Case No. 84739

IN THE SUPREME COURT OF THE STATE OF NEVADA

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ADAM SULLIVAN, P.E., NEVADA STATE ENGINEER, et al.

Appellants,

vs.

LINCOLN COUNTY WATER DISTRICT, et al.

JOINT APPENDIX

VOLUME 26 OF 49

Prepared in cooperation with the National Park Service

Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona

By William R. Page, Daniel S. Scheirer, Victoria E. Langenheim, and Mary A. Berger

Open-File Report 2006–1040

Revised June, 2011

U.S. Department of the Interior
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona

By William R. Page, Daniel S. Scheirer, Victoria E. Langenheim, and Mary A. Berger

Abstract

This report presents revisions to parts of seven of the ten cross sections originally published in U.S. Geological Survey Open-File Report 2006–1040. The revisions were necessary to correct errors in some of the original cross sections, and to show new parts of several sections that were extended and (or) appended to the original section profiles. Revisions were made to cross sections *C–C'*, *D–D'*, *E–E'*, *F–F'*, *G–G'*, *I–I'*, and *J–J'*, and the parts of the sections revised or extended are highlighted below the sections on plate 1 by red brackets and the word "revised", or "extended." Sections not listed above, as well as the interpretive text and figures, are generally unchanged from the original report. Cross section *C–C'* includes revisions in the east Mormon Mountains in the east part of the section; *D–D'* includes revisions in the Mormon Mesa area in the east part of the section; *E–E'* includes revisions in the Muddy Mountains in the east part of the section; *F–F'* includes revisions from the Muddy Mountains to the south Virgin Mountains in the east part of the section; and *J–J*' includes some revisions from the east Mormon Mountains to the Virgin Mountains. The east end of *G–G'* was extended about 16 km from the Black Mountains to the southern Virgin Mountains, and the northern end of *I–I'* was extended about 45 km from the Muddy Mountains to the Mormon Mountains, and revisions were made in the Muddy Mountains part of the original section.

This report contains 10 interpretive cross sections and an integrated text describing the geology of parts of the Colorado, White River, and Death Valley regional groundwater flow systems in Nevada, Utah, and Arizona. The primary purpose of the report is to provide geologic framework data for input into a numerical groundwater model. Therefore, the stratigraphic and structural summaries are written in a hydrogeologic context.

The oldest rocks (basement) are Early Proterozoic metamorphic and intrusive crystalline rocks that are considered confining units because of their low permeability. Late Proterozoic to Lower Cambrian clastic units overlie the crystalline rocks and are also considered confining units within the regional flow systems. Above the clastic units are Middle Cambrian to Lower Permian carbonate rocks that are the primary aquifers in the flow systems. The Middle Cambrian to Lower Permian carbonate rocks are overlain by a sequence of mainly clastic rocks of late Paleozoic to Mesozoic age that are mostly considered confining units, but they may be permeable where faulted.

Tertiary volcanic and plutonic rocks are exposed in the northern and southern parts of the study area. In the Clover and Delamar Mountains, these rocks are highly deformed by north- and

northwest-striking normal and strike-slip faults that are probably important conduits in transmitting groundwater from the basins in the northern Colorado and White River flow systems to basins in the southern part of the flow systems.

The youngest rocks in the region are Tertiary to Quaternary basin-fill deposits. These rocks consist of middle to late Tertiary sediments consisting of limestone, conglomerate, sandstone, tuff, and gypsum, and younger Quaternary surficial units consisting of alluvium, colluvium, playa deposits, and eolian deposits. Basin-fill deposits are both aquifers and aquitards.

The rocks in the study area were complexly deformed by episodes of Mesozoic compression and Cenozoic extensional tectonism. Some Cretaceous thrust faults and folds of the Sevier orogenic belt form duplex zones and define areas of maximum thickness for the Paleozoic carbonate rocks. Cenozoic faults are important because they are the primary structures that control groundwater flow in the regional flow systems.

Introduction

The 10 geologic cross sections (pl. 1) were constructed to better understand the hydrogeologic framework for parts of the Colorado, White River, and Death Valley regional groundwater flow systems in southern Nevada, southwestern Utah, and northwestern Arizona. The main purpose of the cross sections is to provide the National Park Service with geologic framework data for input into a numerical groundwater model. Rapid urbanization and commercial development in the region has increased demand for water from surface-water sources and from local and regional aquifers in these flow systems. As a result, the geology in the area needs to be defined to assist in understanding the complex hydrologic processes that govern groundwater recharge, movement, storage, and discharge.

The study area includes part of the Colorado groundwater flow system (Harrill and Prudic, 1998), the southern part of the White River groundwater flow system (Eakin, 1964, 1966; Thomas and Welch, 1984; and Kirk, 1987), and the eastern part of the Death Valley groundwater flow system (Winograd and Thordarson, 1975; Laczniak and others, 1996; Harrill and Prudic, 1998; D’Agnese and others, 2002; Workman and others, 2002a, 2002b) (fig. 1). The White River flow system is a subset of the Colorado flow system (fig. 1).

The principal discharge for the White River flow system is Muddy River springs (Dettinger and others, 1995) (fig. 2), a series of springs that discharge 36,000 ac-ft/yr to form the Muddy River. Movement of groundwater in the study area is generally southward as indicated by potentiometric maps based on water levels in wells (Thomas and others, 1986; Wilson, 2001). The flow is driven by the hydraulic head parallel to the southward topographic gradient.

Aquifers in the flow systems consist of Paleozoic carbonate rocks, volcanic rocks, and basin-fill sediments (Plume and Carlton, 1988; Dettinger and others, 1995; Prudic and others, 1995; Burbey, 1997; Harrill and Prudic, 1998). The importance of the Paleozoic carbonate-rock aquifer to the flow systems that cover much of southern Nevada and adjacent States is so significant that many regional hydrologic reports have focused on the distribution and features of this aquifer (Dettinger and others, 1995; Burbey, 1997; Wilson, 2001).

Methods

The 10 interpretive cross sections (pl. 1, fig. 3) were hand drawn at 1:250,000-scale using Page and others (2005a) as a geologic base. Many of the units shown in the cross sections are combined from two or more units from the map. This generalization was necessary to portray stratigraphic relations appropriately for the cross section scale. Table 1 shows the relationship between the cross section bedrock units in this report and those in Page and others (2005a). The hand-drawn sections were scanned and converted to digital vector files. The topographic profiles were made using a 90 meter Digital Elevation Model. Most of the sections (*A–A′*, *B–B′*, *C–C′*, *D–D′*, *E–E′*, and *G–G′*) are oriented east-west (fig. 3), perpendicular to major structures in the study area. The east-west sections on plate 1 were hung on longitude 114°40'00" as a reference line (fig. 3) to visually extrapolate the geology between the section lines in a north-south progression.

A systematic unit color scheme was applied to the cross sections for a broad translation of geologic units into hydrostratigraphic units. Proterozoic and Lower Cambrian confining units are shades of brown and orange; Middle Cambrian to Lower Permian carbonate aquifer rocks in shades of blue; upper Paleozoic and Mesozoic confining units are shades of green; Cenozoic volcanic and intrusive rocks are shades of pink and red, respectively; and Tertiary to Quaternary basin-fill rocks are yellow.

The cross sections integrate data from existing maps and reports, geophysical investigations, and well data, and are progressively more interpretive with depth because of the lack of data at deeper levels. Page and others (2005a) provided a comprehensive list of geologic map sources and reports used in their compilation and in this study, and they presented detailed lithologic description and thickness of individual units in the map and cross section region. Data from several deep petroleum exploration wells were used to constrain thickness of basin-fill sediments and bedrock geology along several cross sections. These wells were tied into the cross section lines (fig. 3) and include the Texaco Federal #1 well (*C–C′*), Mobil Virgin River no. 1–A well (*D–D′*), and the Grace Petroleum Arrow Canyon #1 well (*G–G′*). Stratigraphic and structural data from these wells were from well logs and from Garside and others (1988).

The geology of the Virgin Valley area (*B–B′*, *C–C′*, and *D–D′*) was based on seismic-reflection and well data from Bohannon and others (1993), seismic-reflection data from Carpenter and Carpenter (1994), gravity data from Langenheim and others (2000), and magnetic data from Jachens and others (1998). Much of the subsurface geology in the Meadow Valley Wash (*A–A′*, *B–B′*, *C–C′*, and *D–D′*) and Tule Desert (*A–A′*) areas was based on seismic-reflection and gravity data acquired and analyzed by the USGS, and is summarized in Scheirer and others (2006). The subsurface geology in the central part of California Wash (*E–E′* and *F–F′*) was based on Langenheim and others (2001b, 2002). The subsurface geology of Coyote Spring Valley (*B–B′*, *C–C′*, *D–D′*, *E–E′*, and *F–F′*) was partly based on Phelps and others (2000). Cenozoic basin-fill thickness and geometry shown for basins in the western part of the study area (west of Coyote Spring Valley) is based on Blakely and Ponce (2001). Regional and detailed gravity data (fig. 4) were used to constrain Cenozoic basin geometry and depth to crystalline basement in much of the cross section area.

Stratigraphy

Proterozoic and Paleozoic Rocks

Early Proterozoic metamorphic and intrusive rocks consist of gneiss, granite, and schist that are about 1.7 Ga (Quigley and others, 2002). These crystalline rocks form both geologic and hydrologic basement and are considered barriers to groundwater flow because of their low permeability. The crystalline rocks may be locally permeable where highly fractured, but fractures in these rocks are generally poorly connected (D’Agnese and others, 1997). Early

Proterozoic rocks exposed in the Beaver Dam and Virgin Mountains form the eastern boundary of the flow systems (*A–A′*, *B–B′*, *C–C′*, *D–D′* and *E–E′*). Early Proterozoic rocks also form the core of the Mormon Mountains where they act as a local barrier to groundwater flow (Burbey, 1997) (*B–B′* and *C–C′*), although through-going, north-striking faults along the western and eastern Mormon Mountains may provide conduits for some southward groundwater flow through the mountain range.

A north-trending positive gravity anomaly extends from the Meadow Valley Mountains to the central Arrow Canyon Range (fig. 4). We interpret this gravity high to represent a zone of shallow Proterozoic crystalline rocks beneath parts of the Meadow Valley Mountains and Arrow Canyon Range (*C–C′*, *D–D′* and *E–E′*). Termination of the gravity anomaly south of the central Arrow Canyon Range may be due to the development of duplex zones and thicker Paleozoic rocks in the southern Arrow Canyon and Las Vegas Ranges shown along cross sections *F–F′* and *G–G′* (see Mesozoic Thrust Faults section below).

Late Proterozoic sedimentary rocks in the study area consist of quartzite, conglomerate, sandstone, siltstone, and shale, and they contain subordinate amounts of limestone and dolostone. The Late Proterozoic sedimentary rocks are well cemented, contain minimal pore space, and have low permeability. They were deposited in shallow marine waters along a passive continental margin of what is now western North America (Stewart, 1976; Stewart and Poole, 1972) and represent initial deposits of the Cordilleran miogeocline (Stewart and Poole, 1972; Stewart, 1972, 1976).

Lower Cambrian rocks are predominantly well-cemented, clastic units of quartzite, conglomerate, siltstone, and shale with low permeability. Together, the Lower Cambrian and Late Proterozoic sedimentary rocks form a confining unit in the study area. In the Death Valley groundwater flow system, these rocks are referred to as the lower clastic aquitard (Winograd and Thordarson, 1975), or the lower clastic confining unit (Belcher and others, 2002). These rocks are reported to be nearly impermeable and have low transmissivities based on pumping tests and other hydrologic data in the region (Winograd and Thordarson, 1975). Late Proterozoic clastic units are present mostly in the western part of the study area and they pinch out to the east and are absent in the Mormon, Virgin, and Beaver Dam Mountains, and in the Lake Mead area. In these areas, the lower clastic confining rocks include the Lower Cambrian Tapeats Sandstone and the Lower and Middle Cambrian Bright Angel Shale.

Middle Cambrian through Lower Permian rocks record a significant shift in deposition to predominantly carbonate sedimentation, from mostly clastic sedimentation in pre-Bonanza King (and equivalent units) Late Proterozoic and Cambrian units. The carbonate rocks are predominantly limestone and dolostone and form the regional aquifer (Dettinger and others, 1995). The Middle and Upper Cambrian Bonanza King Formation (and partly equivalent Highland Peak Formation and Muav Limestone) forms the basal part of the carbonate aquifer in the White River, Colorado, and Death Valley groundwater flow systems (Winograd and Thordarson, 1975; Laczniak and others, 1996; Belcher and others, 2002; D’Agnese and others, 2002). Groundwater flow through the carbonate rocks is mostly through fractures and faults. Because the rocks are soluble in groundwater, dissolution features are also important in the development of secondary porosity and permeability. Zones of high transmissivity in the carbonate rock aquifer are indicated by large spring discharge (36,000 ac-ft/yr at Muddy River Springs) in areas of low potentiometric gradient, and by water wells exhibiting extremely high hydraulic conductivity (Dettinger and others, 1995).

Middle Cambrian through Lower Permian rocks are predominantly carbonate with the exception of the Upper Cambrian Dunderberg Shale Member of the Nopah Formation (70 to 100 m thick), Middle Ordovician Eureka Quartzite (0 to 120 m), Upper Mississippian Chainman Shale (200 to 285 m), Upper Mississippian Indian Springs Formation (20 to 60 m), and the Lower Permian redbeds (600 m). The Dunderberg Shale Member, Eureka Quartzite, and Indian Springs Formation are probably not thick enough to form regional confining units, but they may act as confining units locally. The Chainman Shale and Lower Permian redbeds are substantially thicker and may be regional confining units in parts of the study area.

The upper part of the carbonate aquifer in the study area consists of Upper Mississippian and Lower Permian units, including the Bird Spring Formation and partly equivalent Callville Limestone and Pakoon Dolomite. Lower Permian redbeds overlie these formations and represent a shift from predominantly carbonate marine to mostly continental sedimentation, although a few carbonate units lie above the Lower Permian redbeds, including the Lower Permian Kaibab and Toroweap Formations, and the Lower Triassic Virgin Limestone Member of the Moenkopi Formation. Continental sedimentation predominated through the Mesozoic and into the lower Tertiary.

Late Proterozoic-Paleozoic Facies Belts

Late Proterozoic-Paleozoic rock units are separated geographically into facies belts even though they may be partly or entirely correlative. This is because facies changes prevent exact correlations between areas, and different names have been applied to rocks of the same age. In the study area, Late Proterozoic-Paleozoic rocks can be broadly subdivided into western, central, and eastern facies belts (Page and others, 2005a).

Rocks in the western belt include Late Proterozoic through Devonian units deposited as part of the Cordilleran miogeocline in offshore carbonate shelf and intertidal depositional settings, and an overlying Mississippian to Permian sequence deposited mostly in a carbonate platform depositional setting. These rocks are exposed as far east as the Las Vegas Range, Arrow Canyon Range, Meadow Valley Mountains, and Delamar Mountains (fig. 2). From oldest to youngest, these rocks include the following formations: Johnnie Formation (Late Proterozoic); Stirling Quartzite (Late Proterozoic) and Wood Canyon Formation (Late Proterozoic and Lower Cambrian) and their equivalent, the Prospect Mountain Quartzite; Carrara Formation (Lower and Middle Cambrian) and northern equivalents, Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), and Pioche Shale (Lower and Middle Cambrian); Bonanza King (Middle and Upper Cambrian) and partly equivalent Highland Peak Formation (Middle Cambrian); Nopah Formation (Upper Cambrian); Pogonip Group (Upper Cambrian to Middle Ordovician); Eureka Quartzite (Middle Ordovician); Ely Springs Dolomite (Upper Ordovician); Laketown Dolomite (Lower Silurian); Sevy Dolomite (Lower Devonian); Simonson Dolomite (Middle Devonian); Guilmette Formation (Middle and Upper Devonian) and the partly equivalent Sultan Limestone (Middle Devonian to Lower Mississippian); Monte Cristo Group (Lower and Upper Mississippian) and the partly equivalent Joana Limestone (Lower Mississippian); Chainman Shale (Lower and Upper Mississippian) and Scotty Wash Quartzite (Upper Mississippian); and Bird Spring Formation (Upper Mississippian to Lower Permian).

