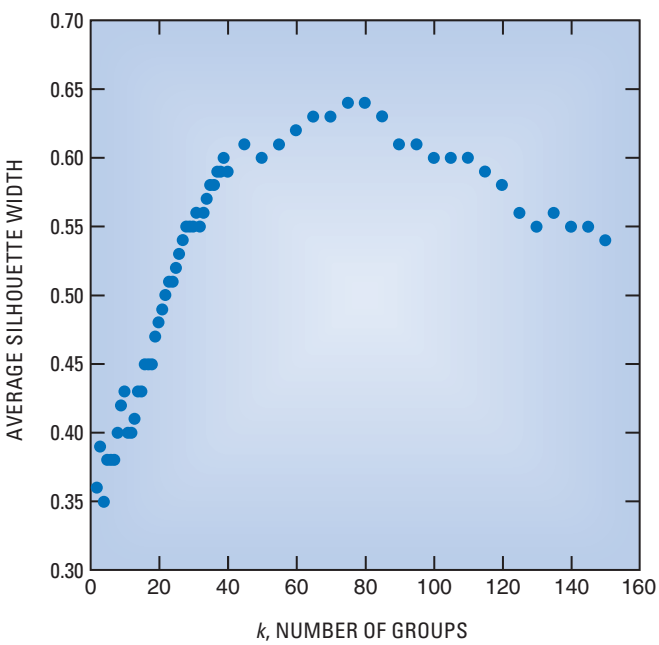

Figure 7. Average silhouette width for different values of *k*, the number of groups of hydrogeologic areas chosen for the analysis.

Although the optimal value of *k* for identifying distinct groups of hydrogeologic areas is 75, this is too many groups to enable a comprehensive understanding of the 344 hydrogeologic areas. As a result, *k* was selected on the basis of the persistence of hydrogeologic areas to remain in the same group when *k* is incremented by one group. For small values of *k*, many hydrogeologic areas change groups as a result of incrementing *k* by one group; however, the number of hydrogeologic areas changing groups decreases substantially as *k* increases (fig. 8). For *k* equal to or greater than 19, less than 10 hydrogeologic areas change groups as a result of incrementing *k* by one group. For this reason, and because the average silhouette distance of 0.47 for *k* =19 (fig. 7) indicated acceptable partitioning, the cluster analysis results for *k*=19 were selected as the best grouping of the hydrogeologic areas.

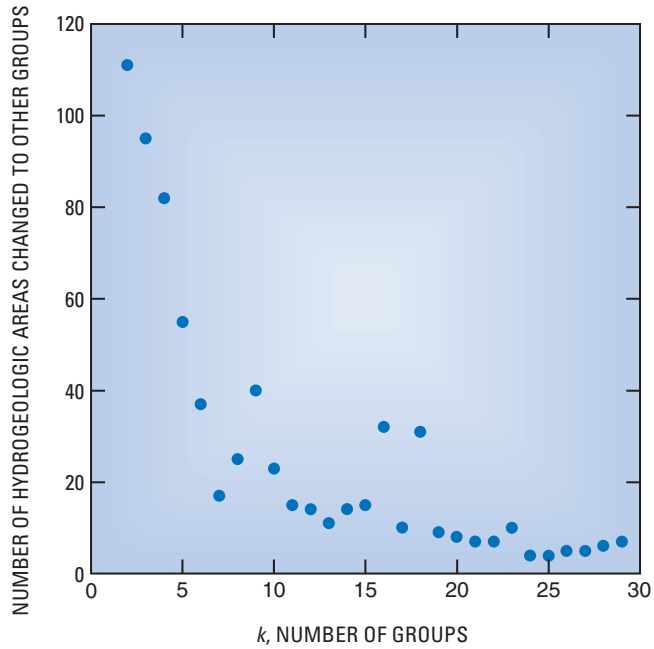

Figure 8. Number of hydrogeologic areas that change to another group of hydrogeologic areas as a result of increasing *k*, the number of groups of hydrogeologic areas chosen for the analysis, by one group.

Groups of Similar Hydrogeologic Areas

The presence or absence of interbasin flows was generally uniform among hydrogeologic areas in a given group (table 1), and as a result, groups can be identified as consisting predominantly of source-, link-, or sink-type hydrogeologic areas (**pl. 2**). Of the 19 groups, there is 1 group of predominantly isolated hydrogeologic areas, 7 groups of predominantly source-type hydrogeologic areas, 9 groups of predominantly link-type hydrogeologic areas, and 2 groups of predominantly sink-type hydrogeologic areas. The seven groups of predominantly source-type hydrogeologic areas are differentiated primarily by which hydrogeologic component(s) have outflow and secondarily by the ground-water/surface-water interactions index and also the water-resources development index. The nine groups of predominantly link-type hydrogeologic areas and two groups of predominantly sink-type hydrogeologic areas are differentiated similarly.

Values for the ground-water/surface-water interactions and the water-resources development indexes for hydrogeologic areas in a given group generally were less uniform than values for the six interbasin flows (**table 1**). For 15 groups, a majority (75 percent or more, as highlighted in table 1) of the hydrogeologic areas had the same value for the ground-water/surface-water interactions index. Of these 15 groups, 6 were "hydraulically connected," 5 were "indirectly and intermittently connected," and 4 were "disconnected." For 4 groups, a majority of the hydrogeologic areas had a water-resources development index larger than the median value of the index (3.5) for all 344 hydrogeologic areas. Similarly, for four groups, a majority of the hydrogeologic areas had a water-resources development index smaller than the average value of the index.

The medoid for each group of hydrogeologic areas is representative of each group on the basis of the eight hydrologic-system characteristics (**table 2** in the appendix). Comparison of coarse-scale conceptual models for the hydrologic system of the medoid for each group facilitates a general comprehension of the group and allows for quick comparison of similarities and differences of hydrologic-system characteristics between groups (**fig. 9**). For example, of the seven groups of source-type hydrogeologic areas, only groups SR1, SR2, SR3, and SR4 have outflow through one hydrogeologic component. Two of these groups, SR2 and SR3, have outflow only through the basin fill. They differ, however, in that the playa in group SR2 is indirectly hydraulically connected to the regional aquifer and, therefore, may discharge ground water through evapotranspiration, whereas the playa in group SR3 is not hydraulically connected to the regional aquifer and, therefore, cannot discharge ground water. Similar comparisons of hydrologic systems can be made between other groups of hydrogeologic areas.

Hydrologic-system characteristics of hydrogeologic areas generally are uniform within each of the 19 groups, which indicates good partitioning and that each characteristic was useful in distinguishing the hydrogeologic areas between groups (tables 1 and 2). The presence or absence of inflow and outflow through soils and streams, basin fill, and consolidated rocks is uniform in nearly all groups. In most groups, however, there are a few hydrogeologic areas that deviate from the majority of areas by having or by lacking an inflow or an outflow through one of the hydrogeologic components. For example, in group I (isolated) two hydrogeologic areas have inflows through consolidated rocks. Consequently, not all hydrogeologic areas in a given group conform rigidly to the generalized descriptions provided on **plate 2**. This nonhomogeneity is the penalty for using a cluster analysis with a selected *k* value less than the optimal 75 groups, or for not using a classification scheme that rigidly assigns hydrogeologic areas into groups having unique hydrologic-system characteristics. The ground-water/surface-water interactions index and the water-resources development index are generally more variable in a given group than the interbasin flow characteristics and are, therefore, somewhat less useful for distinguishing the different groups of hydrogeologic areas.

The classification of groups of hydrogeologic areas in this investigation is dependent on the characteristics selected for use in the analysis and on the accuracy and precision of the data used. If other or additional characteristics had been selected, the appropriate value for *k* likely would be different, as would the assemblage of hydrogeologic areas in each group. Data for hydrologic-system characteristics used in this investigation were assigned to each hydrogeologic area on the basis of current knowledge contained in the cited references. Future investigations will refine what is known about the hydrologic system for these hydrogeologic areas, and the characteristics can be updated with more accurate data. The characteristics for the six interbasin flows were coded as a binary variable. A more accurate clustering would result from using the magnitude of these flows rather that the simple presence or absence of these flows. Data on the magnitude of these flows, however, were not available for many of the hydrogeologic areas.

Classification of Hydrogeologic Flow Systems

Hydrogeologic flow systems in the Basin and Range Physiographic Province were manually classified. First, hydrogeologic flow systems were classified as being either a single-area hydrogeologic flow system or a multiple-area hydrogeologic flow system. Single-area hydrogeologic flow systems are isolated hydrogeologic areas (having no interbasin flows; pl. 2). Multiple-area hydrogeologic flow systems were subsequently classified as being either a terminally open system, which has outflow, or a terminally closed system, which lacks outflow. These two types of multiple-area flow systems were further classified on the basis of the predominant hydrogeologic component(s) through which interbasin flows connect hydrogeologic areas into a hydrogeologic flow system. Predominant hydrogeologic components have a two-thirds majority of all interbasin flows within the hydrogeologic system, which results in seven possible categories for each type of multiple-area flow system. Given the 1 type of single-area hydrogeologic flow system, 7 types of the terminally open, multiple-area hydrogeologic flow systems, and 7 types of the terminally closed, multiple-area hydrogeologic flow systems, there are 15 possible categories for the hydrogeologic flow systems. In the study area, however, only nine

hydrogeologic flow systems occur (pl. 2). Six hydrogeologic areas have interbasin flow out of the study area and were not part of the hydrogeologic flow system classification because they represent part of a system that is largely outside the study area (pl. 2).

Of the 54 hydrogeologic flow systems, 20 are single-area systems. This is the simplest and most common type of system and consists of single isolated-type hydrogeologic areas (group I in pl. 2) that have no interbasin flows. All precipitation recharging the surface- or ground-water bodies must be evaporated along the flow path or in the most downgradient playa to be removed from the hydrogeologic area. Examples of these hydrogeologic systems include Gabbs Valley, Mono Valley, Penoyer Valley, and the Willcox Basin (**pl. 2**).