The eastern facies belt includes cratonic platform rocks of the Colorado Plateau region exposed in the Beaver Dam and Virgin Mountains, and in the Lake Mead area including Frenchman Mountain (table 1). The rocks are mostly shallow marine sediments deposited in near-shore, intertidal, shoreline, and continental settings. The facies belt is characterized by a large magnitude unconformity separating Middle Devonian from Upper Cambrian rocks. The cratonic sequence, or eastern facies belt, includes (from oldest to youngest): Tapeats Sandstone (Lower Cambrian); Bright Angel Shale (Lower and Middle Cambrian); Muav Limestone (Middle Cambrian); Nopah Formation (Upper Cambrian); Temple Butte Formation (Middle? and Upper Devonian); Redwall Limestone (Lower and Upper Mississippian); and Callville Limestone (Pennsylvanian) and Pakoon Dolomite (Lower Permian). The central facies belt includes rocks that are transitional between the eastern and western belts; these rocks are exposed in the Muddy Mountains, Mormon Mountains, and Tule Springs Hills (fig. 2).

The thickness of Middle Cambrian to Lower Permian carbonate rocks that form the regional aquifer decreases dramatically across the belts from west to east over a distance of about 100 km; from a maximum of about 7 km thick in the western belt to less than 2 km thick in the eastern belt. Whereas thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton, the greatest thickness variation across the belts is because the Paleozoic rocks were telescoped into a narrower zone during Mesozoic thrusting.

Mesozoic Rocks

Mesozoic rocks are predominantly continental clastic units consisting of conglomerate, sandstone, siltstone, mudstone, shale, and gypsum, but they also include minor limestone and dolostone. These rocks are exposed mostly in the eastern parts of the study area and were deposited in fluvial, lacustrine, eolian, and marginal marine environments, and they include Triassic, Jurassic, and Cretaceous units. The Mesozoic rocks have low permeability compared with the Paleozoic carbonate rocks because of their high proportion of clastic material. They are generally considered confining units, but they may be permeable where highly fractured. Units containing large amounts of shale and mudstone, such as in the Triassic formations, generally have low permeability. The Jurassic Navajo Sandstone in the Utah part of the study area is an aquifer (Heilweil and others, 2002), but in other parts of southern Nevada, such as in Las Vegas Valley, the Jurassic Aztec Sandstone generally has low permeability. This example illustrates the variability in hydrologic properties of the Mesozoic rocks.

Tertiary-Quaternary Rocks

Tertiary and Quaternary rocks in the cross sections are mostly basin-fill deposits, which consist of alluvium and colluvium, playa deposits, eolian deposits, spring discharge deposits, and landslide breccias of Miocene to Holocene age. Older basin-fill rocks include the Miocene and Pliocene Muddy Creek Formation and equivalent units in the Lake Mead area, and the Oligocene and Miocene Horse Spring Formation and equivalent units. The Muddy Creek Formation is mostly lacustrine and fluvial mudstone, tuffaceous sandstone, gypsum, halite, and conglomerate. The Horse Spring Formation consists of fluvial and lacustrine rocks, comprised of tuffaceous sandstone, tuff, conglomerate, siltstone, mudstone, limestone, and gypsum.

Basin-fill rocks in the study area are both aquifers and aquitards. Basin-fill deposits in the Mesquite basin of the Virgin Valley reach maximum thicknesses of about 8 to 10 km (Langenheim and others, 2001a, 2000). In the Mesquite, Nev., area, the Muddy Creek Formation is the main aquifer (Johnson and others, 2002; Dixon and Katzer, 2002), where it consists of gravel, sand, silt, and clay, and is moderately deformed by high-angle normal faults.

Dettinger and others (1995) hypothesized that Muddy River Springs partly exist due to thick basin deposits of lower Meadow Valley Wash basin which may form a groundwater barrier to eastward flow from the springs (see cross section *D–D')*. The Muddy Creek Formation is widely exposed in this basin, and unlike the Muddy Creek in the Virgin Valley area, the formation is mildly deformed and is mostly low-permeability lacustrine clay and silt.

Unit Tv in the cross sections includes volcanic rocks of Oligocene to Pliocene age. Most of the volcanic rocks are ash-flow tuffs erupted from calderas, but stratovolcanoes were locally present. These rocks also include basalt and lava flows. In the Delamar and Clover Mountains, the volcanic rocks range from several hundred to several thousand meters thick. Intracaldera tuffs are generally thicker than outflow tuffs. Unit Ti consists of granitic intrusive rocks that generally are the source plutons for the volcanic units in unit Tv.

Structural Geology

The physiography of the study area reflects late Mesozoic and Cenozoic structural events that produced a Cretaceous fold-and-thrust belt that was subsequently disrupted by Cenozoic extensional and transform tectonics, and accompanying intrusive and volcanic activity.

Mesozoic Thrust Faults

Major thrust faults in the study area include the Muddy Mountain and Gass Peak thrusts. The Muddy Mountain thrust is exposed in the Muddy Mountains; several equivalent thrusts extend northward (Hintze and Axen, 2001) including: the Glendale thrust in the Glendale, Nev., area; Mormon thrust in the Mormon Mountains; Tule Spring thrust in the Tule Springs Hills, Nevada; and the Square Top Mountain thrust in the northern Beaver Dam Mountains in southwest Utah (fig. 5).

The Gass Peak thrust (Guth, 1980, 1981, 1990) in the Sheep Range is west of and at a structurally higher level than the Muddy Mountain and equivalent thrusts (fig. 5). The thrust faults strike north to northeast and are east to southeast vergent structures of Sevier orogenic belt (Armstrong, 1968; Fleck, 1970). The Muddy Mountain and equivalent thrusts are the frontal thrusts of the Sevier orogenic belt in southern Nevada and southwestern Utah. The Muddy Mountain thrust is reported to be late Albian to Cenomanian(?) in age (Bohannon, 1983; Carpenter and Carpenter, 1994; Fleck and Carr, 1990). Several intermediate thrusts are between the Muddy Mountain (and equivalent thrusts) and Gass Peak thrusts. These include the Delamar thrust in the southern Delamar Mountains (*B–B'*) (Page, 1990), the Meadow Valley and Vigo thrusts in the Meadow Valley Mountains (*B–B'*) (Pampeyan, 1993), and the Dry Lake thrust and other unnamed thrusts in the Arrow Canyon and Dry Lake Ranges (*D–D'*, *F–F'*, and *G–G'*) (Page, 1992; Page and Dixon, 1992). The Summit Willow Tank thrust is a secondary thrust fault below the Muddy Mountain thrust in the Muddy Mountains (*E–E'* and *F–F'*) (Bohannon, 1983).

A commonly accepted model for thrusts in the Sevier belt, which we have conceptually applied to the cross sections, is that of a ramp-flat, decollemont geometry, where thrusts are flat at depth along a basal decollement and detach to ramp at certain stratigraphic levels. We follow Guth (1980) in the interpretation of a flat-ramp-flat geometry for the Gass Peak thrust with decollement zones near the base of the Late Proterozoic-Lower Cambrian sequence (Guth, 1980; fig. 1, case 1, p. 151). East of the Gass Peak thrust, the regional decollement forms an extensive hanging-wall flat near the base of the Middle and Upper Cambrian Bonanza King Formation as indicated by exposure of these rocks at the base of hanging-wall ramps and flats in the Muddy Mountain (*E–E'*, *F–F'*, and *G–G'*), Mormon (*B–B'* and *C–C'*), Tule Spring (*A–A'*), and Delamar (*B–B'*) thrust faults. The eastward transition to a decollement at the base of the Bonanza King Formation is probably controlled by the west to east pinch out of the Late Proterozoic clastic units against the craton (Sweetkind and others, 2001); the pinch out is in a zone between the

Sheep Range and the Arrow Canyon Range/Meadow Valley Mountains because Late Proterozoic rocks at the base of the sedimentary sequence are absent in the Mormon Mountains and Tule Springs Hills, and rocks of the Middle and Lower Cambrian Bright Angel Shale and Lower Cambrian Tapeats Sandstone rest directly on Early Proterozoic crystalline basement.

Duplex zones in the Paleozoic carbonate rocks are interpreted along the Dry Lake and Muddy Mountain thrusts (*F–F′* and *G–G′*). These duplex zones define areas of maximum thickness for the Paleozoic carbonate rocks in the region because the Paleozoic section is essentially repeated along the thrusts. In cross section *G–G′*, these rocks are interpreted to be greater than 7 km thick based on logs from the Grace Petroleum Arrow Canyon no. 1 well. In this well, an upper thrust fault is interpreted at about 2,288 m depth where rocks of the Cambrian Carrara Formation are in the upper plate above rocks of the Cambrian Bonanza King Formation in the lower plate. A lower thrust fault occurs at about 2,800 m depth where rocks of the Bonanza King Formation in the upper plate are above rocks of the Mississippian-Permian Bird Spring Formation in the lower plate, thus repeating the Paleozoic section from the Bird Spring Formation downward. We interpret the upper fault as the Dry Lake thrust and the lower fault as the Muddy Mountain thrust (*G–G′*). The zone between the two faults is characterized by complexly repeated Cambrian units indicating horst blocks and (or) imbrication structures, features commonly associated with thrust fault zones.

Burbey (1997) suggested that Late Proterozoic-Lower Cambrian clastic confining units in the upper plate of the Gass Peak thrust may restrict eastward groundwater flow from the Sheep Range and areas to the west. The upper plate confining units are thrust over Mississippian to Permian rocks of the Bird Spring Formation in the lower plate as shown in cross sections *F–F′* and *G–G′*. North of *F–F′*, however, the Gass Peak thrust loses throw and juxtaposes mainly Paleozoic carbonate rocks in upper and lower plates (*B–B′*).

The Muddy Mountain thrust in the Muddy Mountains juxtaposes Paleozoic carbonate rocks in the upper plate against Mesozoic and Paleozoic rocks in the lower plate (*G–G′*); such a relationship suggests that the less permeable Mesozoic rocks below the thrust may act as a groundwater flow barrier, and the thrust has been characterized as a barrier in local groundwater models. Although the lower plate rocks may act as a barrier in localized zones along strike, we think that overprinting of the thrust by Cenozoic faults (Langenheim and others, 2002) provides linkage between rocks in the upper and lower plates, allowing for some groundwater flow across the thrust. This example may apply to other Mesozoic thrust faults in the map area, especially where the thrusts are highly modified by younger Cenozoic extensional faults.

Mesozoic thrusts have been reactivated by normal faults during Cenozoic extension in parts of the study area. The Delamar thrust has been reactivated by high-angle normal faults in the southern Delamar Mountains (Page, 1990). Guth (1990) reported that parts of the Gass Peak thrust may have been reactivated by Cenozoic normal faults, and structural relations illustrated in cross section *B–B′* suggest extensional Cenozoic reactivation on the thrust based on Tertiary volcanic rocks downfaulted on the thrust in the northern Sheep Range. Axen and others (1990) discussed extensional Cenozoic reactivation of the Tule Spring thrust in the Tule Springs Hills.

Cenozoic Magmatism, Strike-slip Faults, Normal Faults, and Basin Development

Cenozoic tectonics affected the rocks in the study area and includes volcanism and plutonism, normal and strike-slip faulting, and basin development. Cenozoic faults are important because they represent the last major phase of deformation that affected the rocks in the region, and they provide the fractures and faults that control groundwater flow through the Paleozoic carbonate aquifer. Quaternary faults are present in parts of the study area, and faulting is currently active in some areas such as in the Pahranagat shear zone. These younger faults may be especially important in groundwater flow because younger faults and fractures tend to be more open than in older fault systems (Dettinger and others, 1995), and in many cases, they have reactivated older fault zones.

Magmatism

The northern part of the study area is characterized by numerous Oligocene and Miocene volcanic rocks, mainly ash-flow tuffs erupted from calderas, but also some lava flows and granitic plutons. The southern limit of these rocks occurs at about latitude 37^{o}, just north of the Mormon Mountains and Tule Springs Hills, and the negative isostatic gravity anomalies in the northern part of figure 4 reflect low-density volcanic rocks in the Clover Mountains (Scheirer and others, 2006). Volcanic rocks are also exposed in the southeast part of the study area in the southern Virgin Mountains, Black Mountains, and Lake Mead area. These rocks include Miocene andesitic volcanic rocks and calc-alkaline plutons.

The volcanic rocks in the northern part of the study area were erupted mainly from the Caliente caldera complex (Rowley and others, 1995) in the Delamar and Clover Mountains, and the Kane Wash caldera complex (Scott and others, 1995) in the Delamar and Meadow Valley Mountains (fig. 5). The Caliente caldera complex in the Clover Mountains is highly deformed by north- and northwest-striking normal and strike-slip faults (Page and others, 2005a) that may be important conduits in transmitting ground water from basins in the northern part of the Colorado flow system to basins in the southern part of the flow system.

Strike-slip Faults, Normal Faults, and Basin Development

Major strike-slip fault zones include the northeast-striking, left-lateral Pahranagat shear zone, Kane Springs Wash fault zone, and Lake Mead fault zone, and the northwest-striking, right-lateral Las Vegas Valley shear zone (fig. 5). These fault zones represent transfer or accommodation zones that separate structural blocks within the study area that have undergone different rates and amounts of extension (Guth, 1981; Wernicke and others, 1982; Duebendorfer and Black, 1992; Rowley, 1998). Strike-slip faults are denoted on the cross sections with the letters “T” and “A”, indicating relative fault block movement toward or away from the viewer, respectively (see plate symbol explanation).

The Pahranagat shear system is a zone of steeply northwest-dipping faults that shows evidence of dip-slip and strike-slip offset (fig. 5). Tschanz and Pampeyan (1970) estimated about 6 to 9 km of left-lateral displacement on the shear system. Modern fault scarps and fissures in alluvial deposits in southern Delamar Valley (Swadley, 1995), and current seismicity on faults in the shear system (Rogers and others, 1987) indicate that it is active. Strands of the Pahranagat shear system join together and merge with north-striking range front faults bounding the northern Delamar Mountains to the north, and the southern Delamar Mountains and the Sheep Range to the south (Page and others, 2005a). Cross section *B–B′* transects the southern part of the shear zone, and displays a series of closely-spaced, northwest-dipping faults offsetting primarily Late Proterozoic and Paleozoic rocks. The volcanic rocks in *B–B′* are thin near the southern limit of their exposure, but they thicken to the north within the shear zone (Page and others, 2005a).

The Kane Springs Wash fault zone (fig. 5) is a left-lateral fault system that has about 7 to 11 km of displacement based on offset of the Kane Springs Wash caldera (Harding and others, 1995). Northeast-striking faults of the Kane Springs Wash fault zone merge into the north-striking range front fault system on the west side of the Meadow Valley Mountains. In cross section *A–A′*, the Kane Springs Wash fault zone is 3 km wide and cuts mainly volcanic and plutonic rocks of the Kane Wash caldera complex. Southward (*B–B′*), the fault zone is about 5 km wide and cuts mainly Paleozoic carbonate rocks. Early Proterozoic crystalline rocks are interpreted to be present at shallow depths (less than 4 km) near where the fault zone intersects *B–B′*, based on surface exposure of older Paleozoic rocks (Cambrian) and on regional gravity data (fig. 4). Quaternary faulting has been reported along some strands of the Kane Springs Wash fault zone in Kane Springs Wash (Swadley and others, 1994).

The northwest-striking Las Vegas Valley shear zone (LVVSZ) (fig. 5) is a large-magnitude, right-lateral, strike-slip fault zone that formed during Cenozoic extension (Page and others, 2005b). The shear zone truncates the southern Las Vegas, Sheep, Desert, and Pintwater Ranges, and extends for nearly 150 km from the Lake Mead area to Mercury, Nevada. The LVVSZ played a significant role in the tectonic development of Las Vegas Valley (Page and others, 2005b). The effects of the LVVSZ include oroflexural bending and offset of major Mesozoic thrust faults and folds. Offset of Mesozoic thrust faults across Las Vegas Valley indicate 48 ± 7 km of right-lateral separation (Wernicke and others, 1988); this estimate includes bending of the Las Vegas Range. Paleomagnetic data (Sonder and others, 1994; Nelson and Jones, 1987) indicated a 20-km-wide zone of clockwise rotation as great as 100° in rocks as young as 13.5 Ma adjacent to the LVVSZ. The paleomagnetic data, along with other structural data, bracket the principal period of movement along the LVVSZ between 14 and 8.5 Ma (Duebendorfer and Black, 1992; Duebendorfer and Simpson, 1994).