Eight of the hydrogeologic flow systems are terminally open, multiple-area hydrogeologic flow systems that occur in the Colorado River and Rio Grande drainages (pl. 2). Although some water is removed from these hydrogeologic flow systems by evapotranspiration, the remaining water flows out into a downgradient series of hydrogeologic flow systems and ultimately may flow to the ocean. Source-type and link-type hydrogeologic areas form these systems (groups SR1–SR7 and L1–L9 in pl. 2), and by definition, there are no sink-type hydrogeologic areas. The Upper Gila River, Middle Gila River, Lower Gila River, Lower Colorado River, and Rio Grande hydrogeologic flow systems have hydrogeologic areas connected predominantly by interbasin flows through the soils and streams and through the basin fill (pls. 1 and 2). In contrast, hydrogeologic areas are predominantly connected by interbasin flows through only the soils and streams in the Bill Williams River hydrogeologic flow system and through both consolidated rocks and through soils and streams in the Nevada Colorado River and Verde River hydrogeologic flow systems.

The remaining 26 hydrogeologic flow systems are terminally closed, multiple-area hydrogeologic flow systems in California, Nevada, and Utah (pl. 2). Water in these systems is replenished only by precipitation and removed only by evapotranspiration. Source-type, link-type, and sink-type hydrogeologic areas form these systems (groups SR1–SR7, L1–L9, and SK1–SK3 on pl. 2). Eleven of the terminally closed, multiple-area hydrogeologic flow systems, including the Humboldt River system, have hydrogeologic areas connected predominantly by interbasin flows through the soils and streams and through the basin fill (pls. 1 and 2). Three systems, including the Bristol Valley system, have hydrogeologic areas connected predominantly by interbasin flows through the basin fill. Four systems, including the South-Central Marshes system, have hydrogeologic areas connected predominantly by interbasin flows through the basin fill and the consolidated rocks. Two systems, including the Railroad Valley system, have hydrogeologic areas connected predominantly by interbasin flows through the consolidated rocks. Six systems, including the Death Valley system, have hydrogeologic areas connected by a mix of interbasin flows through the soils and streams, basin fill, and consolidated rocks.

Hydrogeologic Regions

Three distinct hydrogeologic regions of the Basin and Range Physiographic Province were identified in an analysis of the spatial distribution of hydrogeologic flow systems—the northern Basin and Range hydrogeologic region, the middle Basin and Range hydrogeologic region, and the southern Basin and Range hydrogeologic region. **The northern Basin and Range hydrogeologic region** is composed predominantly of terminally closed, multiple-area hydrogeologic flow systems that have areas hydraulically connected mostly through the soils and streams and the basin fill (pl. 2). Although this hydrogeologic region is spatially divided by the Great Salt Lake Desert hydrogeologic flow system, it should be recognized that the northern part of this flow system also has interbasin flows that occur mostly through both soil and streams and through the basin fill (**pl. 1**).

The middle Basin and Range hydrogeologic region contains hydrogeologic areas that in most cases are topographically closed. As a result, most of the hydrogeologic flow systems either are single-area flow systems, which have no interbasin flows, or are terminally closed, multiple-area flow systems that have areas hydraulically connected by interbasin flows, mostly through the basin fill and through the consolidated rocks (pl. 2). In fact, most of the single-area hydrogeologic flow systems are in this region. The terminally closed nature of the hydrogeologic flow systems make this region similar to the northern Basin and Range hydrogeologic region and different from the southern Basin and Range hydrogeologic region. The general lack of interbasin flows through soils and streams and the presence of interbasin flows through the consolidated rocks distinguishes the middle Basin and Range hydrogeologic region from the other two regions.

The southern Basin and Range hydrogeologic region mostly contains terminally open, multiple-area hydrogeologic flow systems that delineate the Colorado River and Rio Grande drainages. This region is similar to the northern Basin and Range hydrogeologic region in that the hydrogeologic areas are hydraulically connected predominantly through soils and streams and through the basin fill; however, it is different in that the hydrogeologic flow systems are terminally open in this region, whereas they are terminally closed in the northern region (pl. 2).

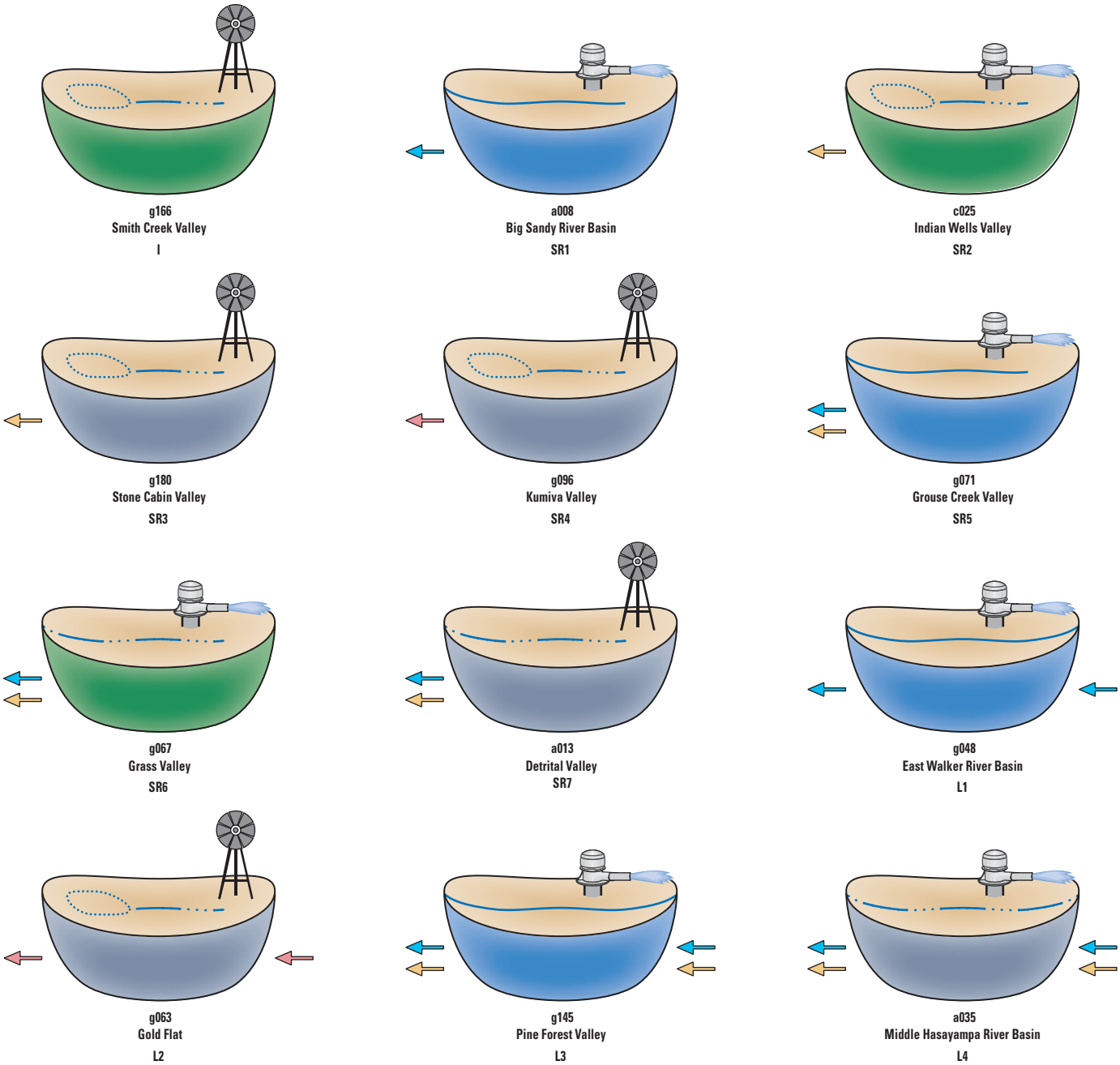

Figure 9. Conceptual model of hydrologic systems for the medoid of each group of hydrogeologic areas in the Basin and Range Physiographic Province.

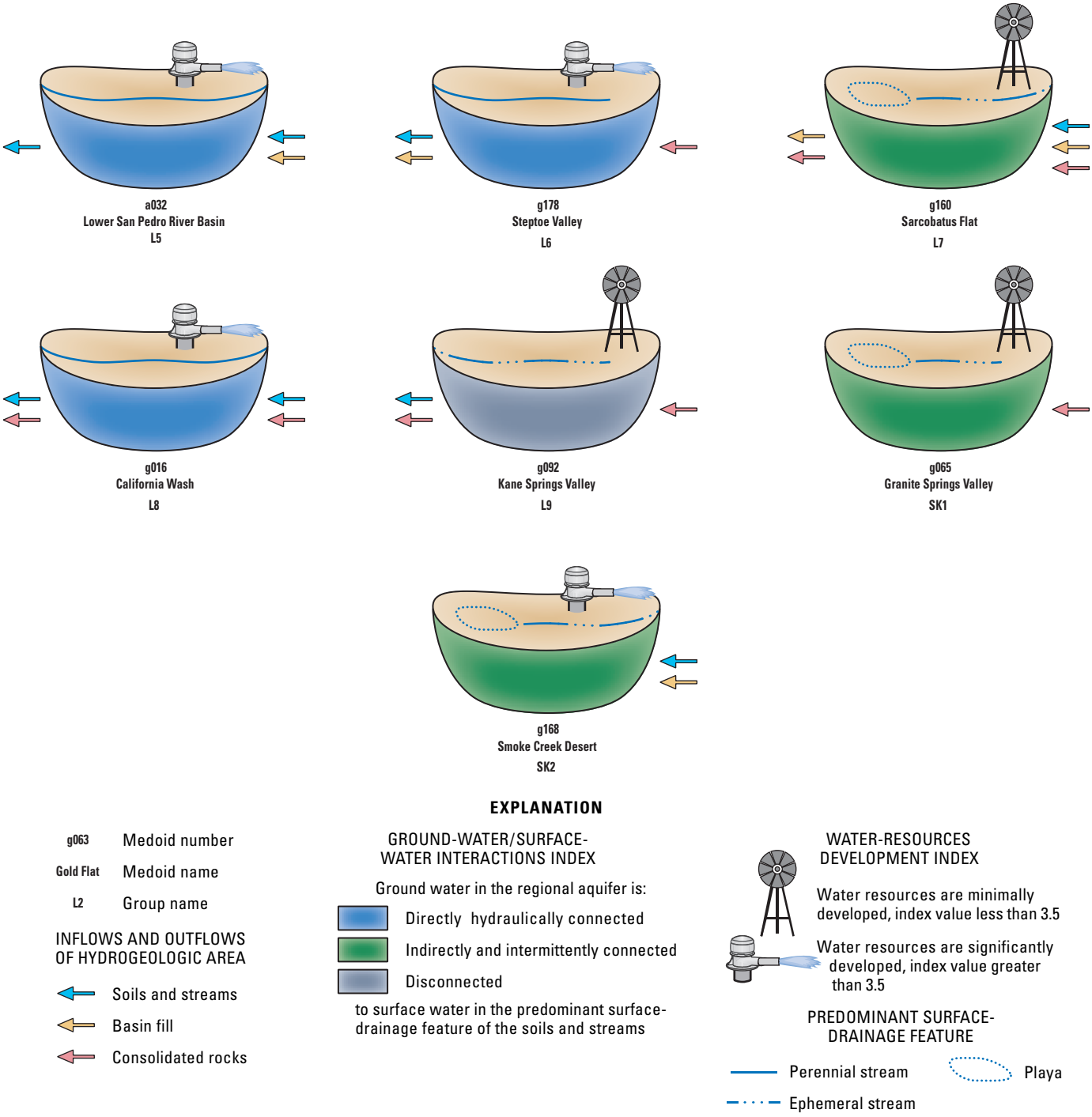

Figure 9. Continued.

Summary and Conclusions

The need for regional synthesis and the necessity to economically research hydrologic systems motivated a hydrogeologic classification of the Basin and Range Physiographic Province. A conceptual model was developed for the spatial hierarchy of the hydrogeology of the Basin and Range Physiographic Province and formed the basis for hydrogeologic classification at different spatial scales. The hierarchy, from smallest to largest scale, consists of hydrogeologic components, hydrogeologic areas, hydrogeologic flow systems, and hydrogeologic regions (fig. 10).

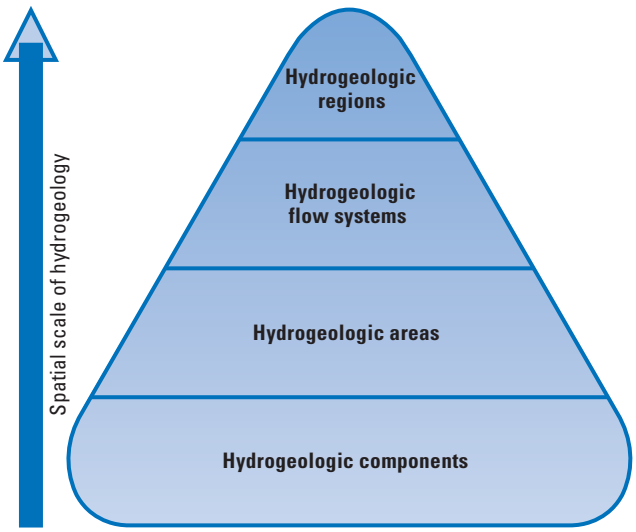

Figure 10. Spatial hierarchy and relation between the hydrogeologic components, areas, flow systems, and regions. Hydrogeologic areas are composed of hydrogeologic components; hydrogeologic flow systems are composed of single or multiple hydrogeologic areas; and hydrogeologic regions are composed of hydrogeologic flow systems.

Hydrogeologic areas are basins that coincidently bound both surface-water and ground-water systems and are conceived as a control volume containing three hydrogeologic components: the soils and steams, the basin fill, and the consolidated rocks. A total of 344 hydrogeologic areas were identified and classified into 19 groups on the basis of a cluster analysis of 8 characteristics of each area's hydrologic system. These characteristics include six interbasin flows through the three hydrogeologic components, the ground-water/surface-water interactions index, and the water-resources development index. Each group is distinguishable primarily on the basis of the six interbasin flows, and secondarily on the basis of the two indexes.

A total of 54 hydrogeologic flow systems were identified on the basis of interbasin flows through 1 or more of the 3 hydrogeologic components that hydraulically connect adjacent hydrogeologic areas. The hydrogeologic flow systems were manually classified into nine groups. One group consisted of single-area hydrogeologic flow systems, and the remaining groups consisted of multiple-area hydrogeologic flow systems that were classified on the basis of whether they are terminally open or terminally closed, and on the basis of which hydrogeologic component(s) predominantly hydraulically connect(s) the hydrogeologic areas of the system. The northern, middle, and southern Basin and Range hydrogeologic regions consist of spatially proximate and similar hydrogeologic flow systems.

Results from this investigation provide a succinct summary and synthesis of the hydrogeology of the Basin and Range Physiographic Province at regional and subregional scales, and have value for future inventory, analysis, and planning studies. The hydrogeologic areas, hydrogeologic flow systems, and hydrogeologic regions delineated in this study will be of value for future multidisciplinary hydrogeologic investigations because their boundaries generally delineate coincident surface-water and ground-water systems and because most of the Basin and Range Physiographic province was delineated. Results from the hydrogeologic classification will expedite searches for similar hydrogeologic areas or similar hydrogeologic flow systems by future investigations and, therefore, facilitate information transfer. The spatial hierarchy and the classification of the hydrogeology developed in this investigation provide a framework that can be used to present results of future basin-scale investigations in a regional context. The spatial hierarchy of the hydrogeology also can be used to build a stratified sampling design, which economizes research. For example one hydrogeologic area from each of the 19 groups could be investigated, or if interests are more specific, several hydrogeologic areas in a single group could be investigated. Similarly, one hydrogeologic flow system from each of the nine groups could be investigated, or several hydrogeologic flow systems in a single group could be investigated. For larger-scale studies, one (or more) of the three hydrogeologic regions could be investigated.

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Appendix

Table 1. Summary of hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province, by groups of hydrogeologic areas

[C, I, and D, the regional aquifer is hydraulically connected, indirectly and intermittently connected, or disconnected, respectively, to surface water in the predominant drainage feature of the hydrogeologic area; %, percent. For interbasin flows and the ground-water/surface-water interactions index, data represent the number of hydrogeologic areas within the group for each category; highlighted values indicate that the majority of the hydrogeologic areas in the group fall in the same category. The 25th, 50th, and 75th percentiles of the water-resources development index are tabulated for hydrogeologic areas in each group; all three percentiles are highlighted where 75 percent of the hydrogeologic areas in that group were either (A) less than the median for all hydrogeologic areas (3.5), or (B) greater than the median for all hydrogeologic areas]

	Interbasin inflow			Interbasin outflow			Ground-water/ surface-water interactions index	Water-resources development index
	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks		
Groups consisting predominantly of isolated hydrogeologic areas								
Group I								
Absent	24	22	24	24	24	24	C: 3	25%: 2.3
Present	0	2	0	0	0	0	I: 19	50%: 3.2
							D: 2	75%: 3.8
Groups consisting predominantly of source-type hydrogeologic areas								
Group SR1								
Absent	16	16	16	0	16	13	C: 12	25%: 3.4
Present	0	0	0	16	0	3	I: 3	50%: 3.9
							D: 1	75%: 4.2
Group SR2								
Absent	19	20	21	21	0	20	C: 3	25%: 3.8
Present	2	1	0	0	21	1	I: 18	50%: 4.1
							D: 0	75%: 4.7
Group SR3								
Absent	14	13	13	14	0	14	C: 0	25%: 1.5
Present	0	1	1	0	14	0	I: 0	50%: 2.5
							D: 14	75%: 2.7
Group SR4								
Absent	24	21	24	22	24	0	C: 0	25%: 1.8
Present	0	3	0	2	0	24	I: 7	50%: 2.0
							D: 17	75%: 2.5
Group SR5								
Absent	13	13	13	0	0	11	C: 13	25%: 4.2
Present	0	0	0	13	13	2	I: 0	50%: 4.4
							D: 0	75%: 4.9
Group SR6								
Absent	17	15	18	0	0	16	C: 0	25%: 3.2
Present	1	3	0	18	18	2	I: 18	50%: 4.0
							D: 0	75%: 4.9

Table 1. Summary of hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province, by groups of hydrogeologic areas—Continued

	Interbasin inflow			Interbasin outflow			Ground-water/ surface-water interactions index	Water-resources development index
	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks		
Groups consisting predominantly of source-type hydrogeologic areas—Continued								
Group SR7								
Absent	34	34	33	0	2	33	C: 0	25%: 2.1
Present	1	1	2	35	33	2	I: 0	50%: 2.5
							D: 35	75%: 3.5
Groups consisting predominantly of link-type hydrogeologic areas								
Group L1								
Absent	0	12	10	0	11	12	C: 12	25%: 3.2
Present	12	0	2	12	1	0	I: 0	50%: 4.0
							D: 0	75%: 4.6
Group L2								
Absent	21	21	0	22	21	0	C: 1	25%: 2.1
Present	1	1	22	0	1	22	I: 6	50%: 2.4
							D: 15	75%: 2.9
Group L3								
Absent	0	3	43	3	0	44	C: 44	25%: 4.2
Present	46	43	3	43	46	2	I: 2	50%: 4.8
							D: 0	75%: 5.4
Group L4								
Absent	2	3	21	2	0	21	C: 0	25%: 2.9
Present	19	18	0	19	21	0	I: 5	50%: 3.8
							D: 16	75%: 4.6
Group L5								
Absent	0	0	11	0	12	12	C: 10	25%: 4.0
Present	12	12	1	12	0	0	I: 2	50%: 4.5
							D: 0	75%: 4.9
Group L6								
Absent	7	8	0	0	0	8	C: 6	25%: 2.3
Present	2	1	9	9	9	1	I: 3	50%: 3.2
							D: 0	75%: 4.4
Group L7								
Absent	1	0	1	4	1	0	C: 1	25%: 2.8
Present	5	6	5	2	5	6	I: 5	50%: 3.0
							D: 0	75%: 3.9