Two strands of the LVVSZ are shown in *H–H′* in the Frenchman Mountain area. The northern strand is concealed by basin-fill sediments between the Dry Lake Range and Frenchman Mountain, and it is shown as a north-dipping fault that juxtaposes a thick section of Paleozoic rocks in the hanging wall against Proterozoic crystalline rocks beneath Frenchman Mountain in the footwall. The southern strand of the LVVSZ juxtaposes cratonic Paleozoic rocks of Frenchman Mountain in the footwall of the fault against presumably thicker, cratonic margin Paleozoic rocks and Tertiary volcanic rocks concealed beneath basin-fill deposits in the hanging wall.

The Lake Mead fault zone (LMFZ) (fig. 5) is a major northeast-striking, left-lateral fault system consisting of about four major fault strands that form a crustal boundary separating the Great Basin to the north from the lower Colorado extensional corridor to the south (Anderson, 1973; Anderson and others, 1994; Bohannon, 1983). The major strands of the fault zone bound structural blocks which have undergone large lateral translations. For example, the Frenchman Mountain block is interpreted to have been displaced 65 km southwestward during Miocene extension (Anderson and others, 1994). Rocks in the lower Colorado extensional corridor (Faulds and others, 2001) consist largely of Proterozoic crystalline rocks, and Tertiary volcanic and plutonic rocks. Paleozoic and Mesozoic rocks are present in isolated blocks on the flanks of crystalline basement uplifts (see east end of *F–F′*). Faults of the LMFZ are shown in the eastern parts of cross sections *F–F′* and *G–G′*. *F–F′* shows the LMFZ juxtaposing Mesozoic and Paleozoic rocks of the Muddy Mountains in the hanging wall against shallow Proterozoic crystalline rocks in the footwall in the South Virgin Mountains. *G–G′* shows near-vertical strands of the LMFZ juxtaposing Paleozoic and Mesozoic rocks in the Muddy Mountains against Proterozoic crystalline rocks and Tertiary volcanic and plutonic rocks in the Lower Colorado extensional corridor.

Strike-slip faults are reported in the Tule Springs Hills and East Mormon Mountains (Anderson and Barnhard, 1993; Hintze and Axen, 2001; Axen and others, 1990). The East Tule

Desert fault (fig. 5) is a left-lateral, strike-slip fault that bounds the west flank of the Tule Springs Hills. In cross section *A–A′* Paleozoic and Mesozoic rocks of the Tule Spring autochthon are offset along the fault, and the downthrown side forms Tule Desert, a shallow basin with less than 500 m of Cenozoic basin-fill deposits (Scheirer and others, 2006). The Sams Camp and Carp Road faults (fig. 5) are probably equivalent to the East Tule Desert fault, and extend farther south along the East Mormon Mountains. These faults juxtapose Paleozoic rocks in the hanging wall against a footwall horst cored by Proterozoic crystalline rocks (*B–B′*). At the south end of the East Mormon Mountains, the Carp Road fault bends southwestward where it merges with the Davidson Peak fault, an east-striking transverse zone composed of highly folded Paleozoic and Mesozoic rocks (fig. 5), and then bends south to bound the west flank of the southern Mormon Mountains (along Candy Peak; *D–D′*; fig. 2). Anderson and Barnhard (1993) interpreted that the large sinistral displacements along these strike-slip faults are kinematically linked to major uplifts and depressions in the Mormon Mountain area that formed during Miocene extension. Alternatively, Axen and others (1990) interpreted that these faults are kinematically linked to the large-magnitude Cenozoic extension on the Tule Spring and Mormon Peak detachment faults (see below).

Locally before 10 Ma, normal block-faulting created north-trending ranges and basins to form the present-day physiography that characterizes the Basin and Range province. These faults, which define the Pintwater, Desert, Sheep, and Arrow Canyon Ranges, and Delamar and Meadow Valley Mountains (fig. 5), are especially prominent in the western part of the study area. These range-bounding faults are predominantly normal faults, but some of them have an oblique-slip component, especially along their margins with transverse structures such as the Las Vegas Valley shear zone and the Pahranagat shear zone. The range-front fault on the west side of the Desert Range juxtaposes Late Proterozoic-Lower Cambrian confining units and overlying Lower Cambrian to Devonian carbonate units in the hanging wall against shallow Proterozoic crystalline and overlying Late Proterozoic confining units in the footwall (*C–C′* and *D–D′*).

The range front fault zone along the west flank of the Sheep Range is characterized by westward tilted blocks of Late Proterozoic and Paleozoic units along a series of west-dipping normal faults extending to the Desert Range (*C–C′*, *D–D’*, and *G-G′*). Guth (1981) estimated 44 percent extension across this area based on restoration of rotated beds in the fault blocks. Faults in this region are interpreted to have a listric geometry to account for tilting, and Wernicke and others (1988) suggested that these faults may sole into a deep regional detachment fault of uncertain depth. Guth (1981) discussed the possibility that a regional detachment may merge with the Mesozoic thrust systems, but we interpret that the normal faults offset the thrusts at depth (rather than merging with them) to produce an irregular basement-sedimentary rock interface.

Range front faults on the west flanks of the southern Delamar Mountains, Meadow Valley Mountains, and Arrow Canyon Range were important in the development of Coyote Spring Valley (*B–B′*, *C–C′*, *D–D′*, and *F–F′*). In general, these fault systems consist of a series of steep, west-dipping normal faults that down-drop Paleozoic strata westward in a step-like pattern (Page, 1998; Page and others, 1990; Page and Pampeyan, 1996). Displacement on individual faults is generally less than 1 km, and cumulative displacements may be as much as 2 km (Page, 1998; Page and others, 1990). Phelps and others (2000) interpreted the subsurface location of some of these faults based on gravity data. Their study also indicates that Cenozoic basin-fill deposits probably reach a maximum thickness of about 1 to 1.5 km in Coyote Spring Valley.

A prominent high-angle normal fault on the west side of the Mormon Mountains is referred to here as the Meadow Valley Wash (MVW) fault (fig. 5). The fault structurally controls Meadow Valley Wash and probably was important in accommodating Miocene uplift of the Mormon Mountains (also see *B–B′* and *C–C′*). Along *A–A′* the fault juxtaposes Paleozoic and Mesozoic rocks of the Tule Spring autochthon in the footwall against Cenozoic basin-fill deposits and underlying Paleozoic rocks of the Tule Spring allochthon in the hanging wall. *B–B′* and *C–C′* show the MVW fault juxtaposing a thick sequence of Paleozoic rocks of the Mormon thrust allochthon in the hanging wall against Proterozoic crystalline rocks in the footwall. South of *C–C′*, the nature of the MVW fault is unknown, although we interpret it to merge with the system of strike-slip faults on the west flank of the southern Mormon Mountains to form the east boundary of lower Meadow Valley Wash basin. Seismic-reflection data (Scheirer and others, 2006) in the northern part of Meadow Valley Wash (in the area of *A–A′*) suggest the MVW fault is a high-angle normal fault.

The MVW fault may be a conduit for north-south groundwater flow beneath Meadow Valley Wash, but the upthrown block of Proterozoic crystalline confining units in the Mormon Mountains probably forms a barrier to eastward groundwater flow across the mountain range. Abundant paleo-spring carbonate deposits fill faults and fractures in bedrock units on the east and south flanks of the Meadow Valley Mountains and in Tertiary basin-fill sediments in Meadow Valley Wash (Page and Pampeyan, 1996; Schmidt, 1994; Schmidt and Dixon, 1995). These spring carbonate features are indicative of groundwater discharge and the existence of a past groundwater flow path through the thick sequence of Paleozoic carbonate rocks concealed beneath the eastern Meadow Valley Mountains and Meadow Valley Wash.

Seismic-reflection and gravity data (Scheirer and others, 2006) indicate that Meadow Valley Wash is partitioned into a series of fault-controlled basins. The deepest basin is between Moapa and Rox, Nev., (figs. 2 and 4). Cenozoic basin-fill deposits in the basin may be 2 to 3 km thick in the central part of the basin, and they are complexly deformed by folds and faults. Basin-fill surface exposures in this area are also complexly deformed. The Permian Kaibab Limestone crops out near Rox (*C–C′*), indicating a bedrock ridge constricts Meadow Valley Wash and bounds a shallower basin to the north. A drill hole in the northern basin (just north of Rox) bottomed out in basin-fill deposits at 730 m, and seismic-reflection data suggest Cenozoic basin-fill deposits may be up to 1 km thick (Scheirer and others, 2006). The northernmost basin of Meadow Valley Wash is between Carp and Leith (fig. 2). Cenozoic basin-fill deposits are interpreted to be 1 to 2 km thick in this basin (Scheirer and others, 2006), and the main basin structure is controlled by the MVW fault.

Wernicke and others (1985) and Axen and others (1990) interpreted that three stacked, west-dipping, low-angle normal (detachment) faults (Mormon Peak, Tule Springs, and Castle Cliff detachments) between the Meadow Valley Mountains and the Beaver Dam Mountains are the first order Cenozoic extensional structures in the region. Axen and others (1990) interpreted the Castle Cliff detachment as the lowest-level fault that projects westward in the subsurface beneath Tule Springs Hills as a continuation of the Castle Cliff fault exposed on the west flank of the Beaver Dam Mountains. The Tule Springs detachment is the intermediate fault interpreted by Axen and others (1990) as a breakaway zone on the west flank of the East Mormon Mountains to project westward below the main part of the Mormon Mountains. Wernicke and others (1985) interpreted the Mormon Peak detachment as the highest-level fault exposed in the Mormon Mountains to project westward beneath the Meadow Valley Mountains. Wernicke and others (1985) and Axen and others (1990) interpreted these as large-magnitude extensional faults that root into crystalline basement and were activated from west to east by processes of simple uniform shear.

Anderson and Barnhard (1993) noted low-angle normal faults in the area but on the basis of fault kinemetics and careful geologic mapping, they challenged the idea that these detachments had large lateral extent, and, alternatively, they viewed detachments as localized structures that accommodated strain associated with extreme vertical uplift. Carpenter and Carpenter (1994) also downplayed the role of detachments as first order Cenozoic extensional structures on the basis of seismic-reflection data and geologic mapping, and they reinterpreted many of the detachments in the Mormon Mountains as localized gravity-slide slip-surfaces. The cross sections in this report are conceptually in agreement with Anderson and Barnhard (1993) and Carpenter and Carpenter (1994), and portray detachments as more localized structures and high-angle normal and strike-slip faults as the first order extensional structures in this region.

The Piedmont fault (fig. 5) is the major fault bounding the west flanks of the Beaver Dam and Virgin Mountains (Bohannon and others, 1993), and it forms the boundary between the Colorado Plateau and Basin and Range provinces (*A–A′*, *B–B′*, *C–C′*). In most areas, the fault juxtaposes an east-tilted section of Paleozoic and Mesozoic rocks overlain by thick Tertiary-Quaternary basin-fill deposits in the hanging wall against Proterozoic crystalline rocks in the footwall (*B–B′*, and *C–C′*). The fault is estimated to have about 12 km of normal separation (Bohannon and others, 1993) and was most active from 13 to 10 Ma (Quigley and others, 2002). Quigley and others (2002) suggested that Cenozoic uplift in the Virgin-Beaver Dam Mountains along the Piedmont fault may have been controlled by older Proterozoic shear zones along a former accretionary crustal boundary. Carpenter and Carpenter (1994) reported the southern end of the fault, south of Mesquite (fig. 1), to have a left-lateral component as illustrated in sections *D–D′*, *E–E′*, and *J–J′*.

Virgin Valley is segmented into two deep northeast-trending basins (fig. 4), the Mormon basin to the southwest and the Mesquite basin to the northeast (Bohannon and others, 1993; Langenheim and others, 2000, 2001a). The basins formed by subsidence caused by Miocene extension mainly along the Piedmont fault. Cenozoic basin-fill deposits in the Mesquite basin are estimated to have maximum thicknesses of about 8 to 10 km, with the deepest part of the basin beneath the Littlefield, Ariz., area (Langenheim and others, 2000, 2001a) (fig. 2). Cross sections *B–B′* and *C–C′* extend across the Mesquite basin and show an east-dipping sequence of deformed Paleozoic and Mesozoic rocks overlain by moderately deformed Cenozoic basin-fill rocks. The subsurface stratigraphy and structure portrayed in the cross sections are derived mostly from seismic-reflection data from Bohannon and others (1993) and Carpenter and Carpenter (1994), and gravity data from Langenheim and others (2000, 2001a). Cross sections *D–D′* and *E–E′* extend across the Mormon basin where Cenozoic basin-fill deposits reach maximum thicknesses of 5 to 6 km. The subsurface stratigraphy and structure portrayed in the cross sections in the Mormon basin is mostly from seismic-reflection data from Bohannon and others (1993), gravity data from Langenheim and others (2000, 2001a), and the Mobil Virgin River no. 1–A deep petroleum test well on Mormon Mesa. The Mobil well encountered the base of Cenozoic basin fill at about 2 km, and the well bottomed out in Proterozoic crystalline rocks at about 5.9 km depth (Bohannon and others, 1993).

Muddy River Springs (fig. 2 and *D–D′*) are structurally controlled by a broad north-striking fault zone that forms the east range front of the southern Meadow Valley Mountains and Arrow Canyon Range (Schmidt and Dixon, 1995; Schmidt and others, 1996; Page and others, 2005a). The fault zone is informally referred to here as the east Arrow Canyon Range fault zone (fig. 5). Faults in the fault zone are exposed in the Paleozoic carbonate rocks on the east flanks of the Meadow Valley Mountains (Schmidt, 1994) and Arrow Canyon Range (Page, 1992; Schmidt and others, 1996), and in the Cenozoic basin-fill deposits in lower Meadow Valley and California Wash. East-striking faults intersect the north-striking faults (Schmidt and others, 1996; Schmidt, 1994; Page and others, 2005) and potentially enhance permeability. Seismic-reflection data (Scheirer and others, 2006) indicate an east-trending buried bedrock ridge separates lower Meadow Valley Wash basin from California Wash basin (fig. 4). The ridge is structurally controlled by east-striking faults (Scheirer and others, 2006), and it connects the Paleozoic carbonate rocks in the subsurface between the Arrow Canyon Range and Muddy Mountains. Near Ute (fig. 2), along the east flank of the Arrow Canyon Range, spring carbonate mounds represent past spring discharge from the fault zone (Schmidt and Dixon, 1995). Quaternary faults are exposed in this area, which may have increased permeability in the fault zone.

Cenozoic basin-fill deposits in California Wash basin are estimated to be 2 to 3 km deep based on gravity and seismic-reflection data (Langenheim and others, 2001b, 2002). The basin is bounded by the California Wash fault zone, a zone of west-dipping normal faults on the west flank of the Muddy Mountains (*E–E′*, *F–F′*, and *G–G′*). Bidgoli and others (2003) reported Quaternary faulting in the fault zone.

The Rogers Spring fault is located on the southeast side of the Muddy Mountains where it bounds a moderately deep basin in the Lake Mead Overton Arm area (fig. 5, *F–F′*); Cenozoic basin-fill deposits are 2 to 3 km thick in the Overton Arm basin. The fault dips from 60° to 70° southeast and juxtaposes Paleozoic carbonate rocks of the Muddy Mountain thrust allochthon against deformed Tertiary basin-fill deposits that overlie autochthonous Mesozoic rocks (*F–F′*). Bohannon (1983) interpreted the fault as a normal fault, but he reported local evidence of strike-slip displacement suggesting multiple stages of movement. We agree with Bohannon’s interpretation of strike-slip and normal movement on the fault, but a reverse component of displacement is also indicated because the Paleozoic allochthon of the Muddy Mountain thrust on the northwest side of the fault is presumably downdropped against autochthonous Mesozoic rocks on the southeast side (*F–F′*) based on exposure of the Jurassic Aztec Sandstone farther to the southwest along the fault. Rogers and Blue Point Springs are probably both structurally controlled by the Rogers Spring fault, and warm water discharging from the springs (85°–86° F) suggests a relatively deep source. The springs may exist partly due to juxtaposition of the Paleozoic-Mesozoic sequence in the fault footwall against Early Proterozoic crystalline rocks in the hanging wall, and the presence of thick basin-fill sediments containing impermeable evaporate deposits in the fault hanging wall (Laney and Bales, 1996).