Table 1. Summary of hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province, by groups of hydrogeologic areas—Continued

	Interbasin inflow			Interbasin outflow			Ground-water/ surface-water interactions index	Water-resources development index
	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks		
Groups consisting predominantly of link-type hydrogeologic areas—Continued								
Group L8								
Absent	1	7	0	0	8	1	C: 6	25%: 3.4
Present	7	1	8	8	0	7	I: 2	50%: 3.8
							D: 0	75%: 4.2
Group L9								
Absent	9	11	1	0	10	0	C: 0	25%: 2.2
Present	2	0	10	11	1	11	I: 2	50%: 2.5
							D: 9	75%: 3.9
Groups consisting predominantly of sink-type hydrogeologic areas								
Group SK1								
Absent	9	6	0	10	10	10	C: 1	25%: 1.8
Present	1	4	10	0	0	0	I: 8	50%: 2.4
							D: 1	75%: 4.6
Group SK2								
Absent	3	0	19	22	21	19	C: 9	25%: 2.9
Present	19	22	3	0	1	3	I: 12	50%: 3.7
							D: 1	75%: 4.2

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province

[A, absent; P, present; C, I, and D, the regional aquifer is hydraulically connected, indirectly and intermittently connected, or disconnected, respectively, to surface water in the predominant surface-drainage feature of the hydrogeologic area; hydrogeologic area identifier corresponds to that shown in plate 2. Hydrogeologic area in bold type is medoid of group]

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group I					
a059	Willcox Basin	A	A	A	A	A	A	I	5.3
c001	Adobe Lake Valley	A	A	A	A	A	A	I	1.7
c008	Cadiz Valley	A	P	A	A	A	A	I	2.5
c012	Coyote Lake Valley	A	A	A	A	A	A	I	2.6
c036	Mono Valley	A	A	A	A	A	A	C	2.3
c046	Rose Valley	A	A	A	A	A	A	C	1.8
c049	Searles Valley	A	P	A	A	A	A	I	3.0
c053	Superior Valley	A	A	A	A	A	A	D	2.2
g008	Big Smoky Valley—Northern Part	A	A	A	A	A	A	I	3.9
g011	Buena Vista Valley	A	A	A	A	A	A	I	3.8
g012	Buffalo Valley	A	A	A	A	A	A	I	2.9
g043	Duck Lake Valley	A	A	A	A	A	A	I	3.4
g049	Edwards Creek Valley	A	A	A	A	A	A	I	2.9
g059	Gabbs Valley	A	A	A	A	A	A	I	3.3
g066	Grass Valley	A	A	A	A	A	A	I	3.8
g116	Mesquite Valley	A	A	A	A	A	A	I	3.7
g120	Monte Cristo Valley	A	A	A	A	A	A	I	1.5
g139	Parowan Valley	A	A	A	A	A	A	I	4.7
g142	Penoyer Valley	A	A	A	A	A	A	I	4.0
g166	**Smith Creek Valley**	A	A	A	A	A	A	I	3.3
g182	Summit Lake Valley	A	A	A	A	A	A	C	.8
g184	Swan Lake Valley	A	A	A	A	A	A	I	.9
n013	Playas Basin	A	A	A	A	A	A	I	4.1
n014	San Agustin Basin	A	A	A	A	A	A	D	3.7
				Group SR1					
a001	Agua Fria River Basin	A	A	A	P	A	A	C	4.1
a004	Aravaipa Valley	A	A	A	P	A	A	C	3.5
a007	Big Chino Basin	A	A	A	P	A	P	I	4.2
a008	**Big Sandy River Basin**	A	A	A	P	A	A	C	3.8
a010	Burro Creek Basin	A	A	A	P	A	A	C	2.7
a024	Kirkland Creek Basin	A	A	A	P	A	A	C	4.0
c031	Long Valley	A	A	A	P	A	P	C	4.2
a029	Little Chino Basin	A	A	A	P	A	P	I	4.3
g017	Carico Lake Valley	A	A	A	P	A	A	C	3.3
g027	Clover Valley	A	A	A	P	A	A	D	3.5
g073	Hardscrabble Area	A	A	A	P	A	A	C	1.9
g104	Little Humboldt Valley	A	A	A	P	A	A	C	4.6
g183	Susie Creek Basin	A	A	A	P	A	A	C	2.3
g197	Upper Reese River Valley	A	A	A	P	A	A	C	4.4
g203	Warm Springs Valley	A	A	A	P	A	A	I	3.7
g208	Willow Creek Valley	A	A	A	P	A	A	C	4.3

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group SR2					
c002	Antelope Valley	A	A	A	A	P	A	I	5.9
c025	**Indian Wells Valley**	A	A	A	A	P	A	I	4.1
c026	Johnson Valley	A	A	A	A	P	A	I	3.0
c029	Lavic Valley	A	A	A	A	P	A	I	2.9
c034	Lucerne Valley	A	A	A	A	P	A	I	4.0
c057	Ward and Rice Valleys	A	A	A	A	P	A	I	2.3
g021	Cedar City Valley	A	A	A	A	P	A	I	4.7
g033	Crescent Valley	P	A	A	A	P	A	I	3.2
g045	East Park Valley	A	A	A	A	P	A	C	4.4
g052	Escalante Desert	A	P	A	A	P	A	I	5.0
g054	Fernley Area	A	A	A	A	P	A	I	4.0
g055	Fish Lake Valley	A	A	A	A	P	A	I	4.7
g077	Hualapai Flat	A	A	A	A	P	A	I	4.1
g098	Lake Valley	A	A	A	A	P	A	I	4.2
g101	Lemmon Valley	A	A	A	A	P	A	I	3.8
g114	Massacre Lake Valley	A	A	A	A	P	A	I	4.2
g124	North Butte Valley	A	A	A	A	P	A	C	3.8
g141	Pavant Valley	A	A	A	A	P	A	C	5.1
g157	Rush Valley	A	A	A	A	P	P	I	4.5
g174	South Railroad Valley	P	A	A	A	P	A	I	1.6
n018	Tularosa Basin	A	A	A	A	P	A	I	4.8
				Group SR3					
c007	Broadwell Valley	A	P	A	A	P	A	D	2.0
c014	Cuddeback Valley	A	A	A	A	P	A	D	2.3
c020	Fenner Valley	A	A	A	A	P	A	D	2.7
c044	Red Pass Valley	A	A	A	A	P	A	D	2.5
g044	Dugway Valley	A	A	A	A	P	A	D	2.6
g047	East Soda Spring Valley	A	A	P	A	P	A	D	1.2
g053	Fairview Valley	A	A	A	A	P	A	D	1.3
g164	Sink Valley	A	A	A	A	P	A	D	1.2
g172	South Ivanpah Valley	A	A	A	A	P	A	D	2.5
g180	**Stone Cabin Valley**	A	A	A	A	P	A	D	2.5
g206	West Soda Spring Valley	A	A	A	A	P	A	D	1.0
n005	Jornada del Muerto Basin—Northern Part	A	A	A	A	P	A	D	2.9
n006	Jornada del Muerto Basin—Southern Part	A	A	A	A	P	A	D	3.7
n010	Mimbres River Basin	A	A	A	A	P	A	D	5.1

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow			Ground-water and surface-water interactions index	Water-resources development index
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks		
				Group SR4					
c017	Deep Springs Valley[1]	A	A	A	A	A	P	I	3.1
c022	Goldstone Valley[1]	A	A	A	A	A	P	D	2.5
c032	Lost Lake and Owl Lake Valleys[1]	A	A	A	A	A	P	I	2.4
g014	Cactus Flat	A	A	A	A	A	P	D	1.9
g020	Cave Valley	A	A	A	A	A	P	D	2.2
g041	Dry Lake Valley	A	A	A	A	A	P	D	2.2
g051	Emigrant Valley	A	A	A	A	A	P	D	2.0
g061	Garfield Flat	A	A	A	A	A	P	D	.9
g062	Garnet and Hidden Valleys	A	A	A	A	A	P	D	2.0
g074	Hidden Valley	A	A	A	A	A	P	D	2.0
g075	High Rock Lake Valley	A	A	A	A	A	P	D	2.6
g085	Huntoon Valley	A	A	A	A	A	P	I	1.1
g093	Kawich Valley	A	P	A	A	A	P	D	1.5
g096	**Kumiva Valley**	A	A	A	A	A	P	D	2.0
g103	Little Fish Lake Valley	A	A	A	P	A	P	I	1.5
g105	Long Valley	A	A	A	A	A	P	D	1.6
g115	Mercury Valley	A	A	A	P	A	P	D	1.8
g126	North Ivanpah Valley	A	P	A	A	A	P	D	2.5
g136	Pahrump Valley	A	A	A	A	A	P	I	4.4
g146	Pine Valley	A	A	A	A	A	P	D	2.9
g152	Ralston Valley	A	P	A	A	A	P	I	2.4
g170	South Butte Valley	A	A	A	A	A	P	I	3.1
g190	Tippett Valley	A	A	A	A	A	P	D	1.5
g210	Yucca Flat	A	A	A	A	A	P	D	1.8
				Group SR5					
a012	Cienega Creek Basin	A	A	A	P	P	A	C	2.8
a053	Upper San Pedro River Basin	A	A	A	P	P	A	C	4.9
g007	Beaver Valley	A	A	A	P	P	A	C	4.7
g019	Carson, Dayton, and Eagle Valleys	A	A	A	P	P	A	C	5.2
g071	**Grouse Creek Valley**	A	A	A	P	P	A	C	4.3
g084	Huntington Valley	A	A	A	P	P	P	C	4.4
g112	Maggie Creek Basin	A	A	A	P	P	A	C	4.2
g132	Northern Juab Valley	A	A	A	P	P	A	C	4.8
g147	Pine Valley	A	A	A	P	P	P	C	4.2
g163	Silver State and Quinn River Valleys	A	A	A	P	P	A	C	5.8
g171	South Fork Area	A	A	A	P	P	A	C	4.3
g186	Thousand Springs Valley—Herrell Siding and Brush Creek Areas	A	A	A	P	P	A	C	3.8
g196	Upper Humboldt River Basin	A	A	A	P	P	A	C	5.2

[1]See footnote at end of table.