Summary

The oldest rocks in the study area are Early Proterozoic crystalline rocks. These rocks form basement and are confining units in the regional groundwater flow systems. Late Proterozoic to Lower Cambrian rocks are predominantly clastic rocks and are also considered confining units in the region.

Above the Late Proterozoic to Lower Cambrian clastic rocks are Middle Cambrian to Lower Permian units that are predominantly carbonate rocks, and they form the main aquifer in the regional groundwater flow systems. The Paleozoic carbonate rocks thin from west to east in the study area, from as much as 7 km in the western part to less than 2 km in the eastern part.

Much of the thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton.

Above the Paleozoic carbonate rocks are mainly clastic units of late Paleozoic to Mesozoic age that are generally considered confining units in the flow systems, but they may be permeable where fractured. Tertiary volcanic and plutonic rocks are exposed in the extreme northern and southern parts of the study area and may be aquifers where they are highly faulted, such as in the Delamar and Clover Mountains. Basin-fill deposits consist of middle to late Tertiary sediments of variable lithologies, and younger Quaternary surficial units consisting mainly of alluvium. Basin-fill sediments are both aquifers and aquitards in the region.

Movement of groundwater through the aquifers is through fractures and faults, and through solution channels formed in the carbonate rocks. The rocks in the area were complexly deformed by episodes of Mesozoic compression and Cenozoic extension. Cretaceous thrust faults and folds in the area formed during the Sevier orogeny. Duplex zones along some of the thrust faults resulted in structural thickening and define areas of maximum thickness of the Paleozoic carbonate rocks.

Cenozoic extensional tectonics affected the rocks in the region and included normal and strike-slip faulting, volcanism, and plutonism. Cenozoic faults are significant because they are the primary structures that control groundwater flow in the regional groundwater flow systems.

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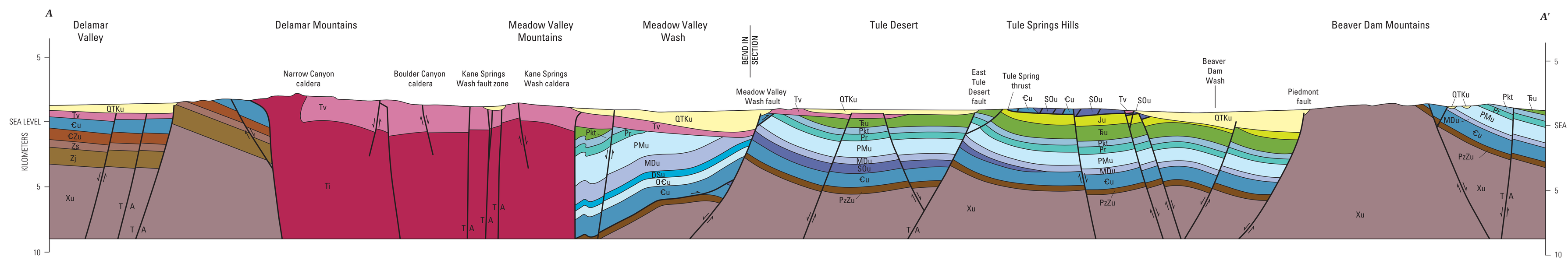
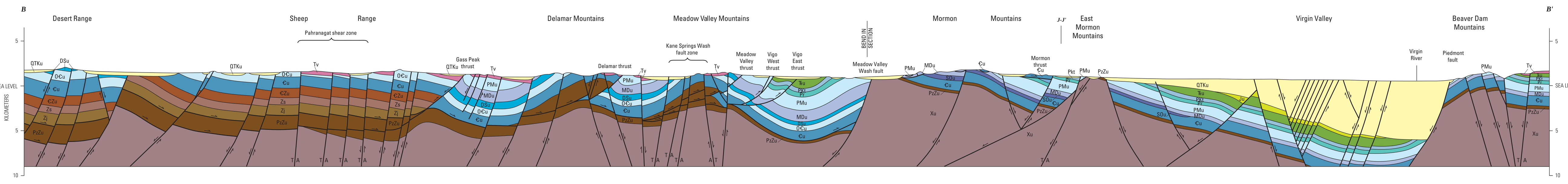
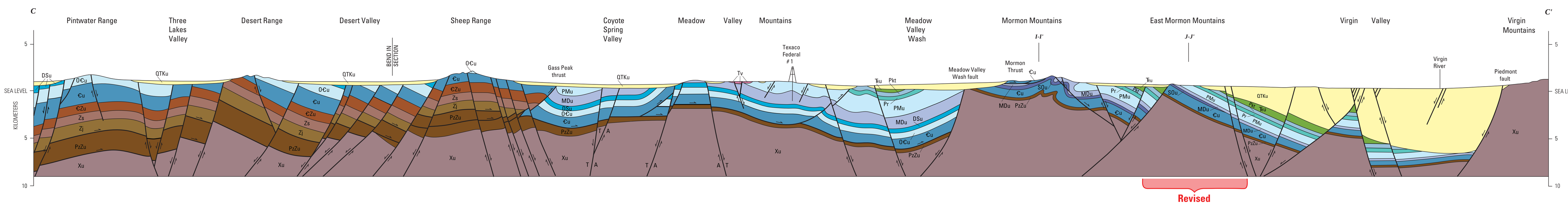
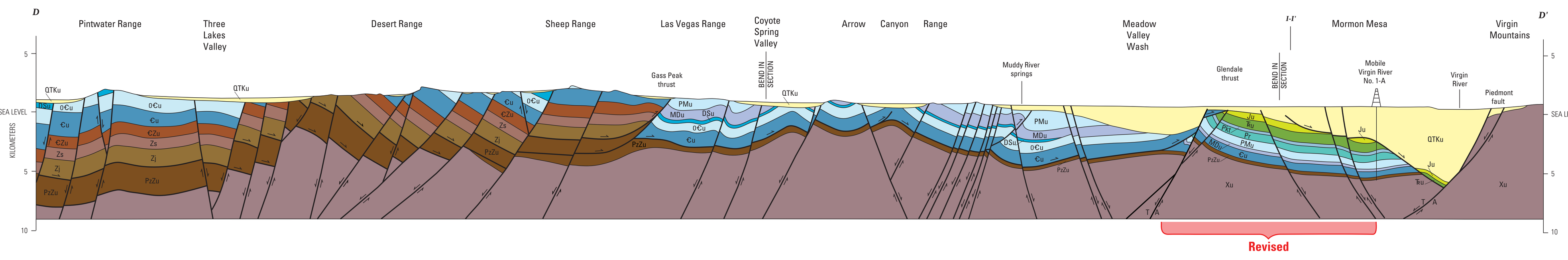
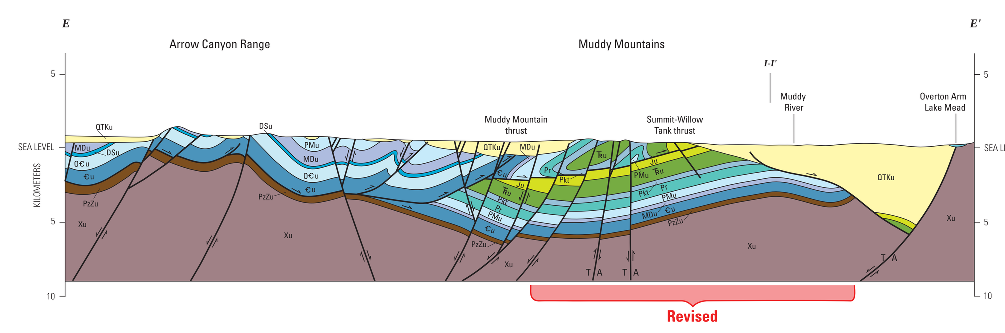
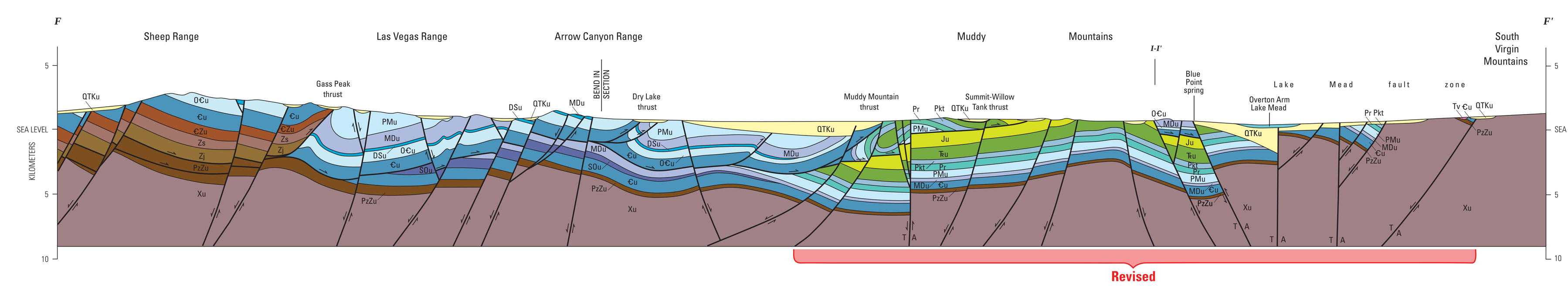


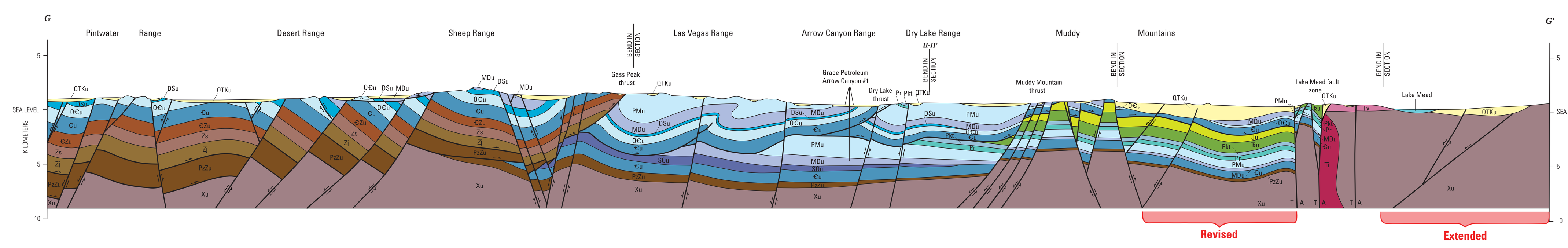


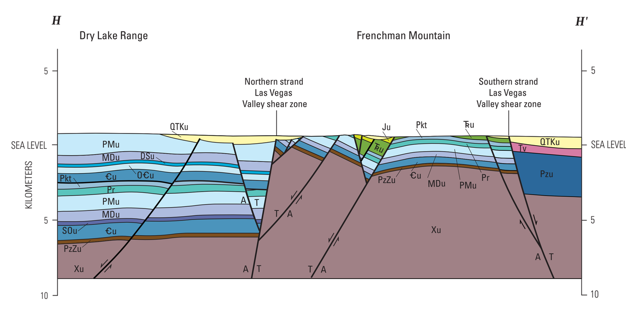


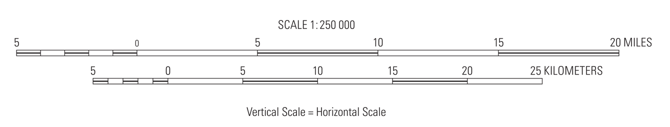


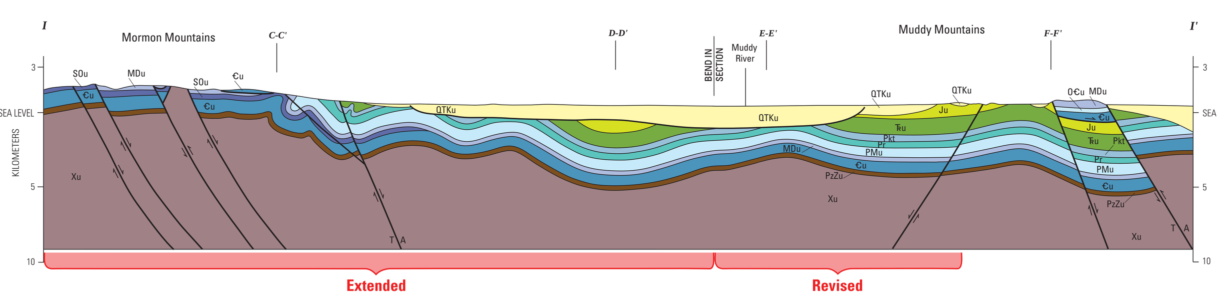


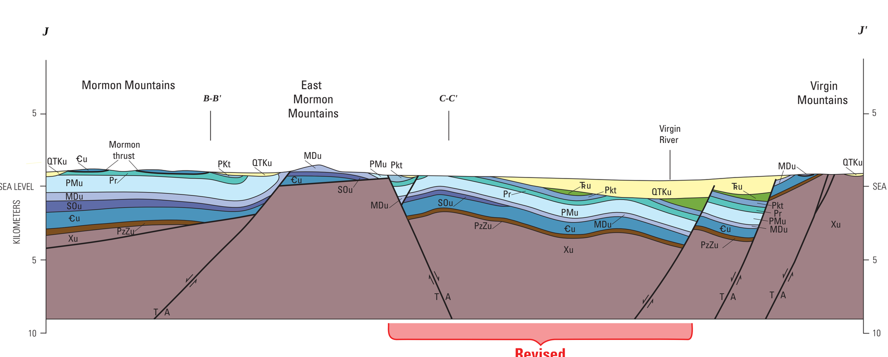




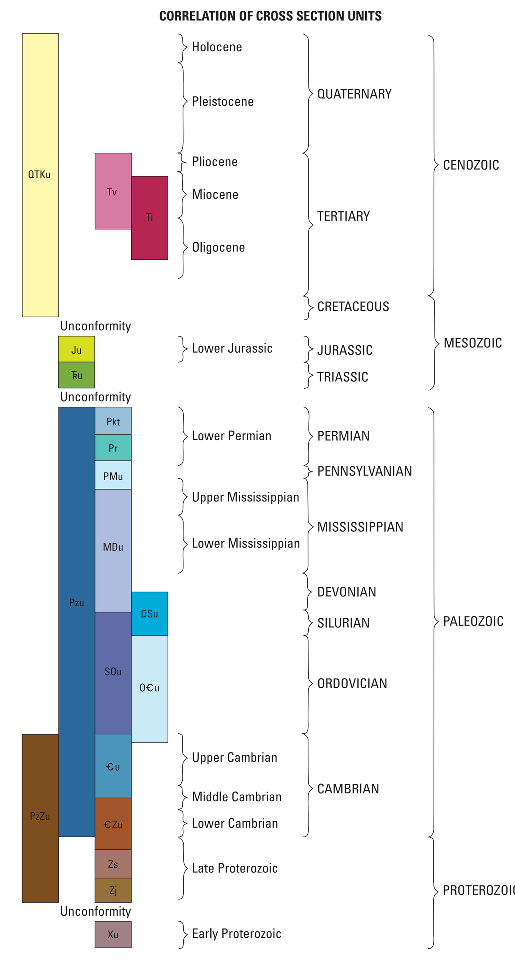








CORRELATION OF CROSS SECTION UNITS



DESCRIPTION OF CROSS SECTION UNITS

QTKu — **Quaternary to Cretaceous rocks, undivided (Holocene to Cretaceous)**—Alluvium (Holocene to Pliocene), playa deposits (Holocene to Pleistocene), eolian deposits (Holocene), spring discharge deposits (Holocene to Pleistocene), calcrete (Pleistocene to Pliocene), and landslide megabreccia deposits (Pleistocene to Miocene). Includes sedimentary rocks equivalent to the Muddy Creek Formation (Pliocene-Miocene), and the Horse Spring Formation (Miocene and Oligocene). Unit locally includes Cretaceous synorogenic basin-fill deposits in the Muddy Mountains area, which consist of the Baseline Sandstone (Upper and Lower Cretaceous), and Willow Tank Formation (Lower Cretaceous). Unit from 0 to greater than 8,000 m thick

Tv — **Tertiary volcanic rocks, undivided (Pliocene to Oligocene)**—Ash-flow tuff, airfall tuff, lava flows, and basalt flows. Exposed in the Delamar Mountains (***A-A'***) and in the Lake Mead area (***G-G'***). Several hundred meters to greater than several thousand meters thick

Ti — **Tertiary intrusive rocks, undivided (Miocene and Oligocene)**—Granitic or silicic intrusive rocks in the Delamar Mountains (***A-A'***) and in the Lake Mead area (***G-G'***)