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group SR6					
a015	Douglas Basin	A	A	A	P	P	A	I	4.9
a048	San Simon Valley	A	A	A	P	P	A	I	5.2
c005	Borrego Valley	P	A	A	P	P	A	I	4.6
c011	Coachella Valley	A	A	A	P	P	A	I	5.7
c055	Upper Mojave River Valley	A	P	A	P	P	A	I	5.0
g004	Antelope Valley	A	A	A	P	P	P	I	1.8
g006	Antelope Valley	A	A	A	P	P	A	I	3.9
g026	Clover Valley	A	A	A	P	P	A	I	4.7
g034	Curlew Valley	A	P	A	P	P	P	I	5.6
g067	**Grass Valley**	A	A	A	P	P	A	I	4.1
g070	Gridley Lake Valley	A	A	A	P	P	A	I	3.3
g102	Lida Valley	A	A	A	P	P	A	I	2.1
g119	Monitor Valley	A	A	A	P	P	A	I	2.1
g148	Pleasant Valley	A	A	A	P	P	A	I	3.4
g159	San Emidio Desert	A	A	A	P	P	A	I	3.6
g165	Skull Valley	A	A	A	P	P	A	I	3.8
g191	Tooele Valley	A	P	A	P	P	A	I	4.8
g204	West Park Valley	A	A	A	P	P	A	I	2.9
				Group SR7					
a002	Aguirre Valley	A	A	A	P	P	A	D	4.0
a003	Altar Valley	A	A	A	P	P	A	D	3.6
a006	Baboquivari and Tecolote Valleys	A	A	A	P	P	A	D	3.9
a011	Butler Valley	A	A	A	P	P	A	D	2.0
a013	**Detrital Valley**	A	A	A	P	P	A	D	2.5
a034	McMullen Valley	A	A	A	P	P	A	D	5.2
a040	Paradise Valley	A	A	A	P	P	A	D	5.0
a044	Sacramento Valley	A	A	A	P	P	A	D	3.5
a051	Truxton Wash	A	A	A	P	P	A	D	2.8
a052	Upper Hassayampa River Basin	A	A	A	P	P	A	D	3.5
a055	Valley of the Ajo	A	A	A	P	P	A	D	3.4
a056	Vekol Valley	A	A	A	P	P	A	D	2.5
c003	Arroyo Seco Basin	A	A	A	P	P	A	D	2.0
c009	Chemehuevi Valley	A	A	A	P	P	A	D	1.8
c016	Darwin Plateau Basins	A	A	A	P	A	A	D	2.0
c018	East Pilot Knob and Brown Mountain Valleys	A	A	A	P	P	A	D	2.4
c027	Kelso Valley	A	A	A	P	P	A	D	2.2
c028	Lanfair Valley	A	A	A	P	A	A	D	2.1
c038	North Piute Valley	A	A	A	P	P	A	D	2.5
c039	Ogilby Valley	A	A	A	P	P	A	D	2.5

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow			Ground-water and surface-water interactions index	Water-resources development index
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks		
Group SR7—Continued									
c040	Orocopia Valley	A	A	A	P	P	A	D	1.6
c042	Pinto Basin	A	A	A	P	P	A	D	2.4
c056	Vallecito, Carrizo, and Coyote Well Valleys	A	A	A	P	P	A	D	3.2
g032	Crater Flat	A	A	P	P	P	A	D	2.1
g088	Ione Valley	A	A	A	P	P	A	D	1.5
g091	Jersey Valley	A	A	A	P	P	A	D	1.4
g131	North Tikapoo Valley	A	A	P	P	P	A	D	1.9
g140	Patterson Valley	A	P	A	P	P	P	D	2.7
g149	Pocatello and Blue Creek Valleys	A	A	A	P	P	A	D	5.4
g162	Shadow Valley	A	A	A	P	P	A	D	2.5
g175	South Spring Valley	A	A	A	P	P	A	D	3.7
g179	Stingaree Valley	A	A	A	P	P	A	D	2.3
n007	La Jencia Basin	P	A	A	P	P	P	D	2.7
n008	Lordsburg Basin	A	A	A	P	P	A	D	4.1
n011	Montecello-Cuchillo Basin	A	A	A	P	P	A	D	3.0
Group L1									
a014	Donnelly Wash	P	A	A	P	A	A	C	2.7
a016	Dripping Springs Wash	P	A	A	P	A	A	C	2.5
a033	Lower Verde River Basin	P	A	A	P	A	A	C	4.2
a057	Verde Valley	P	A	P	P	A	A	C	4.6
a061	Yuma Wash	P	A	A	P	P	A	C	3.2
g003	Antelope Valley	P	A	A	P	A	A	C	4.7
g013	Cache Valley	P	A	A	P	A	A	C	6.2
g048	**East Walker River Basin**	P	A	A	P	A	A	C	4.1
g109	Lower Meadow Valley Wash	P	A	P	P	A	A	C	4.0
g154	Rock Creek Valley	P	A	A	P	A	A	C	3.2
g193	Truckee River Basin—Reno/Sparks Segment	P	A	A	P	A	A	C	5.0
g194	Truckee River Basin—Tracy Segment	P	A	A	P	A	A	C	3.8

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group L2					
c004	Bicycle Valley[1]	A	A	P	A	A	P	D	2.5
c019	Eureka Valley[1]	A	A	P	A	A	P	D	2.5
c030	Leach Valley[1]	A	A	P	A	A	P	I	2.3
c043	Race Track and Hidden Valleys[1]	A	A	P	A	A	P	D	1.6
c047	Saline Valley[1]	A	A	P	A	A	P	C	2.7
g001	Alkali Spring Valley	A	A	P	A	A	P	I	2.1
g005	Antelope Valley	A	P	P	A	A	P	D	2.4
g028	Coal Valley	P	A	P	A	A	P	D	1.7
g037	Delamar Valley	A	A	P	A	A	P	D	1.6
g050	Eldorado Valley	A	A	P	A	A	P	D	3.5
g063	**Gold Flat**	A	A	P	A	A	P	D	2.3
g087	Indian Springs Valley	A	A	P	A	A	P	D	3.0
g089	Jakes Valley	A	A	P	A	A	P	D	2.9
g090	Jean Lake Valley	A	A	P	A	A	P	D	2.1
g129	North Spring Valley	A	A	P	A	A	P	I	4.5
g130	North Three Lakes Valley	A	A	P	A	A	P	D	2.2
g169	Snake Valley	A	A	P	A	P	P	I	4.7
g173	South Little Smoky Valley	A	A	P	A	A	P	D	1.6
g176	South Three Lakes Valley	A	A	P	A	A	P	D	2.8
g181	Stonewall Flat	A	A	P	A	A	P	I	2.0
g195	Tule Valley	A	A	P	A	A	P	I	2.1
g201	Wah Wah Valley	A	A	P	A	A	P	D	3.0
				Group L3					
a018	Eloy Area	P	P	A	P	P	A	C	5.9
a019	Gila Bend Basin	P	P	A	P	P	A	C	5.4
a023	King and San Cristobal Valleys	P	P	A	P	P	A	C	4.7
a028	Lechuguilla Desert	P	P	A	P	P	A	C	5.2
a031	Lower Hassayampa River Basin	P	P	A	P	P	A	C	5.0
a037	Mohawk Valley	P	P	A	P	P	A	C	5.0
a039	Palomas and Sentinal Plains	P	P	A	P	P	A	C	5.2
a041	Parker and Vidal Valleys	P	P	A	P	P	A	C	5.5
a046	Salt River Valley—Chandler Area	P	P	A	P	P	A	C	6.0
a047	Salt River Valley—Phoenix Area	P	P	A	P	P	A	C	6.0
a054	Upper Santa Cruz River Basin	P	P	A	P	P	A	C	5.4
a060	Yuma Basin	P	P	A	P	P	A	C	5.7
c024	Imperial Valley	P	P	A	P	P	A	I	6.3
c033	Lower Mojave River Valley	P	P	A	P	P	A	I	4.6
g024	Churchill Valley	P	P	A	P	P	A	C	4.2
g030	Continental Lake Valley	P	P	A	A	P	A	C	3.9

[1]See footnote at end of table.