Ju — **Lower Jurassic rocks, undivided**—Includes the Aztec Sandstone in most of southern Nevada (Basin and Range province), and the correlative Navajo Sandstone in southwest Utah and northwest Arizona (Colorado Plateaus Province). Unit also includes the Kayenta and Moenave Formations, which underlie both the Aztec Sandstone and Navajo Sandstone. Exposed in Tule Springs Hills, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit has combined thickness of 1,000 to 2,200 m

TRu — **Triassic rocks, undivided**—Chinle (Upper Triassic) and Moenkopi (Middle? and Lower Triassic) Formations exposed in the eastern Meadow Valley Mountains, Tule Springs Hills, Mormon Mountains, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit has combined thickness of about 1,000 m

Pzu — **Paleozoic rocks undivided (Lower Permian to Cambrian)**—May include parts of all Paleozoic units listed below. Shown in ***H-H'*** south of Frenchman Mountain

Pkt — **Kaibab and Toroweap Formations, undivided (Lower Permian)**—Exposed in the eastern Meadow Valley Mountains, Tule Springs Hills, Mormon Mountains, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit is 300 to 500 m thick

Pr — **Lower Permian redbeds**—Unit defined by Longwell and others (1965) and correlated with parts of the Queantoweap and Esplanade Sandstones and the Hermit Formation. Exposed in the eastern Meadow Valley Mountains, Tule Springs Hills, Mormon Mountains, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit is 400 to 600 m thick

PMu — **Lower Permian to Upper Mississippian rocks, undivided**—Bird Spring (Lower Permian to Upper Mississippian) and Indian Springs (Upper Mississippian) Formations in west and central parts of the study area as far east as the Muddy Mountains, Tule Springs Hills, and Mormon Mountains, and Callville Limestone (Pennsylvanian) and Pakoon Dolomite in the eastern part of the study area in the Lake Mead area and in the Virgin and Beaver Dam Mountains. Combined thickness of unit from about 460 to 2,500 m thick

MDu — **Upper Mississippian to Middle Devonian rocks, undivided**—In the west and central parts of the study area includes the Joana Limestone (Lower Mississippian) or Monte Cristo Group (Upper and Lower Mississippian), Crystal Pass Limestone or Pilot Shale (Lower Mississippian to Upper Devonian), Guilmette Formation (Upper and Middle Devonian) or Sultan Limestone (Lower Mississippian to Middle Devonian). Also includes Scotty Wash Quartzite and Chainman Shale (Upper Mississippian) in the northern Meadow Valley Mountains and Delamar Mountains. In the eastern part of the study area, in the Lake Mead area and the Virgin and Beaver Dam Mountains, includes the Redwall Limestone (Upper and Lower Mississippian) and Temple Butte Formation (Upper and Middle(?) Devonian). Combined thickness of unit is from about 300 to 1,800 m

DSu — **Middle Devonian to Silurian rocks, undivided**—Rocks equivalent to parts of the Simonson Dolomite (Middle Devonian), Sevy Dolomite (Lower Devonian), and Laketown Dolomite (Silurian). Combined thickness from 200 to 780 m

SOu — **Silurian and Ordovician rocks, undivided**—Rocks equivalent to the Laketown Dolomite (Silurian), the Ely Springs Dolomite (Upper Ordovician), Eureka Quartzite (Middle Ordovician), and the Pogonip Group (mostly Upper and Middle Ordovician, but includes Cambrian rocks in the Sheep Range area). These rocks extend as far east as the Muddy Mountains, Mormon Mountains, and Tule Springs Hills. Unit only includes Ordovician rocks in the Muddy Mountains; Silurian and Ordovician rocks are absent in the Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Combined thickness of unit from 0 to 1,500 m

OЄu — **Upper Ordovician to Upper Cambrian rocks, undivided**—Rocks equivalent to the Ely Springs Dolomite (Upper Ordovician), Eureka Quartzite (Middle Ordovician), and Pogonip Group (Middle Ordovician to Upper Cambrian). Combined thickness from about 550 to 1,200

Єu — **Upper and Middle Cambrian rocks, undivided**—Includes Nopah (Upper Cambrian) and Bonanza King (Upper and Middle Cambrian) Formations in most parts of the study area. Equivalent rocks along the west end of ***A-A'*** in the northern Delamar Mountains include the Nopah Formation and Highland Peak Formation (Middle Cambrian). In the eastern part of the study area in the Beaver Dam and Virgin Mountains, and in the Lake Mead area, includes the Nopah and Muav (Middle Cambrian) Formations. Combined thickness of unit from about 500 to 2,200 m

PzZu — **Paleozoic and Late Proterozoic rocks, undivided**—In western part of study area unit may consist of Cambrian and Late Proterozoic units including the Nopah Formation (Upper Cambrian), Bonanza King Formation (Upper and Middle Cambrian), Carrara Formation (Middle and Lower Cambrian), Wood Canyon Formation (Lower Cambrian and Late Proterozoic), Stirling Quartzite (Late Proterozoic), and Johnnie Formation (Late Proterozoic). Late Proterozoic rocks pinch out in the eastern part of the study area where unit includes only the Bright Angel Shale (Middle and Lower Cambrian) and Tapeats Sandstone (Lower Cambrian) in the Mormon Mountains, Tule Springs Hills, Beaver Dam and Virgin Mountains, and Lake Mead area. Combined thickness of unit from 125 to greater than 2,000 m

ЄZu — **Middle Cambrian and Late Proterozoic rocks, undivided**—In Pintwater, Desert, and Sheep Ranges includes the Carrara (Middle and Lower Cambrian) and Wood Canyon (Lower Cambrian and Late Proterozoic) Formations. In northern Delamar Mountains (west side of ***A-A'***) includes the Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), and Pioche Shale (Middle and Lower Cambrian), and Wood Canyon Formation. Combined thickness of unit from 360 to 1,000 m

Zs — **Late Proterozoic rocks, undivided**—Includes the Stirling Quartzite in the Pintwater, Desert, and Sheep Ranges, and northern Delamar Mountains (western part of ***A-A'***). Unit is 600 to 800 m thick

Zj — **Johnnie Formation (Late Proterozoic)**—In the Pintwater, Desert, and Sheep Ranges includes Johnnie Formation; in northern Delamar Mountains includes rocks partly equivalent to the Johnnie Formation. About 1,000 m thick but greater than 1,000 m in northern part of study area

Xu — **Early Proterozoic crystalline rocks**—Gneiss, schist, and granite exposed at Frenchman Mountain, Lake Mead area, Virgin Mountains, Beaver Dam Mountains, and Mormon Mountains

Explanation of Cross Section Symbols

Contact

Normal fault—Arrows indicate direction of fault block movement

Oblique-slip fault—Arrows indicate direction of vertical movement; T indicates fault block movement toward the viewer, A indicates fault block movement away from viewer

Strike-slip fault—T indicates fault block movement toward the viewer, A indicates fault block movement away from viewer

Low-angle fault (low-angle normal or thrust fault)—Arrow indicates relative movement of overriding plate

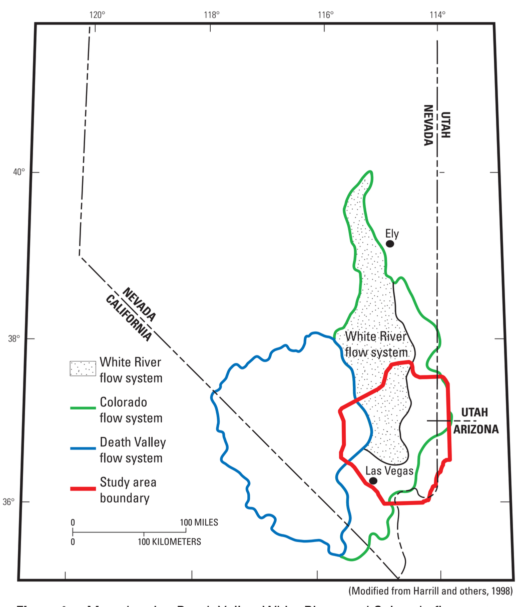


Figure 1. Map showing Death Valley, White River, and Colorado flow systems, and study area boundary.

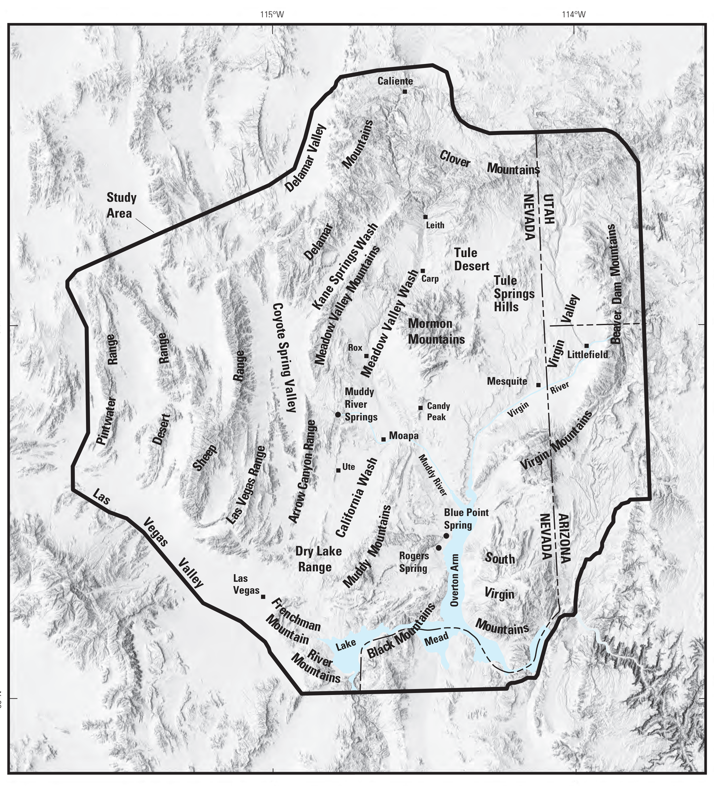


Figure 2. Index map showing major physiographic features in the study area.

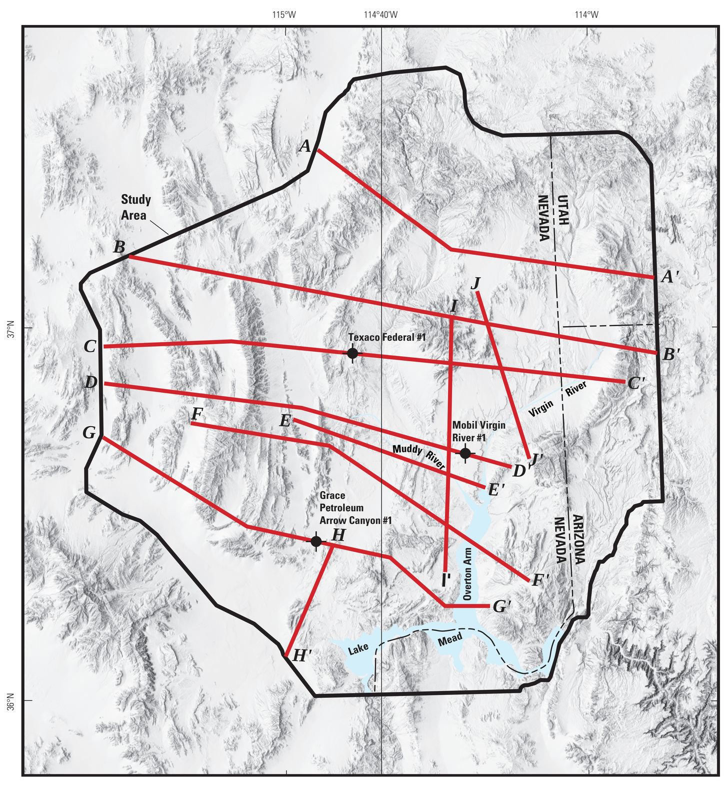


Figure 3. Location of cross sections and oil wells in the study area. East-west cross sections are hung on longitude 114°40'00'' as a reference line to visually extrapolate the geology between the section lines in a north-south progression.

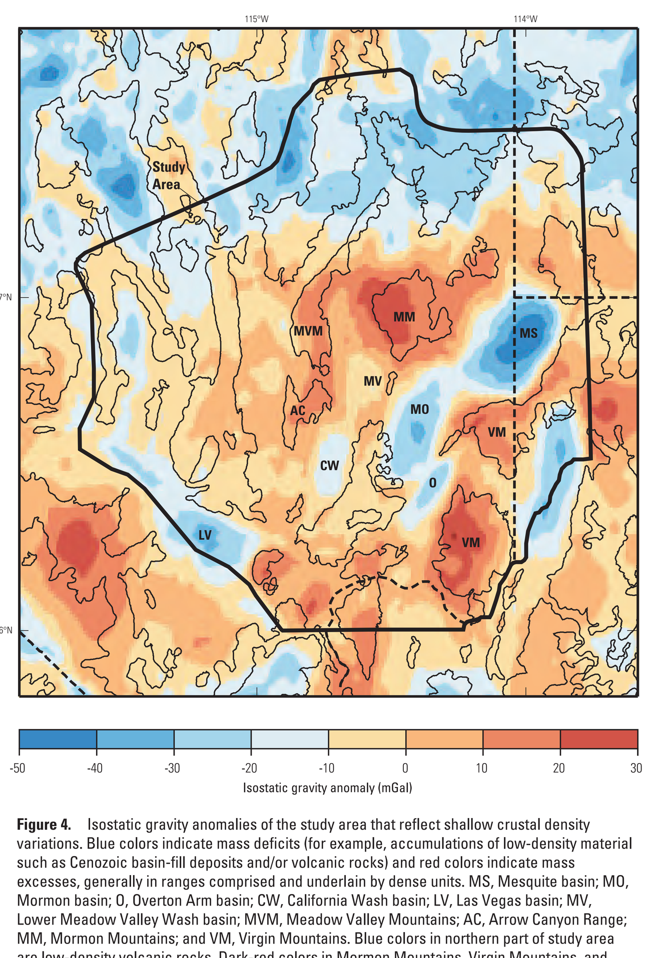


Figure 4. Isostatic gravity anomalies of the study area that reflect shallow crustal density variations. Blue colors indicate mass deficits (for example, accumulations of low-density material such as Cenozoic basin-fill deposits and/or volcanic rocks) and red colors indicate mass excesses, generally in ranges comprised and underlain by dense units. MS, Mesquite basin; MO, Mormon basin; O, Overton Arm basin; CW, California Wash basin; LV, Las Vegas basin; MV, Lower Meadow Valley Wash basin; MVM, Meadow Valley Mountains; AC, Arrow Canyon Range; MM, Mormon Mountains; and VM, Virgin Mountains. Blue colors in northern part of study area are low-density volcanic rocks. Dark-red colors in Mormon Mountains, Virgin Mountains, and Lake Mead area are Early Proterozoic crystalline rock. Thin black solid lines are range outlines.

Figure 5. Generalized map of the principal structural features in the study area.

This Report	Page and others (2005): Pintwater, Desert, Sheep, and Las Vegas Ranges	Clover and N. Delamar Mountains	S. Delamar and N. Meadow Valley Mountains	Arrow Canyon Range and S. Meadow Valley Mountains	Tule Springs Hills, Mormon and Muddy Mountains	Beaver Dam and Virgin Mountains, and Lake Mead area
Ju	Not Exposed	Jam Aztec Ss. Kayenta Fm. Moenave Fm.	Not Exposed	Not Exposed	Jam Aztec Ss. Kayenta Fm. Moenave Fm.	Jct Carmel Fm. Temple Cap Fm. (UT); Jam Aztec Ss. (NV) Navajo Ss. (UT, AZ) Kayenta Fm. Moenave Fm.
TRu		TRu Chinle Fm. Moenkopi Fm.	TRu Chinle Fm. Moenkopi Fm.		TRu Chinle Fm. Moenkopi Fm.	TRu Chinle Fm. Moenkopi Fm.
Pkt		Pkt Kaibab Fm. Toroweap Fm.	Pkt Kaibab Fm. Toroweap Fm.		Pkt Kaibab Fm. Toroweap Fm.	Pkt Kaibab Fm. Toroweap Fm.
Pr		Pr Lower Permian redbeds	Pr Lower Permian redbeds		Pr Lower Permian redbeds	Pr Lower Permian redbeds
PMu		PMb Bird Spring Fm. Indian Springs Fm.	PMb Bird Spring Fm. Indian Springs Fm.	PMb Bird Spring Fm. Indian Springs Fm.	PMb Bird Spring Fm. Indian Springs Fm.	PPc Pakoon Dol. Callville Ls.
MDu	MDu Joana Ls. Pilot Sh. Guilmette Fm.	Not Exposed	Msc Scotty Wash Qtz. and Chainman Sh.; MDu Joana Ls. Guilmette Fm.	Mm Monte Cristo Gp.; MDu Crystal Pass Ls. Guilmette Fm.	Mm Monte Cristo Gp.; MDu	Mr Redwall Ls.; Dtb Temple Butte Fm.
DSu	DSu Simonson Dol. Sevy Dol. Laketown Dol.		DSu Simonson Dol. Sevy Dol. Laketown Dol.	DSu Simonson Dol. Sevy Dol. Laketown Dol.	Absent	Absent
OЄu / SOu	Oes Ely Springs Dol.; Oe Eureka Qtz.; OЄp Pogonip Gp.		Oes Ely Springs Dol.; Oep Eureka Qtz. Pogonip Gp.	Oes Ely Springs Dol.; Oep Eureka Qtz. Pogonip Gp.	SOu Laketown Dol. Ely Springs Dol. Eureka Qtz. Pogonip Gp.; Op Pogonip Gp. (Muddy Mtns.)	
PzZu / Єu	Єn Nopah Fm.; Єbk Bonanza King Fm.	Єn Nopah Fm.; Єhp Highland Peak Fm.	Єn Nopah Fm.; Єbk Bonanza King Fm.	Єn Nopah Fm.	Єnb Nopah Fm. Bonanza King Fm.	Єn Nopah Fm.; Єm Muav Ls.
PzZu / ЄZu	Єc Carrara Fm.; ЄZw Wood Canyon Fm.	Єcp Lyndon Ls. Chislom Sh. Pioche Sh.; ЄZw Wood Canyon Fm.	Not Exposed	Not Exposed	Єbt Bright Angel Sh. Tapeats Ss.	Єbt Bright Angel Sh. Tapeats Ss.
PzZu / Zs	Zs Stirling Qtz.	Zs Stirling Qtz.			Absent	Absent
PzZu / Zj	Zj Johnnie Fm.	Not Exposed				
Xu	Not Exposed				Xu	Xu

Table 1. Relationships between bedrock map units (Mesozoic-Proterozoic) in the cross sections and geologic map of Page and others (2005).

REVISED GEOLOGIC CROSS SECTIONS OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY REGIONAL GROUNDWATER FLOW SYSTEMS, NEVADA, UTAH, AND ARIZONA

By
William R. Page, Daniel S. Scheirer,
Victoria E. Langenheim, and
Mary A. Berger
2011

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Hydrogeology and Potential for Ground-Water Development, Carbonate-Rock Aquifers, Southern Nevada and Southeastern California

By Thomas J. Burbey

U.S. GEOLOGICAL SURVEY

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1997

U.S. DEPARTMENT OF THE INTERIOR
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PLATE

[Plate is in pocket]

FIGURES

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CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY UNIT

Multiply	By	To obtain
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-feet per foot (acre-ft/ft)	0.004047	cubic hectometer per meter
acre-feet per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Abbreviated Water-Quality Unit Used in this Report
mg/L (milligram per liter)

Hydrogeology and Potential for Ground-Water Development, Carbonate-Rock Aquifers, Southern Nevada and Southeastern California

by Thomas J. Burbey

Abstract

In southern Nevada, 17 hydrographic areas were selected by the U.S. Geological Survey to assess the potential for development of ground water in the underlying carbonate-rock aquifers. The assessment was based on a summary of geologic and hydrologic information developed as part of the Nevada Carbonate Aquifers Study and information compiled from previous investigations.

The 17 hydrographic areas were selected from among 48 hydrographic areas in southern Nevada on the basis of an evaluation of the geologic framework, hydrologic setting, and public accessibility. All selected hydrographic areas lie within the miogeoclinal belt where thick sequences of carbonate rock accumulated over hundreds of millions of years. Major deformational episodes greatly modified the area, but in general, the less-extended areas tend to contain the thickest continuous sequences of carbonate rock at depth. Most of the selected hydrographic areas lie within these less-extended terranes; however, several areas, or parts of areas, lie within severely extended terranes where deformed blocks of carbonate rock are discontinuous and isolated from surrounding carbonate rock or where little or no carbonate rock remains at depth.

Three principal criteria were used to assess the development potential beneath the basin-fill deposits of each selected hydrographic area. These quantitative criteria are (1) depth to water, (2) depth to and thickness of carbonate rocks, and (3) water quality. Other site-specific factors such as accessibility and effects of ground-water development are also discussed. However, water-right availability under Nevada water law was not considered.

Results of the hydrographic-area appraisals based on available geologic and hydrologic information suggest that sites with high potential for development of ground water in carbonate rocks may be scarce in southern Nevada. Areas described as favorable by using the three criteria were assessed qualitatively on the basis of possible short- and long-term effects associated with development and on the amount of available data used to make the assessment. These results suggest that many sites classified as favorable from the quantitative assessment were deemed unfavorable on the basis of the qualitative criteria. The most favorable sites appear to be in more severely extended terranes where development of isolated areas of carbonate-rock aquifers would be less likely to affect adjacent areas.

INTRODUCTION

As the population of Nevada continues to grow at a rapid rate, the Nation's driest State faces increasing demands for water. Sources of ground water from basin-fill aquifers are fully or over appropriated in many areas in southern Nevada. The possibility, therefore, of tapping the relatively unexplored carbonate-rock aquifers as a source of potable ground water has been the focus of much interest in recent years.

In 1985, a cooperative effort began with the State of Nevada, Las Vegas Valley Water District, Desert Research Institute, City of North Las Vegas, and U.S. Department of the Interior (U.S. Geological Survey and Bureau of Reclamation) to study and test the carbonate-rock aquifers to assess their potential for development (known as the Nevada Carbonate Aquifers Study). As one of several reports from the study, this publication is intended to provide water managers, landowners, scientists, and policy makers with a reference that summarizes hydrogeologic information for specific hydrographic areas.

Purpose and Scope

The purpose of this report is (1) to describe the geology and hydrology of the carbonate-rock aquifers in southern Nevada, and (2) to evaluate the potential for development of their water resources. To achieve these objectives, 17 hydrographic areas were selected by the U.S. Geological Survey from the 48 such areas that constitute the southern part of the State. The 17 areas were selected on the basis of the presence of thick sections of carbonate rock within the hydrographic area, the availability of geologic and hydrologic information needed to adequately evaluate the potential for development, and the accessibility to the area. The potential for development of each selected area was determined on the basis of depth to water, depth and thickness of carbonate rocks, and water quality.

In addition, this report describes the geologic processes that have affected each of the selected areas and provides such information as the depth to, and the thickness and extent of, carbonate rocks beneath basin fill. The hydrologic framework of each area is described and pertinent data such as estimates of recharge and discharge, depth to water, water quality, and location of wells and springs tapping basin fill and carbonate rocks are provided. Geologic controls that affect the location and movement of ground water are also described.

Hydrogeology of Southern Nevada

The area that includes the present southern Great Basin has undergone a diverse and complex geologic history that has spanned hundreds of millions of years. The fault-block mountains and alluvial basins that are dominant in the area today are a result of only the past 20 million years of geologic activity (Stewart, 1980; Guth and others, 1988; Smith and others, 1987a, b; Wernicke and others, 1988a). Most of the geologic past has been pieced together from the structure and composition of the rocks exposed at the surface. This formidable task was somewhat simplified in this study by segregating the numerous lithologic units into five hydrogeologic units on the basis of their ability to transmit ground water and their effect on ground-water quality. The five units are described in chronological order beginning with the youngest unit (see table 1 for approximate ages).

Quaternary and Tertiary basin-fill deposits—includes alluvial, fluvial, fanglomerate, lake, and mudflow deposits. These deposits also include the Muddy Creek and Horse Spring Formations of Tertiary age. These Tertiary formations include siltstone, gypsiferous sandstone, conglomerate, gypsum, and tuffaceous sedimentary rocks. Basin-fill deposits generally are of high permeability and constitute the primary aquifers in the State, but may produce low-quality ground water in areas where evaporite minerals (for example, Tertiary deposits containing gypsum) are present.

Tertiary rocks—chiefly volcanic rocks consisting of welded to nonwelded ash-flow and ash-fall tuffs, basalt, and rhyolite flows. The unit may also contain varying amounts of sandstone, siltstone, and conglomerate, as well as intrusive rocks. This unit is generally of low permeability, although some welded tuffs are effective aquifers (Winograd, 1971). Generally, this unit tends to act as a barrier to ground-water flow.

Table 1. Geologic time scale showing eras, periods, and approximate ages used by the U.S. Geological Survey

Era	Period	Age (approximate millions of years before present)
Cenozoic	Quaternary	0-1.7
	Tertiary	1.7-66
Mesozoic	Cretaceous	66-138
	Jurassic	138-205
	Triassic	205-240
Paleozoic	Permian	240-290
	Pennsylvanian	290-330
	Mississippian	330-360
	Devonian	360-410
	Silurian	410-435
	Ordovician	435-500
	Cambrian	500-570
Precambrian		Greater than about 570

Late Paleozoic and Mesozoic sedimentary rocks—chiefly siltstone, sandstone, shale, limestone, dolomite, and gypsum. This unit can vary from mostly carbonate to mostly noncarbonate in composition. The permeability of this unit varies from very low in shale layers to very high in fractured dolomites with solution cavities (resulting from dissolving gypsum). However, due to the presence of gypsum (an evaporite), the ground-water quality within this unit is generally unsuitable for most water uses.

Paleozoic carbonate rocks—primarily limestone and dolomite containing varying amounts of silt with interbedded shale. These rocks constitute the regional aquifer systems upon which this study is based. The carbonate rocks tend to be of low permeability except where fractured and jointed. The sequences of carbonate rock in most areas are likely to have a large number of fractures and joints.

Precambrian and Cambrian noncarbonate rocks—chiefly siltstone, sandstone, granite, and metamorphic rocks such as quartzite, gneiss, and schist. These rocks are generally of very low permeability and tend to form barriers to ground-water flow.

A short summary of the geologic history pertinent to the current hydrologic setting of the area is provided to (1) familiarize the reader with the terminology, events, and chronology that have led to the formation of the present-day Basin and Range Province (Fiero, 1986), and (2) build a hydrologic framework from which the reader can better understand the structural processes that have influenced regional ground-water flow and accessibility of water resources in carbonate-rock aquifers. A glossary of the geologic and hydrologic terminology used in this and subsequent discussions is at the end of this report.

Although the present-day fault-block structure evolved during only the past 20 million years of geologic time, the entire geologic history is much longer and more complex. It dates back to Precambrian time (table 1). Until Cambrian time, most of the geologic activity involved accretion of land masses at the continental margins resulting from merging of island arc systems (see glossary) with the continent. These deposits make up the Precambrian and Cambrian noncarbonate unit described above and are considered to be barriers to ground-water flow. Because these rocks make up the bottom or lowest unit, geologists commonly refer to these rocks in a broad sense as "basement."

Beginning in Late Cambrian time, eastern Nevada became a continental shelf (fig. 1) where carbonate rocks were deposited and accumulated to thicknesses of as much as 30,000 ft. This region is referred to as the Cordilleran miogeocline which has produced the present carbonate-rock province. This thick wedge of deposits makes up the Paleozoic carbonate-rock hydrogeologic unit that forms the carbonate-rock aquifers being evaluated for development in this report.

The Permian Period marked the end of thick accumulations of carbonate rock when compressional forces began affecting the region, resulting in the deposition of thick sequences of clastic rocks. These deposits from Permian through Cretaceous time constitute the upper Paleozoic and Mesozoic sedimentary-rock hydrogeologic unit. This unit can be a confining unit where appreciable thicknesses of clay or shale have accumulated. Structurally, the crust was greatly deformed during this episode of compression, causing thick sheets of sediment and carbonate (and basement, in some instances) rock to be thrust over one another in an eastward direction. Thrusting also produced folds in the previously flat-lying rocks. In places, the total thickness of carbonate rock was doubled or tripled. These areas today can constitute massively thick aquifer systems. Figure 2 shows how compressional forces affected the physiography of the southern Great Basin.

Beginning in the middle Tertiary period, stretching or extension of the crust occurred, resulting in large-scale faulting that caused huge blocks to be dropped, tilted, or rotated in response to being pulled apart or thinned. Figure 3 shows a schematic diagram of how extension has modified the geologic structure of the southern Great Basin. In some areas the regional carbonate aquifer system is disrupted and smaller local aquifer systems may predominate. In other areas, initially thick sections of carbonate-rock aquifer may have been thinned and fractured, but today represent prolific regional aquifer systems. Coincident with extension during the Tertiary period was widespread volcanic activity that produced rhyolitic, andesitic, and basaltic volcanic rocks. These volcanic rocks make up the Tertiary rock hydrogeologic unit defined above. Volcanic rocks can be prolific aquifers in some settings and impermeable barriers in others. In general, this unit is less permeable than the Paleozoic carbonate-rock unit.

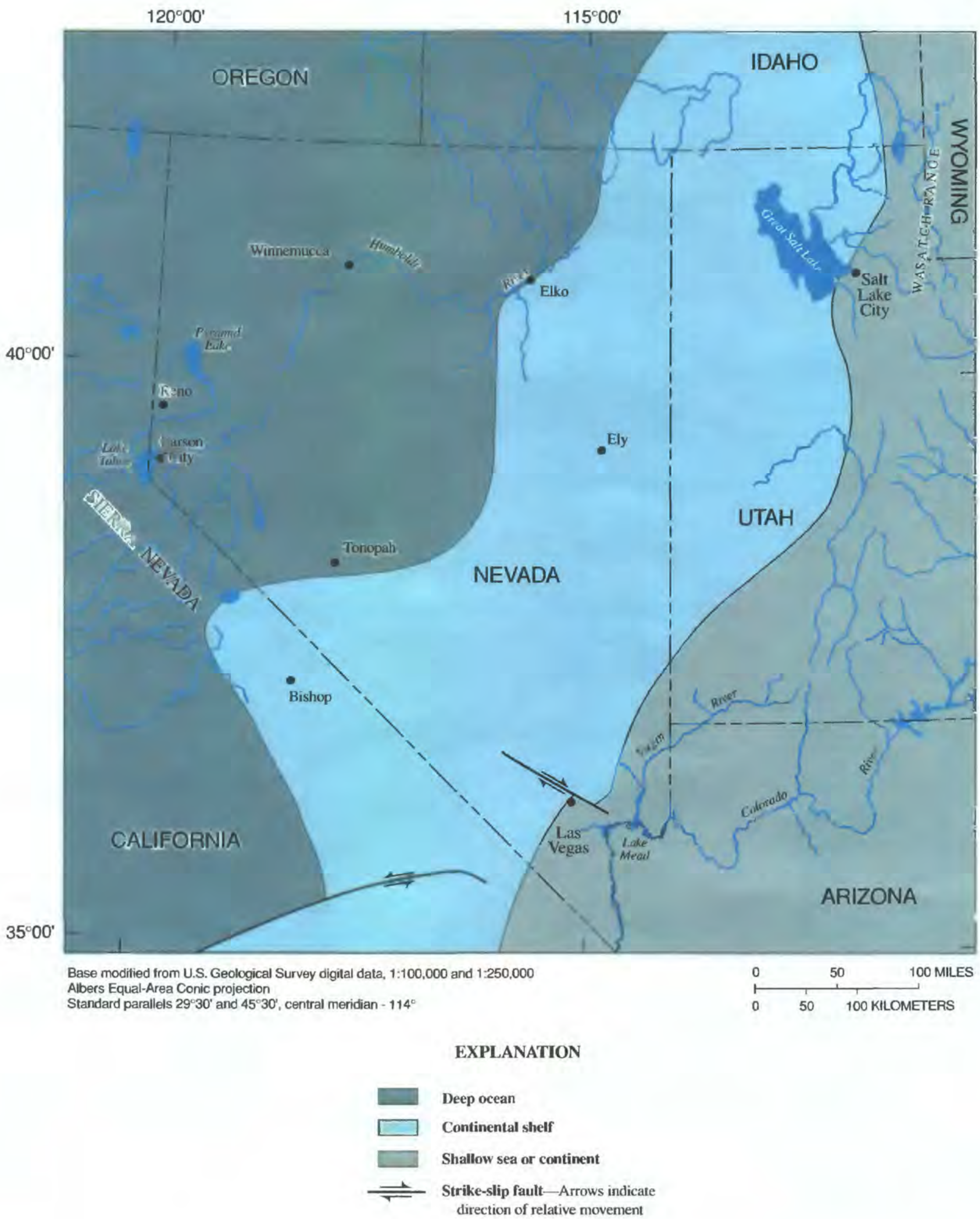
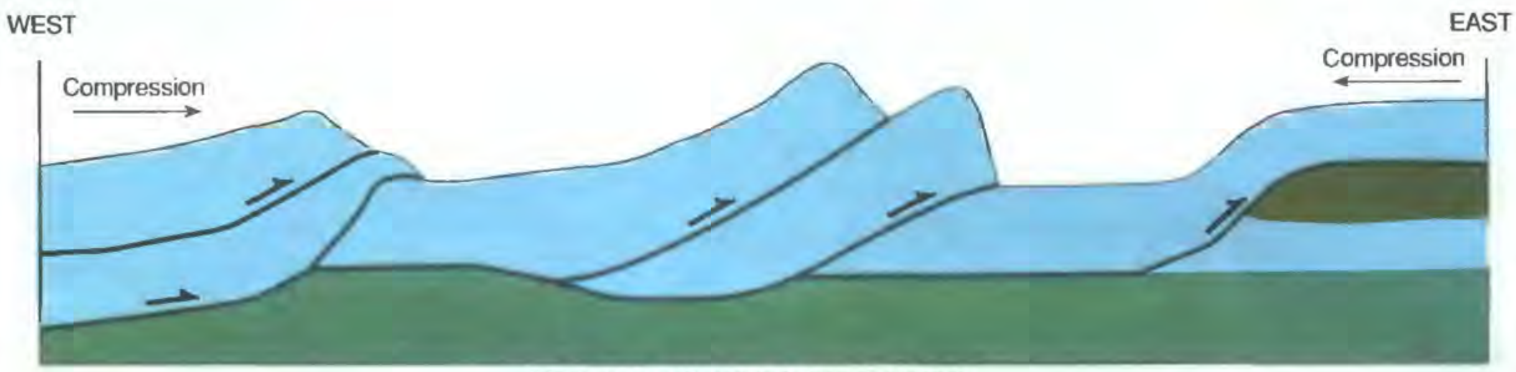