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group L3—Continued					
g039	Dixie Creek and Tenmile Creek Basin	P	P	A	P	P	A	C	4.1
g046	East Shore Area	P	A	A	P	P	A	C	5.5
g078	Humboldt River Basin—Boulder Flat Segment	P	P	A	P	P	A	C	4.7
g080	Humboldt River Basin—Imlay Segment	P	P	A	P	P	A	C	4.5
g081	Humboldt River Basin—Lovelock Segment	P	P	A	A	P	A	C	4.8
g083	Humboldt River Basin—Winnemucca Segment	P	P	A	P	P	A	C	4.7
g094	Kings River and Desert Valleys	P	P	A	P	P	A	C	5.2
g100	Leamington Canyon Area	P	A	A	P	P	A	C	4.8
g108	Lower Bear River Basin	P	P	A	P	P	A	C	5.6
g111	Lower Reese River Valley	P	P	A	P	P	A	C	3.5
g113	Mason Valley	P	P	A	P	P	A	C	5.1
g117	Middle Reese River Valley	P	P	A	P	P	A	C	4.1
g118	Milford Area	P	P	A	P	P	P	C	4.9
g125	North Fork Humboldt River Basin and Lamoille Valley	P	P	A	P	P	A	C	5.1
g145	**Pine Forest Valley**	P	P	A	P	P	A	C	4.8
g158	Salt Lake Valley	P	P	A	P	P	A	C	5.5
g167	Smith Valley	P	A	A	P	P	A	C	4.8
g187	Thousand Springs Valley—Montello and Crittenden Area	P	P	P	P	P	A	C	4.1
g188	Thousand Springs Valley—Rocky Butte Area	P	P	A	P	P	A	C	3.4
g189	Thousand Springs Valley—Toano and Rock Spring Areas	P	P	A	P	P	P	C	3.9
g192	Truckee River Basin—Dodge Flat	P	P	A	P	P	A	C	3.2
g198	Utah Valley	P	P	P	P	P	A	C	5.6
n001	Albuquerque-Belen Basin	P	P	A	P	P	A	C	5.5
n003	Engle Basin	P	P	A	P	P	A	C	3.5
n004	Española Basin	P	P	A	P	P	A	C	4.6
n009	Mesilla Basin	P	P	A	P	P	A	C	5.3
n012	Palomas Basin	P	P	A	P	P	A	C	4.9
n015	San Marcial Basin	P	P	A	P	P	A	C	2.2
n016	Santo Domingo Basin	P	P	A	P	P	A	C	4.3
n017	Socorro Basin	P	P	P	P	P	A	C	4.6

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group L4					
a005	Avra Valley	P	P	A	P	P	A	D	5.2
a009	Bullard Wash	P	A	A	P	P	A	D	3.5
a020	Growler Valley	P	P	A	P	P	A	D	1.9
a021	Harquahala Basin	P	P	A	P	P	A	D	5.3
a022	Hualapai Basin	P	P	A	A	P	A	D	3.9
a025	La Posa Plain	P	P	A	P	P	A	D	3.0
a035	**Middle Hassayampa River Basin**	P	P	A	P	P	A	D	3.7
a042	Quijotoa Valley	P	P	A	P	P	A	D	2.4
a043	Renegras Plain	P	P	A	P	P	A	D	4.6
a049	Santa Rosa Valley	P	A	A	P	P	A	D	3.9
a050	Stanfield Area	P	P	A	P	P	A	D	5.7
a058	Waterman Wash	A	P	A	P	P	A	D	4.7
c035	Middle Mojave River Valley	P	P	A	P	P	A	I	3.8
c045	Riggs Valley	P	P	A	P	P	A	I	2.4
c050	Soda Lake Valley	P	P	A	P	P	A	I	2.9
c052	South Piute Valley	P	P	A	P	P	A	D	2.0
c054	Twentynine Palms Area	A	P	A	P	P	A	D	4.1
g138	Paradise Valley	P	A	A	P	P	A	D	5.2
g144	Pilot Valley	P	P	A	P	P	A	I	3.1
g199	Valjean Valley	P	P	A	P	P	A	I	2.7
n002	Animas Basin	P	P	A	A	P	A	D	4.4
				Group L5					
a017	Duncan Basin	P	P	A	P	A	A	C	4.6
a026	Lake Havasu Basin	P	P	A	P	A	A	C	4.0
a030	Lower Bill Williams River Basin	P	P	A	P	A	A	C	4.1
a032	**Lower San Pedro River Basin**	P	P	A	P	A	A	C	4.5
a036	Mohave Valley	P	P	A	P	A	A	C	4.9
a038	Palo Verde Valley	P	P	A	P	A	A	C	5.6
a045	Safford Valley	P	P	A	P	A	A	C	5.1
g042	Dry, Rose, and Eagle Valleys	P	P	A	P	A	A	I	3.9
g079	Humboldt River Basin—Elko and Marys Creek Segment	P	P	A	P	A	A	C	4.5
g082	Humboldt River Basin—Red House Segment	P	P	A	P	A	A	C	4.9
g095	Kobeh Valley	P	P	A	P	A	A	I	3.2
g097	Lake Mead Basin	P	P	P	P	A	A	C	3.4

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group L6					
c037	North Owens Valley	P	A	P	P	P	A	C	4.9
g056	Fish Springs Flat	A	P	P	P	P	A	C	2.3
g072	Hansel and Northern Rozel Flat	A	A	P	P	P	P	I	4.8
g110	Lower Moapa Valley	P	A	P	P	P	A	C	4.2
g121	Mud Meadow Creek Basin	A	A	P	P	P	A	C	1.9
g127	North Little Smoky Valley	A	A	P	P	P	A	I	3.2
g143	Pilot Creek Valley	A	A	P	P	P	A	I	2.5
g178	**Steptoe Valley**	A	A	P	P	P	A	C	4.4
g200	Virgin Valley	A	A	P	P	P	A	C	1.8
				Group L7					
g002	Amargosa Desert	P	P	P	P	P	P	I	3.0
g064	Goshute Valley	P	P	A	A	P	P	I	2.5
g123	Newark Valley	P	P	P	A	A	P	I	4.2
g133	Oasis Valley	A	P	P	P	P	P	I	2.7
g160	**Sarcobatus Flat**	P	P	P	A	P	P	I	2.9
g161	Sevier Desert	P	P	P	A	P	P	C	5.3
				Group L8					
a027	Lake Mohave Basin	P	A	P	P	A	A	C	3.5
g016	**California Wash**	P	A	P	P	A	P	C	3.7
g076	Hot Creek Valley	P	A	P	P	A	P	I	3.2
g107	Lower Amargosa Valley	P	P	P	P	A	P	C	3.3
g122	Muddy River Springs Area	P	A	P	P	A	P	C	3.8
g134	Pahranagat Valley	P	A	P	P	A	P	I	4.5
g137	Panaca Valley	P	A	P	P	A	P	C	4.1
g207	White River Valley	A	A	P	P	A	P	C	4.5
				Group L9					
g015	California Valley	A	A	P	P	A	P	D	2.1
g022	Cedar Valley	A	A	P	P	A	P	D	4.4
g023	Chicago Valley	A	A	P	P	A	P	I	1.2
g031	Coyote Spring Valley	P	A	P	P	A	P	D	2.2
g036	Deep Creek Valley	A	A	P	P	A	P	I	4.2
g057	Fortymile Wash	A	A	P	P	A	P	D	3.5
g060	Garden Valley	A	A	A	P	A	P	D	3.2
g092	**Kane Springs Valley**	A	A	P	P	A	P	D	2.5
g099	Las Vegas Valley	A	A	P	P	P	P	D	5.5
g135	Pahroc Valley	P	A	P	P	A	P	D	2.2
g155	Rock Valley	A	A	P	P	A	P	D	2.0

Table 2. Hydrologic-system characteristics of hydrogeologic areas in the Basin and Range Physiographic Province—Continued

Hydrogeologic area		Interbasin inflow			Interbasin outflow				
Identifier	Name	Soils and streams	Basin fill	Consolidated rocks	Soils and streams	Basin fill	Consolidated rocks	Ground-water and surface-water interactions index	Water-resources development index
				Group SK1					
g025	Clayton Valley	A	A	P	A	A	A	I	2.1
g029	Columbus Salt Marsh Valley	A	P	P	A	A	A	I	1.7
g038	Diamond Valley	P	A	P	A	A	A	I	4.9
g058	Frenchman Flat	A	A	P	A	A	A	D	2.3
g065	**Granite Springs Valley**	A	A	P	A	A	A	I	2.4
g106	Long Valley	A	P	P	A	A	A	I	4.7
g128	North Railroad Valley	A	A	P	A	A	A	I	4.2
g153	Rhodes Salt Marsh Valley	A	P	P	A	A	A	I	1.1
g156	Ruby Valley	A	P	P	A	A	A	C	4.7
g185	Teels Marsh Valley	A	A	P	A	A	A	I	1.3
				Group SK2					
c006	Bristol Valley	A	P	A	A	A	A	I	3.7
c010	Chuckwalla Valley	P	P	A	A	P	A	I	4.3
c013	Cronise Valley	P	P	A	A	A	A	I	2.8
c015	Dale Valley	P	P	A	A	A	A	I	2.8
c021	Fremont Valley	A	P	A	A	A	A	I	4.3
c023	Harper Valley	A	P	A	A	A	A	I	4.5
c041	Panamint Valley[1]	P	P	A	A	A	P	I	2.9
c048	Salton Sea	P	P	A	A	A	A	C	4.0
c051	South Owens Valley	P	P	A	A	A	A	C	4.2
g009	Big Smoky Valley—Tonopah Flat	P	P	A	A	A	P	I	3.8
g010	Black Rock Desert	P	P	A	A	A	A	C	4.0
g018	Carson Desert	P	P	A	A	A	A	C	5.2
g035	Death Valley	P	P	P	A	A	A	C	2.8
g040	Dixie Valley	P	P	A	A	A	A	I	3.5
g068	Great Salt Lake	P	P	P	A	A	A	C	4.0
g069	Great Salt Lake Desert	P	P	P	A	A	A	I	3.3
g086	Independence Valley	P	P	A	A	A	A	I	3.4
g151	Pyramid Lake Valley	P	P	A	A	P	A	C	3.3
g168	**Smoke Creek Desert**	P	P	A	A	A	A	I	3.5
g177	South Tikapoo Valley	P	P	A	A	A	P	D	2.0
g202	Walker Lake Valley	P	P	A	A	A	A	C	4.3
g209	Winnemucca Lake Valley	P	P	A	A	A	A	C	2.0

[1]Interbasin inflows and outflows within consolidated rocks, and surface-water/ground-water interactions index determined on the basis of cited literature and written communication dated March 15, 2004, from James R. Harrill, hydrologist, U.S. Geological Survey (retired).