Figure 1. Extent of encroachment of ocean upon the continent during Cambrian time. The continental shelf was an area of carbonate-mineral deposition. Location is approximately coincident with the carbonate-rock province of today (Modified from Fiero, 1986).



VERTICAL EXAGGERATION ABOUT X5

EXPLANATION

- **Upper Paleozoic and Mesozoic sedimentary rock**
- **Carbonate rock**
- **Precambrian and Cambrian noncarbonate rock**
- **Low-angle fault**—Arrow indicates direction of block movement

Figure 2. Diagrammatic section depicting how compressional forces caused thrust faulting and subsequent thickening of the crust in the southern Great Basin.

VERTICAL EXAGGERATION ABOUT X5

EXPLANATION

- **Tertiary and Quaternary basin fill**
- **Paleozoic carbonate rock**
- **Precambrian and Cambrian noncarbonate rock**
- **Fault**—Arrow indicates direction of block movement

Figure 3. Diagrammatic section depicting how extensional forces caused normal faulting and thinning of the crust in the southern Great Basin.

During the later stages of extension, block faulting produced the north-trending mountain ranges characteristic of the Great Basin. Erosion of these mountain ranges and subsequent deposition filled the valleys with several hundred to more than 10,000 ft of sediment, which constitutes the uppermost and most recent hydrogeologic unit. Most of the production wells are completed in this unit because of its ease of accessibility and usually high yield. Where extension was greatest, basin fill generally is thickest. Basin fill commonly lies directly on carbonate rock, but Tertiary volcanic rocks may be interlayered between the basin fill and the carbonate rocks, especially in the northern part of the study area. Hence, developing water supplies from the carbonate rocks may require drilling through thousands of feet of saturated basin fill and volcanic rock before reaching carbonate-rock aquifers. Consequently, selection of potential sites requires an understanding of the geologic structure of southern Nevada. The once flat-lying carbonate rocks are today an aggregate of greatly deformed and faulted rock masses intermingled with noncarbonate rock types.

Acknowledgments

The author thanks the State of Nevada and the Las Vegas Valley Water District for their contributions to this study.

POTENTIAL FOR GROUND-WATER DEVELOPMENT OF CARBONATE-ROCK AQUIFERS IN SELECTED HYDROGRAPHIC AREAS

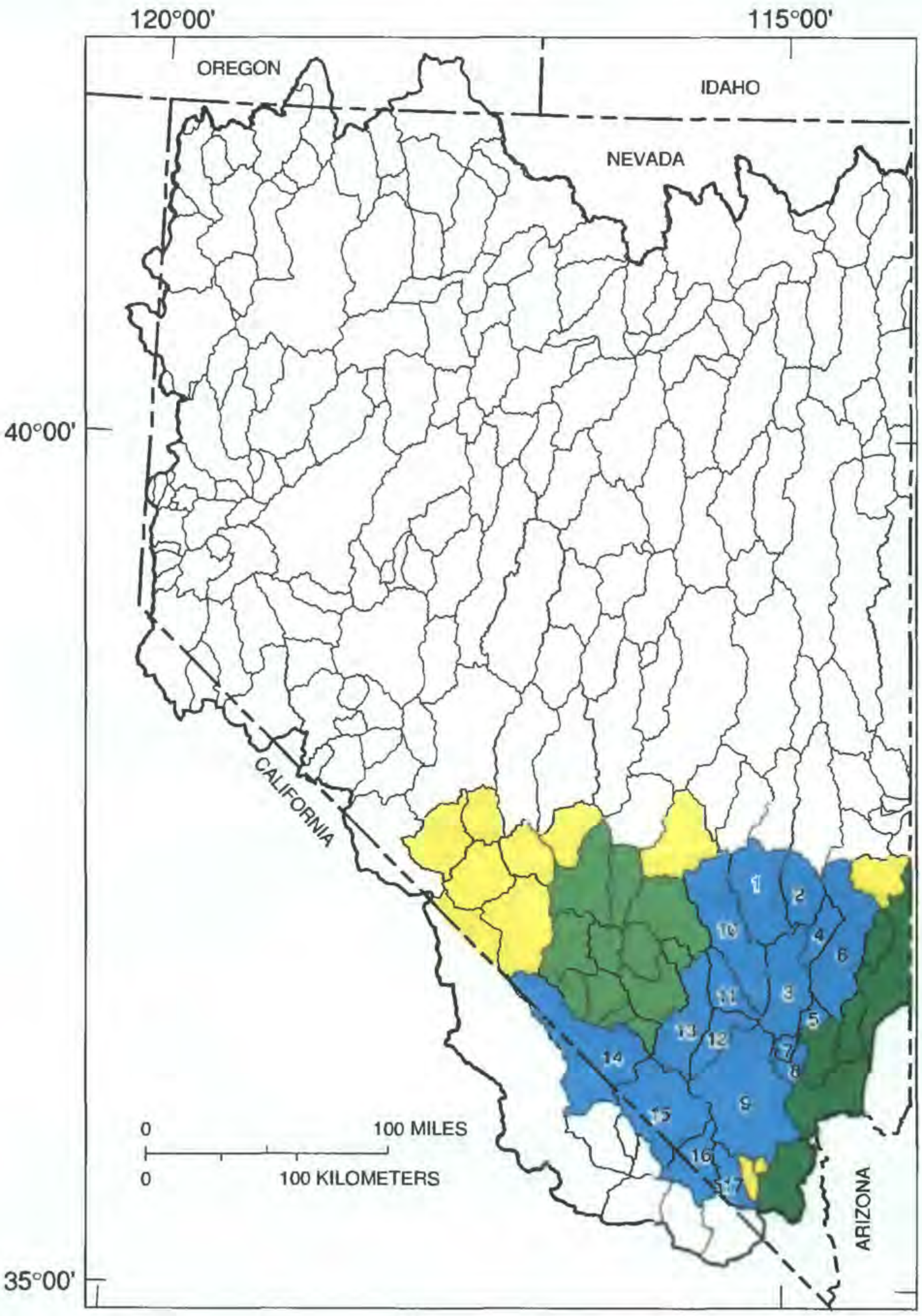
The term "hydrographic area" was first used and defined by Rush (1968b, p. 4) in place of "valley," but it also applies to areas that are called flat, desert, basin, meadow, wash, plain, area, canyon, and mesa. The names of most of the hydrographic areas are the names used by the people who live in and near the areas, and that are found on topographic maps. The boundaries of each hydrographic area generally are drawn along topographic ridges. In some localities, the lines are drawn across nearly flat alluvial terrain. Aerial photographs were used to aid in locating a suitable boundary in these flat-lying areas. Hydrographic-area boundaries are used by the Nevada State Engineer's office for water-management purposes throughout the State.

Selection of Hydrographic Areas for Analysis

The southern part of Nevada is divided into 48 hydrographic areas (Rush, 1968b). Of these, 17 were selected for analysis of their potential for ground-water development (fig. 4). The 17 areas were selected on the basis of (1) presence of thick sections of carbonate rock within the hydrographic area, (2) availability of geologic and hydrologic information needed to adequately evaluate development potential, and (3) accessibility (the Nevada Test Site and most of the Nellis Bombing Range are restricted areas).

The location and name of each selected hydrographic area is shown in figure 4. The format for discussion of selected areas consists of the hydrographic setting, geology, hydrology, and potential for development of the carbonate-rock aquifers underlying the valley within the hydrographic area. The hydrographic setting section includes a brief discussion of the physiographic features. The geology section describes the thickness and distribution of rock types found in the area, as well as a simplified discussion of how extensional and compressional forces have modified the structural setting and consequently the redistribution of carbonate rocks and the resulting aquifer systems. The hydrology section contains a summary of available hydrologic information including estimates of recharge and discharge, depth to water, direction and magnitude of ground-water flow, and geologic controls on the movement and occurrence of flow. The last section pertains to the potential for development and is based on all available geologic and hydrologic information. Finally, the available information is used to determine how short- and long-term development may affect the immediate area as well as surrounding areas.

Ground-water storage in the carbonate rocks of each hydrographic area in southern Nevada was estimated using the following assumptions. (1) Only unconfined storage is considered significant and a uniform specific yield of 1 percent is used for all carbonate rocks within each hydrographic area. This value is a combination of both effective interstitial porosity and fracture porosity in the carbonate rocks. Details of how this value was obtained are discussed in a report by Dettinger and others (1995). (2) Carbonate rocks in mountainous areas are at least 2,000 ft thick within the saturated zone (beneath the potentiometric surface). (3) Storage within the valley of each area is included



EXPLANATION

Hydrographic areas:

- Excluded from study on the basis of sparse information
- Excluded from study because of restricted access
- Excluded from study because they are dominated by noncarbonate rocks
- 2 Selected for this study

Map number	Official number[1]	Name
1	209	Pahranagat Valley
2	182	Delamar Valley
3	210	Coyote Spring Valley
4	206	Kane Springs Valley
5	219	Muddy River Springs Area
6	205	Lower Meadow Valley Wash
7	217	Hidden Valley
8	216	Garnet Valley
9	212	Las Vegas Valley
10	169	Tikaboo Valley
11	168	Northern Three Lakes Valley
12	211	Southern Three Lakes Valley
13	161	Indian Springs Valley
14	230	Amargosa Desert
15	162	Pahrump Valley
16	163	Mesquite Valley
17	164	Ivanpah Valley

- Boundary of Great Basin Regional Aquifer-System Analysis (RASA) study area
- Boundary of hydrographic area or subarea

[1] Rush, 1968b

Base modified from U.S. Geological Survey digital data, 1:100,000 and 1:250,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian - 114°

Figure 4. Hydrographic areas selected for and excluded from this study.

in the total estimate only if a minimum of 2,000 ft of carbonate rock lies within the top 5,000 ft of rock or sediment. Because of the uncertainty in estimating effective porosity, thickness, and extent of carbonate rocks within a given area, estimates of storage should be considered only as approximations. Actual values may vary significantly from those presented here. Basin-fill storage was not estimated for this report, but estimates for all the basins within the state are in State of Nevada Water Planning Report 3 (Scott and others, 1971).

Additional information and discussions of special features or problems specific to a particular hydrographic area are also presented in the following area-by-area assessments.

Criteria Used to Assess Potential for Ground-Water Development

Each selected hydrographic area was individually appraised for potential for development of the carbonate-rock aquifers. Three principal criteria were used in this report to assess the potential of each selected hydrographic area for water development. The most favorable areas would have (1) depth to water less than 500 ft below land surface, (2) depth to carbonate rock beneath the valley floor less than 1,500 ft and thickness of carbonate rock exceeding 2,000 ft, and (3) good water quality within the carbonate rocks, defined by a dissolved-solids concentration of less than 1,000 mg/L. Plate 1 shows areas where one, two, or three of these criteria are met.

In addition to these three criteria, other factors were considered in the selection of potential areas for development. These additional factors, discussed in the individual hydrographic-area appraisals, include (1) long- and short-term effects of development, (2) quantity of potential ground-water storage, (3) geologic controls influencing development, (4) environmental sensitivity of the potential site (such as Devils Hole), and (5) possible access problems in restricted areas.

Appraisal of development potential in many areas is extremely subjective because, for the most part, adequate hydrologic and geologic data are not available. The amount and accuracy of data varies greatly from area to area and no attempt was made to define the magnitude or temporal duration of potential ground-water development. Consequently, appraisal of each selected area (pl. 1) should be viewed as a generalized preliminary evaluation. Additional site-specific information may be needed before making major decisions about the development potential of selected local areas. All ground-water development, regardless of magnitude, is subject to regulation by Nevada water law.

Pahranagat Valley

Hydrographic Setting

Pahranagat Valley is in west-central Lincoln County in south-central Nevada. The hydrographic area encompasses about 768 mi^2 and is bounded on the west by the Pahranagat Range and on the east by the South Pahroc Range (fig. 5). The northern boundary is a bedrock high traversed by the White River at the narrows that separates Pahranagat Valley from Pahroc Valley to the north. To the south, a volcanic-rock canyon defines the hydrographic area boundary. Pahranagat Valley is a southward-sloping, open-drainage system of the presently dry White River (Eakin, 1963b). The most prominent hydrologic features of the basin are three large regional springs aligned in a north-south trend along the eastern margin of the valley. The average hydraulic gradient indicated by well data and springs in the valley is about 26 ft/mi in a southerly direction. The population of Pahranagat Valley is less than 2,000.

Geology

Exposed consolidated rock in the Pahranagat Valley hydrographic area is primarily Paleozoic carbonate rocks and Tertiary volcanic rocks which are composed mostly of ash-flow tuffs. Paleozoic rocks beneath the valley probably exceed 10,000 ft in thickness (Reso, 1963; Dolgoff, 1963; and Stewart, 1980). A section of more than 18,000 ft of Paleozoic carbonate rock has been measured in the Pahranagat Range by Reso (1963). Tertiary volcanic rocks lie unconformably on the thick carbonate-rock section beneath the valley and range in thickness from several hundred feet near the margins of the valley to more than 2,000 ft near the west-central part of the valley (fig. 5). These rocks are probably thickest in the South Pahroc Range (Bedsun, 1980). Thicknesses of basin-fill deposits vary significantly beneath the valley, but reach a maximum of about 2,000 ft near the center of the valley (Bedsun, 1980).

Features associated with both compressional and extensional forces are evident in Pahranagat Valley. Compressional forces have produced a major thrust fault in the Pahranagat Range (Tschanz and Pampeyan, 1970; fig. 5) resulting in significant thickening of the carbonate-rock section that is nearly double the estimated thickness of carbonate rock beneath the valley to the east. There is no conclusive evidence that thickening of the carbonate-rock section beneath Pahranagat Valley occurred.