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Anning and Konieczki—CLASSIFICATION OF HYDROGEOLOGIC AREAS AND HYDROGEOLOGIC FLOW SYSTEMS IN THE BASIN AND RANGE PHYSIOGRAPHIC PROVINCE, SOUTHWESTERN UNITED STATES—U.S. Geological Survey Professional Paper 1702

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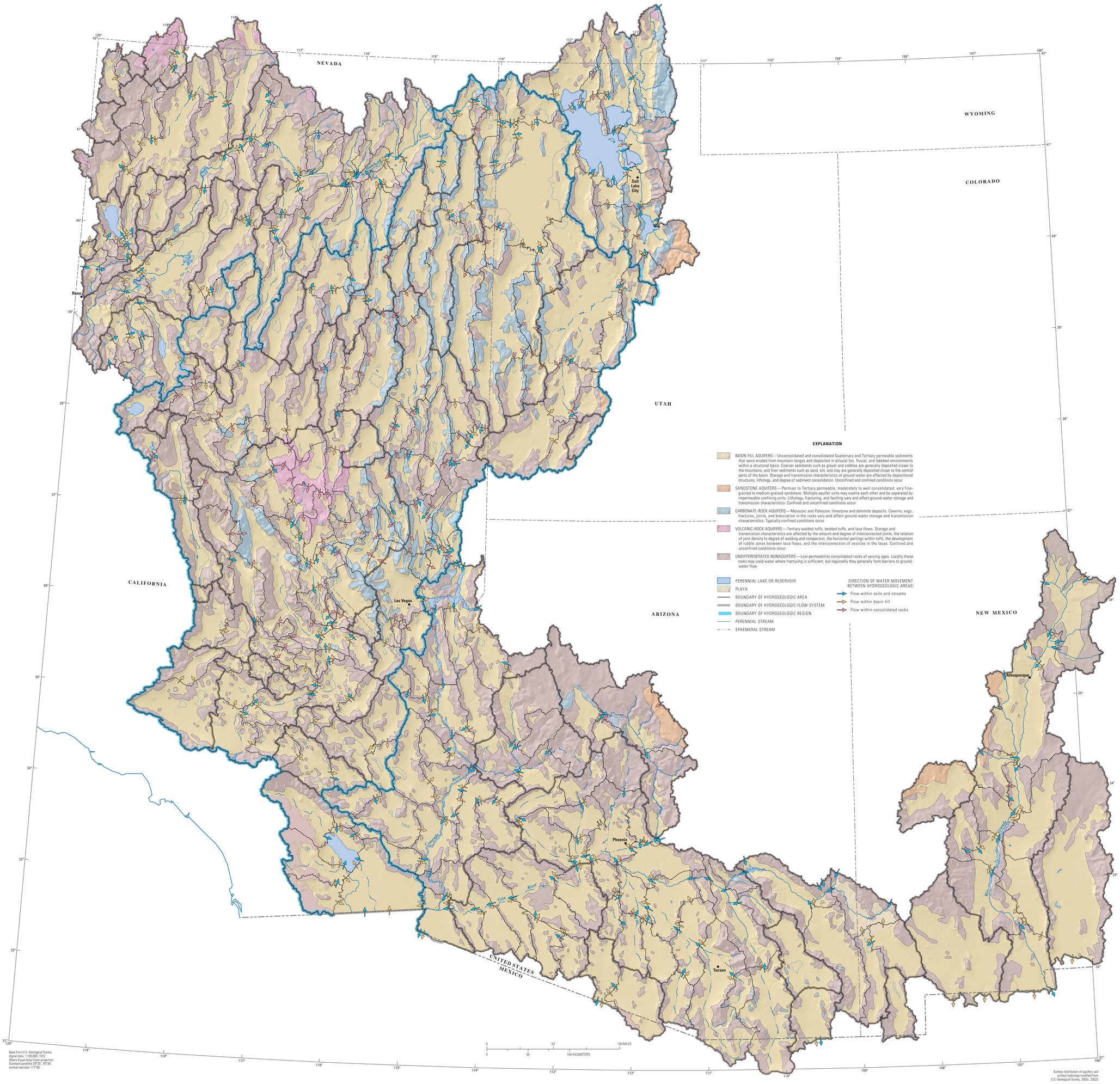

GENERALIZED INTERBASIN FLOWS, SURFACE DISTRIBUTION OF MAJOR AQUIFERS, AND SURFACE HYDROLOGY IN THE BASIN AND RANGE PHYSIOGRAPHIC PROVINCE, SOUTHWESTERN UNITED STATES

By
David W. Anning and and A.D. Konieczki
2005

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PROFESSIONAL PAPER 1702
Hydrogeologic areas, hydrogeologic flow systems, and hydrogeologic regions—Plate 2 of 2
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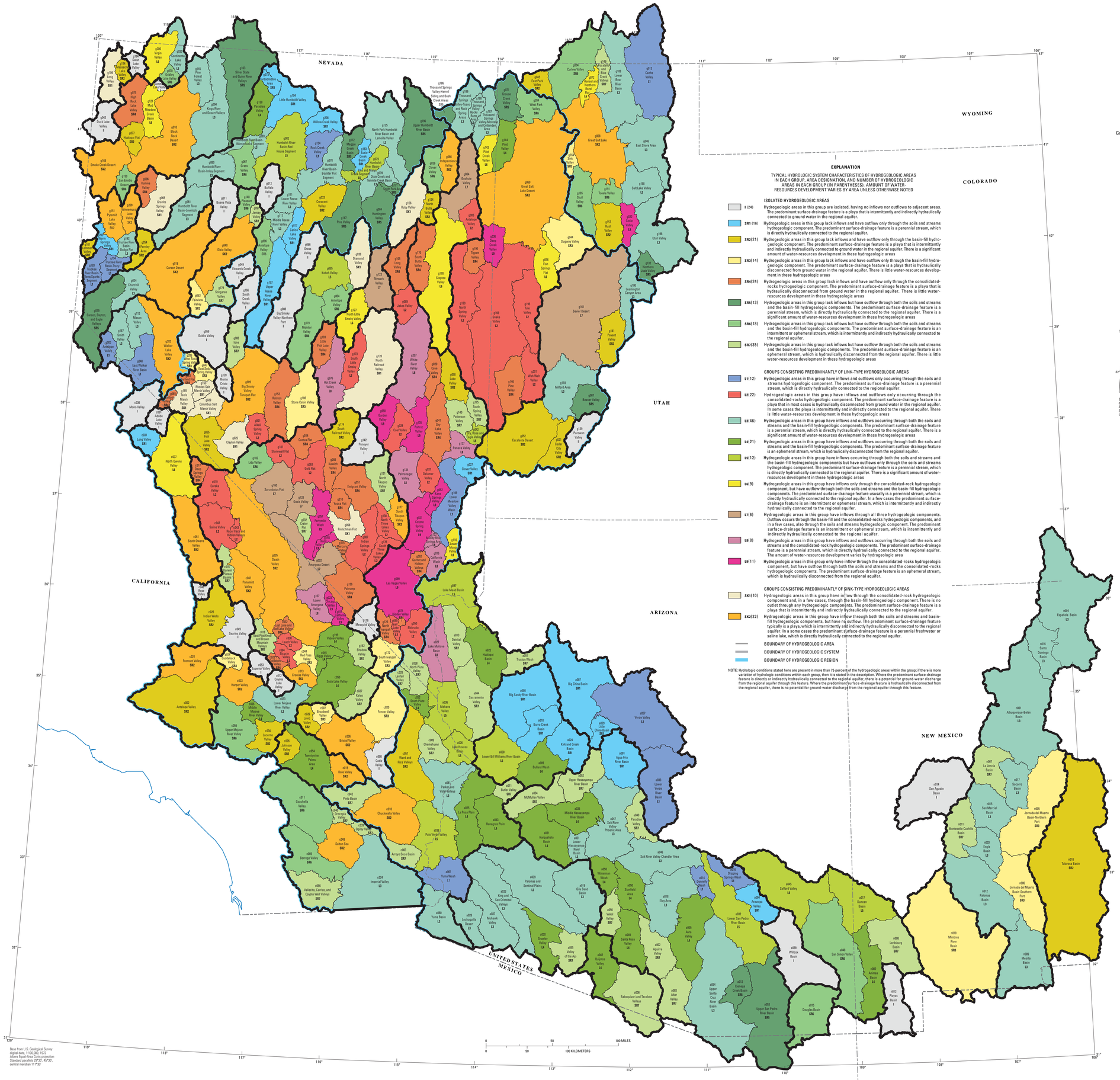


Base from U.S. Geological Survey digital data, 1:100,000, 1972
Albers Equal-Area Conic projection
Standard parallels 29°30', 45°30', central meridian 111°30'

EXPLANATION

TYPICAL HYDROLOGIC SYSTEM CHARACTERISTICS OF HYDROGEOLOGIC AREAS IN EACH GROUP, AREA DESIGNATION, AND NUMBER OF HYDROGEOLOGIC AREAS IN EACH GROUP (IN PARENTHESES). AMOUNT OF WATER-RESOURCES DEVELOPMENT VARIES BY AREA UNLESS OTHERWISE NOTED

ISOLATED HYDROGEOLOGIC AREAS

- **I (24)** Hydrogeologic areas in this group are isolated, having no inflows nor outflows to adjacent areas. The predominant surface-drainage feature is a playa that is intermittently and indirectly hydraulically connected to ground water in the regional aquifer.
- **SR1 (16)** Hydrogeologic areas in this group lack inflows and have outflow only through the soils and streams hydrogeologic component. The predominant surface-drainage feature is a perennial stream, which is directly hydraulically connected to the regional aquifer.
- **SR2 (21)** Hydrogeologic areas in this group lack inflows and have outflow only through the basin-fill hydrogeologic component. The predominant surface-drainage feature is a playa that is intermittently and indirectly hydraulically connected to ground water in the regional aquifer. There is a significant amount of water-resources development in these hydrogeologic areas
- **SR3 (14)** Hydrogeologic areas in this group lack inflows and have outflow only through the basin-fill hydrogeologic component. The predominant surface-drainage feature is a playa that is hydraulically disconnected from ground water in the regional aquifer. There is little water-resources development in these hydrogeologic areas
- **SR4 (24)** Hydrogeologic areas in this group lack inflows and have outflow only through the consolidated-rocks hydrogeologic component. The predominant surface-drainage feature is a playa that is hydraulically disconnected from ground water in the regional aquifer. There is little water-resources development in these hydrogeologic areas
- **SR5 (13)** Hydrogeologic areas in this group lack inflows but have outflow through both the soils and streams and the basin-fill hydrogeologic components. The predominant surface-drainage feature is a perennial stream, which is directly hydraulically connected to the regional aquifer. There is a significant amount of water-resources development in these hydrogeologic areas
- **SR6 (18)** Hydrogeologic areas in this group lack inflows but have outflow through both the soils and streams and the basin-fill hydrogeologic components. The predominant surface-drainage feature is an intermittent or ephemeral stream, which is intermittently and indirectly hydraulically connected to the regional aquifer.
- **SR7 (35)** Hydrogeologic areas in this group lack inflows but have outflow through both the soils and streams and the basin-fill hydrogeologic components. The predominant surface-drainage feature is an ephemeral stream, which is hydraulically disconnected from the regional aquifer. There is little water-resources development in these hydrogeologic areas

GROUPS CONSISTING PREDOMINANTLY OF LINK-TYPE HYDROGEOLOGIC AREAS

- **L1 (12)** Hydrogeologic areas in this group have inflows and outflows only occurring through the soils and streams hydrogeologic component. The predominant surface-drainage feature is a perennial stream, which is directly hydraulically connected to the regional aquifer.
- **L2 (22)** Hydrogeologic areas in this group have inflows and outflows only occurring through the consolidated-rocks hydrogeologic component. The predominant surface-drainage feature is a playa that in most cases is hydraulically disconnected from ground water in the regional aquifer. In some cases the playa is intermittently and indirectly connected to the regional aquifer. There is little water-resources development in these hydrogeologic areas
- **L3 (46)** Hydrogeologic areas in this group have inflows and outflows occurring through both the soils and streams and the basin-fill hydrogeologic components. The predominant surface-drainage feature is a perennial stream, which is directly hydraulically connected to the regional aquifer. There is a significant amount of water-resources development in these hydrogeologic areas
- **L4 (21)** Hydrogeologic areas in this group have inflows and outflows occurring through both the soils and streams and the basin-fill hydrogeologic components. The predominant surface-drainage feature is an ephemeral stream, which is hydraulically disconnected from the regional aquifer.
- **L5 (12)** Hydrogeologic areas in this group have inflows occurring through both the soils and streams and the basin-fill hydrogeologic components but have outflows only through the soils and streams hydrogeologic component. The predominant surface-drainage feature is a perennial stream, which is directly hydraulically connected to the regional aquifer. There is a significant amount of water-resources development in these hydrogeologic areas
- **L6 (9)** Hydrogeologic areas in this group have inflows only through the consolidated-rock hydrogeologic component, but have outflow through both the soils and streams and the basin-fill hydrogeologic components. The predominant surface-drainage feature usually is a perennial stream, which is directly hydraulically connected to the regional aquifer. In a few cases the predominant surface-drainage feature is an intermittent or ephemeral stream, which is intermittently and indirectly hydraulically connected to the regional aquifer.
- **L7 (6)** Hydrogeologic areas in this group have inflows through all three hydrogeologic components. Outflow occurs through the basin-fill and the consolidated-rocks hydrogeologic components, and in a few cases, also through the soils and streams hydrogeologic component. The predominant surface-drainage feature is an intermittent or ephemeral stream, which is intermittently and indirectly hydraulically connected to the regional aquifer.
- **L8 (8)** Hydrogeologic areas in this group have inflows and outflows occurring through both the soils and streams and the consolidated-rock hydrogeologic components. The predominant surface-drainage feature is a perennial stream, which is directly hydraulically connected to the regional aquifer. The amount of water-resources development varies by hydrogeologic area
- **L9 (11)** Hydrogeologic areas in this group only have inflow through the consolidated-rocks hydrogeologic component, but have outflow through both the soils and streams and the consolidated-rocks hydrogeologic components. The predominant surface-drainage feature is an ephemeral stream, which is hydraulically disconnected from the regional aquifer.

GROUPS CONSISTING PREDOMINANTLY OF SINK-TYPE HYDROGEOLOGIC AREAS

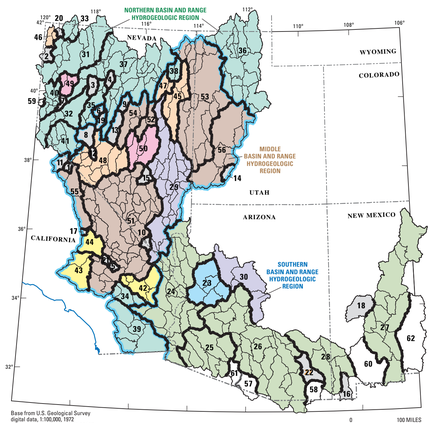
- **SX1 (110)** Hydrogeologic areas in this group have inflow through the consolidated-rock hydrogeologic component and, in a few cases, through the basin-fill hydrogeologic component. There is no outlet through any hydrogeologic components. The predominant surface-drainage feature is a playa that is intermittently and indirectly hydraulically connected to the regional aquifer.
- **SX2 (22)** Hydrogeologic areas in this group have inflow through both the soils and streams and basin-fill hydrogeologic components, but have no outflow. The predominant surface-drainage feature typically is a playa, which is intermittently and indirectly hydraulically disconnected to the regional aquifer. In a some cases the predominant surface-drainage feature is a perennial freshwater or saline lake, which is directly hydraulically connected to the regional aquifer.

BOUNDARY OF HYDROGEOLOGIC AREA
BOUNDARY OF HYDROGEOLOGIC SYSTEM
BOUNDARY OF HYDROGEOLOGIC REGION

NOTE: Hydrologic conditions stated here are present in more than 75 percent of the hydrogeologic areas within the group; if there is more variation of hydrologic conditions within each group, then it is stated in the description. Where the predominant surface-drainage feature is directly or indirectly hydraulically connected to the regional aquifer, there is a potential for ground-water discharge from the regional aquifer through this feature. Where the predominant surface-drainage feature is hydraulically disconnected from the regional aquifer, there is no potential for ground-water discharge from the regional aquifer through this feature.

Groups of similar hydrogeologic flow systems in the Basin and Range Physiographic Province and the distribution of interbasin flows that hydraulically connect adjacent hydrogeologic areas within each system.

Hydrogeologic flow systems



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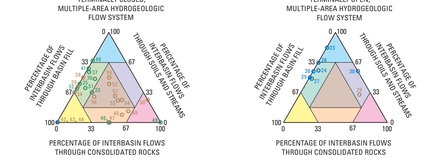
Distribution of interbasin flows



EXPLANATION

SINGLE-AREA HYDROGEOLOGIC FLOW SYSTEM

1 Adobe Lake Valley
2 Duck Lake Valley
3 Buena Vista Valley
4 Buffalo Valley
5 Coyote Valley
6 Edwards Creek Valley
7 Fernley System
8 Gabbs Valley
9 Grass Valley
10 Mesquite Valley
11 Mono Valley
12 Monte Cristo Valley
13 Northern Big Smoky Valley
14 Parowan Valley
15 Penoyer Valley
16 Playas Basin
17 Rose Valley
18 San Agustin Basin
19 Smith Creek Valley
20 Swan Lake Valley
21 Superior Valley
22 Willcox Basin

TERMINALLY OPEN, MULTIPLE-AREA HYDROGEOLOGIC FLOW SYSTEMS CONSISTING OF HYDROGEOLOGIC AREAS THAT ARE HYDRAULICALLY CONNECTED BY INTERBASIN FLOWS PREDOMINANTLY OCCURRING THROUGH:

Soils and streams
23 Bill Williams River

Soils and streams; and basin fill
24 Lower Colorado River
25 Lower Gila River
26 Middle Gila River
27 Rio Grande
28 Upper Gila River

Consolidated rocks; and soils and streams
29 Nevada Colorado River
30 Verde River

TERMINALLY CLOSED, MULTIPLE-AREA HYDROGEOLOGIC FLOW SYSTEMS CONSISTING OF HYDROGEOLOGIC AREAS THAT ARE HYDRAULICALLY CONNECTED BY INTERBASIN FLOWS PREDOMINANTLY OCCURRING THROUGH:

Soils and streams; and basin fill
31 Black Rock Desert System
32 Carson River
33 Continental Lakes
34 Dale Valley
35 Dixie Valley
36 Great Salt Lake
37 Humboldt River
38 Independence Valley
39 Salton Sea
40 Trucker River
41 Walker River

Basin fill
42 Bristol Valley
43 Fremont Valley
44 Searles Lake

Basin fill and consolidated rocks
45 Goshute Valley
46 Long Valley
47 Ruby Valley
48 South-Central Marshes

Consolidated rocks
49 Granite Springs Valley
50 Railroad Valley

Soils and streams, basin fill, and consolidated rocks
51 Death Valley
52 Diamond Valley
53 Great Salt Lake Desert
54 Newark Valley
55 Owens River
56 Sevier Lake

HYDROGEOLOGIC AREAS THAT BELONG TO HYDROGEOLOGIC FLOW SYSTEMS THAT LARGELY LIE OUTSIDE OF THE STUDY AREA
57 Babaquivari and Tecolote Valleys
58 Douglas Basin
59 Lemmon Valley
60 Mimbres River Basin
61 Quijotoa Valley
62 Tularosa Basin

BOUNDARY OF HYDROGEOLOGIC AREA
BOUNDARY OF HYDROGEOLOGIC FLOW SYSTEM
BOUNDARY OF HYDROGEOLOGIC REGION

HYDROGEOLOGIC FLOW SYSTEM AND NUMBER:

SOUTHERN BASIN AND RANGE HYDROGEOLOGIC REGION — 28 Southern basin and range hydrogeologic flow system and number
MIDDLE BASIN AND RANGE HYDROGEOLOGIC REGION — 29 Middle basin and range hydrogeologic flow system and number
NORTHERN BASIN AND AND RANGE HYDROGEOLOGIC REGION — 35 Northern basin and range hydrogeologic flow system and number

HYDROGEOLOGIC AREAS, HYDROGEOLOGIC FLOW SYSTEMS, AND HYDROGEOLOGIC REGIONS OF THE BASIN AND RANGE PHYSIOGRAPHIC PROVINCE, SOUTHWESTERN UNITED STATES

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