Volcanic activity probably preceded extensional faulting in the area. Volcanic rocks beneath Pahranagat Valley form a north-trending trough with steep east and west sides, according to geophysical studies by Snyder (1983, p. 6); the trough resembles a "syncline or fault-controlled sag" (fig. 5; Dolgoff, 1963). Following much of the volcanic activity, numerous north-south aligned block faults resulting from extensional forces produced the Pahranagat and Hiko Ranges as well as Pahranagat Valley, but thinning of the carbonate rocks beneath Pahranagat Valley probably was not extensive; hence, the carbonate rocks beneath Pahranagat Valley may represent an extensive (both laterally and vertically) ground-water flow system that is contiguous with the flow system in valleys to the north and south. The structural trough beneath the valley is truncated to the south by the Pahranagat shear zone containing several left-lateral strike-slip faults (fig. 5). Schweikert (University of Nevada, Reno, oral commun., 1988) suggested that this fault system may represent a transitional boundary between extensional movement that occurred at different times north and south of the shear zone. This structural boundary may partially restrict southeastward flow of ground water, but may enhance southwestward flow (Eakin, 1966; Winograd and Thordarson, 1975).

Hydrology

Recharge to Pahranagat Valley from the adjacent ranges has been estimated by the Maxey-Eakin method (Eakin, 1963b) for three different reports (table 2). Values range from 1,500 to 2,000 acre-ft/yr with the differences resulting from calibration of the techniques used by the investigator in developing a water, or isotopic, balance. Discharge within the valley is almost entirely from springs issuing from carbonate rocks and totals about 25,000 acre-ft/yr (tables 2 and 3). The large difference between recharge and discharge reflects throughflow of ground water in the valley, which Eakin (1966) included as part of the much larger White River ground-water flow system that originates in Jakes Valley to the north and extends to the Muddy Springs in the lower part of Moapa Valley to the south. Table 2 lists the recharge and discharge rates, as well as sources and destinations of ground-water flow into and out of Pahranagat Valley as reported by previous investigators. Most of the reported flow occurs in carbonate rocks.

Depth to water along the White River channel is at or near land surface from Hiko south to Maynard Lake. North of Hiko, the depth to ground water increases substantially. In Pahroc Valley to the north, for instance, the depth to ground water is 250 ft or more (Eakin, 1963b). The land-surface gradient from Pahroc Valley into Pahranagat Valley dips more steeply than does the water-table gradient; this, coupled with favorable geologic structure, results in the emergence of the three springs (P1, P2, and P3) along the eastern margin of Pahranagat Valley (fig. 5, table 3).

The potentiometric surface in the carbonate rocks is believed to be nearly coincident with (or is slightly higher than) the water level in the basin fill (Thomas and others, 1986). This coincidence indicates good hydraulic connection between the carbonate rocks and basin fill. The welded tuffs that separate the carbonate rocks from the basin fill are considered as aquifers in other parts of the State because they can transmit large quantities of ground water (Winograd, 1971; Winograd and Thordarson, 1975). The moderate amount of pumping from the basin fill in the past has had no apparent effect on spring discharge rates in the valley (Eakin, 1963b). Inflow from the carbonate rocks probably contributes a significant quantity of recharge to the basin-fill aquifer.

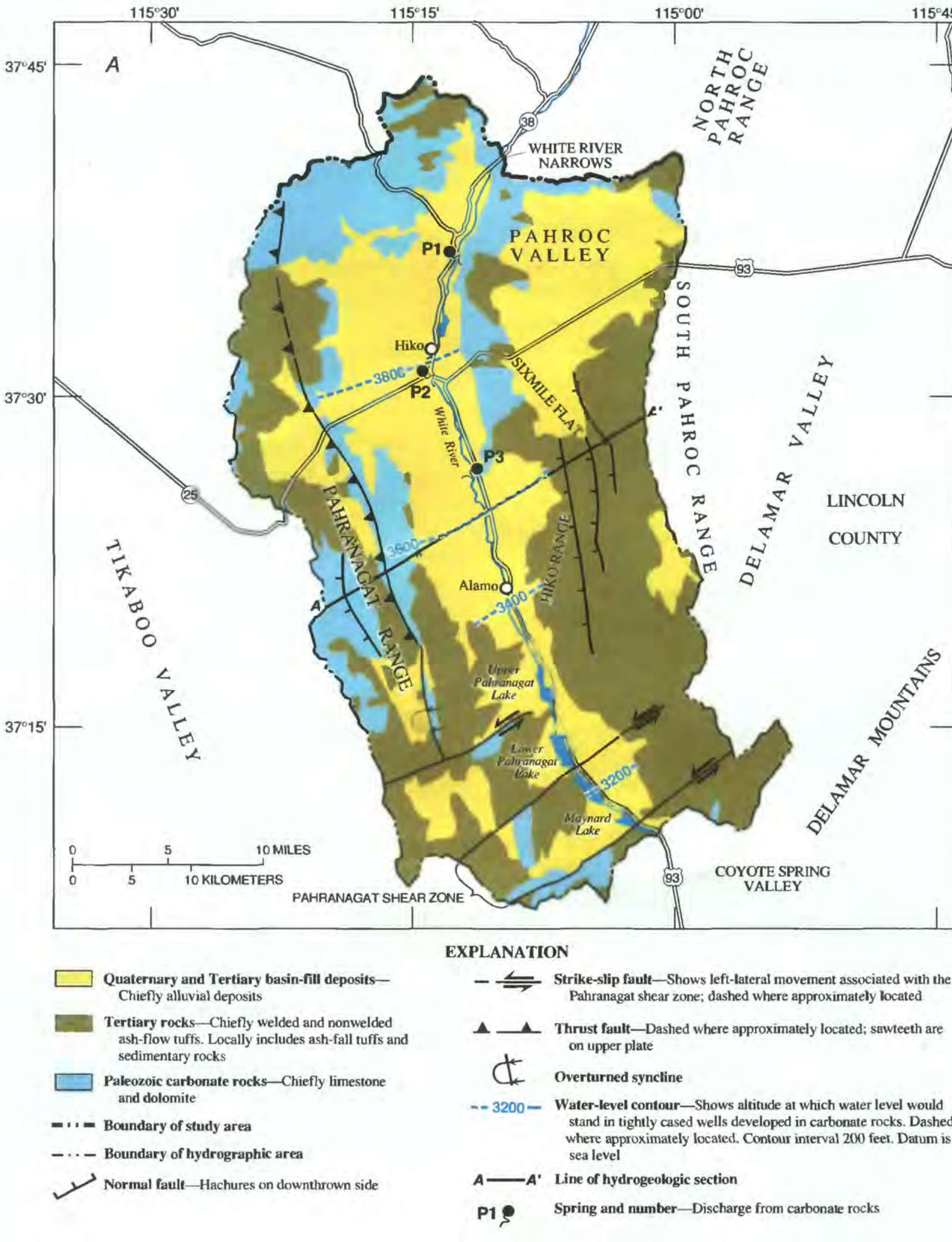


Figure 5. Hydrogeologic map and generalized section through Pahranagat Valley. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, water levels in the carbonate rocks, and springs where ground-water data are available (structural geology from Tschanz and Pampeyan, 1970, pl. 3; Ekren and others, 1977; hydrogeology from Thomas and others, 1986). *B*, Generalized hydrogeologic section through Pahranagat Valley. Arrows show direction of relative movement along faults. (Geology modified from Reso, 1963; Dolgoff, 1963; Bedsun, 1980).

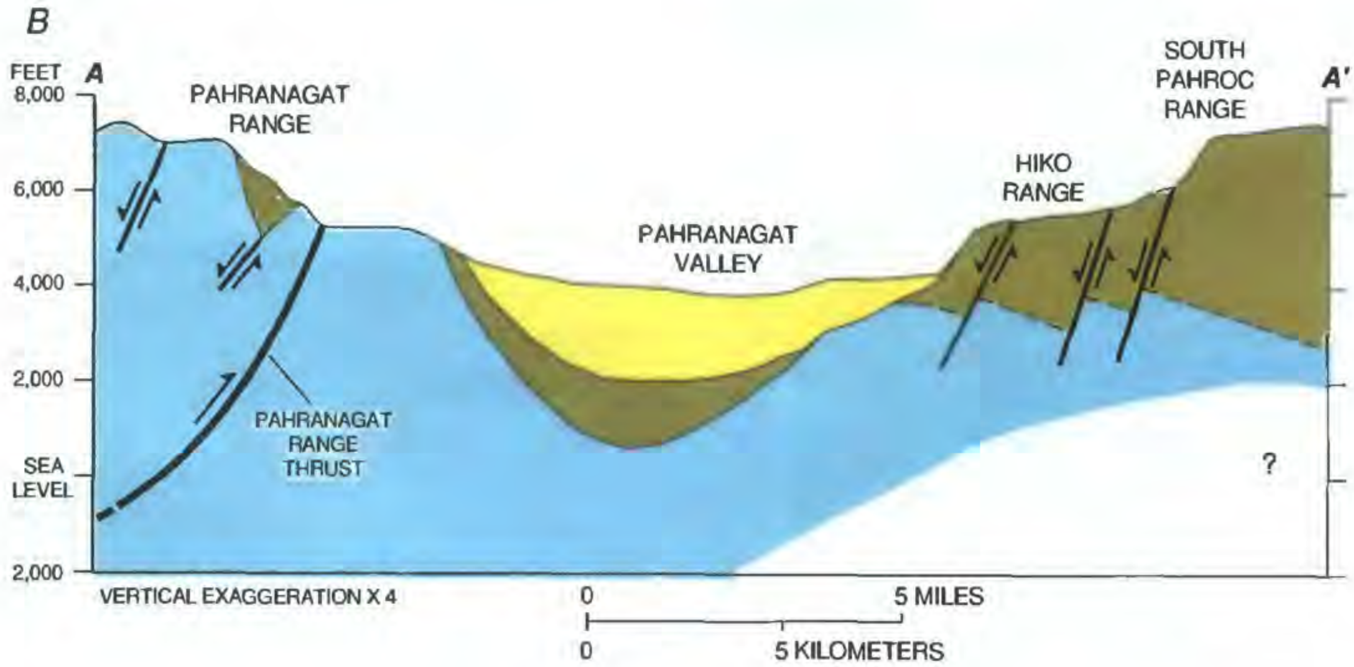


Figure 5. Continued.

Table 2. Recharge and discharge estimates for Pahranagat Valley

Component of recharge or discharge	Quantity (acre-feet per year)
Recharge	
Precipitation in Pahranagat and Hiko Ranges	
Eakin (1963b)	1,800
Welch and Thomas (1984)	2,000
Kirk (1987)	1,500
Subsurface inflow from Pahroc, Coal, Garden, Dry Lake, and Delamar Valleys	
Eakin (1966)	60,000
Welch and Thomas (1984)	51,000
Kirk (1987)	52,000
Discharge	
Evapotranspiration from phreatophytes and bare soils	
Eakin (1963b)	0
Springs issuing from carbonate rocks	
Eakin (1963b)	25,000
Pumpage from basin fill	
Eakin (1963b)	2,000
Frick [a]	250
Evaporation from lakes, ponds, and streams due to spring discharge	0 [b]
Subsurface outflow to Coyote Spring Valley and Ash Meadows flow system	
Eakin (1966)	35,000
Welch and Thomas (1984)	25,000
Kirk (1987)	29,400
Total recharge (rounded)	52,000-62,000
Total discharge (rounded)	50,000-62,000

[a] E.A. Frick, U.S. Geological Survey, oral commun., 1986.

[b] Budget values reflect that lakes, ponds, and streams result from spring discharge.

Table 3. Information on springs issuing from carbonate rocks and used for irrigation in Pahranagat Valley

(Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987)

Number (fig. 5)	Name	Discharge (acre-feet per year)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)
P1	Hiko	4,800	320	23
P2	Crystal	8,300	286	24
P3	Ash	11,800	286	32

The Pahranagat shear zone and other structures at the southern end of the valley may restrict subsurface flow from the valley toward the south. Thomas and others (1986) reported a steep hydraulic gradient at the south end of the valley with much lower water levels in Coyote Spring Valley than in southern Pahranagat Valley. Flow from the south end of the valley (about 6,000 acre-ft/yr) toward Ash Meadows has been suggested (Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Welch and Thomas, 1984; Kirk, 1987) and may be coincident with the Pahranagat shear zone.

The quantity of stored ground water within the carbonate rocks in the Pahranagat Valley hydrographic area has been estimated, on the basis of the assumptions made in the introduction of this report, to be 2.9 million acre-ft. Local storage (beneath the basin-fill deposits only) has been estimated to be 1.8 million acre-ft.

Potential for Ground-Water Development

Pahranagat Valley may be a potential site for development of the carbonate-rock aquifers, according to the criteria listed on plate 1. The entire valley is underlain by a thick section of carbonate rock (fig. 5) containing ground water of high quality (table 3). However, depth to water and depth to carbonate rock may limit to some degree the areas most favorable for potential development. Good hydraulic connection between basin fill and carbonate rock suggests that ground water may be induced to flow from the carbonate aquifers to wells drilled in basin fill. The most favorable area for development is a narrow north-trending zone along the White River channel in the northern half of the valley (fig. 5).

Development of the carbonate-rock aquifers beneath the valley could (1) reduce spring discharge in the surrounding area, (2) lower the water table within the basin fill because of the apparently good hydraulic connection between the carbonate rocks and overlying basin fill, (3) tap the potentially large storage reservoir beneath the valley, and (4) divert throughflow that leaves Pahranagat Valley to downgradient areas, such as the upper part of Moapa Valley and Ash Meadows (pl. 1), ultimately affecting spring discharge at these localities. Eakin (1963b) indicated that moderate pumping (2,000 acre-ft/yr) in the basin fill along the eastern part of Pahranagat Valley had no apparent effect on spring discharge, and water-level declines were minimal. Larger pumping volumes (or perhaps much longer pumping times), however, would likely affect storage and lower water levels within the basin fill. In addition, spring discharge in the nearby areas would almost certainly be reduced. The quantity of pumping required for these effects to occur is not known, but the location of development and the hydraulic characteristics of the carbonate rocks at depth would likely influence the quantity and commencement of the effects.

Delamar Valley

Hydrographic Setting

The Delamar Valley hydrographic area encompasses 383 mi^2 in central Lincoln County (fig. 6). The valley is surrounded by mountains except to the north where it is separated from Dry Lake Valley by a low topographic divide in the basin fill. Delamar Valley, however, is not hydrologically isolated from Dry Lake Valley, because ground water flows without restriction southward into Delamar Valley. A surface-drainage gradient in Delamar Valley of about 30 ft/mi terminates at a dry playa in the southernmost part of the area. There are no perennial streams in the valley. Ground-water outflow from Delamar Valley is tributary to the White River ground-water flow system to the southwest (Eakin, 1966), which terminates in the Muddy River Springs area (pl. 1). Development of the valley has been limited to livestock grazing as the depths to water are generally prohibitive for other economic activities.

Geology

The ranges surrounding Delamar Valley are dominated by Tertiary volcanic rocks, primarily ash-flow tuffs which may reach thicknesses of 4,000 ft in the South Pahroc Range (Tschanz and Pampeyan, 1970; fig. 6). However, at the Kane Springs Wash caldera complex in the Delamar Range, basaltic and rhyolitic volcanic rocks are common; thicknesses of volcanic rocks in the caldera complexes are unknown, but are likely to be great. Cambrian crystalline clastic rocks and Paleozoic carbonate rocks occupy parts of northwestern Delamar Mountains. Basin-fill deposits in Delamar Valley have been estimated to be about 4,000 ft thick, by use of geophysical methods (Bedsun, 1980). Bedsun also estimated the depth to Paleozoic carbonate rocks beneath the valley to be approximately 10,000 ft. If correct, the Tertiary volcanic rocks beneath Delamar Valley and overlying the carbonate rocks may be as much as 6,000 ft thick (fig. 6).

Compressional tectonics probably have not greatly affected the original thickness of carbonate rocks in the area, but the units may have undergone extreme extension that possibly thinned the carbonate-rock section in a manner similar to the extension that thinned a section described by Taylor and Bartley (1987) in Dry Lake Valley to the north, where four distinct extensional episodes were recognized. The Paleozoic carbonate-rock section in the Delamar Mountains is thin because only the lower part (Cambrian) of the section is exposed. However, the entire carbonate-rock section is probably present (but significantly thinned) beneath the valley (Taylor and Bartley, 1987). In addition, extension may have dropped the valley relative to the mountains by many thousands of feet as evidenced by the extremely thick basin-fill and Tertiary deposits beneath the valley floor (fig. 6). Consequently, most of the ground-water flow is likely to be through basin fill rather than carbonate rock.

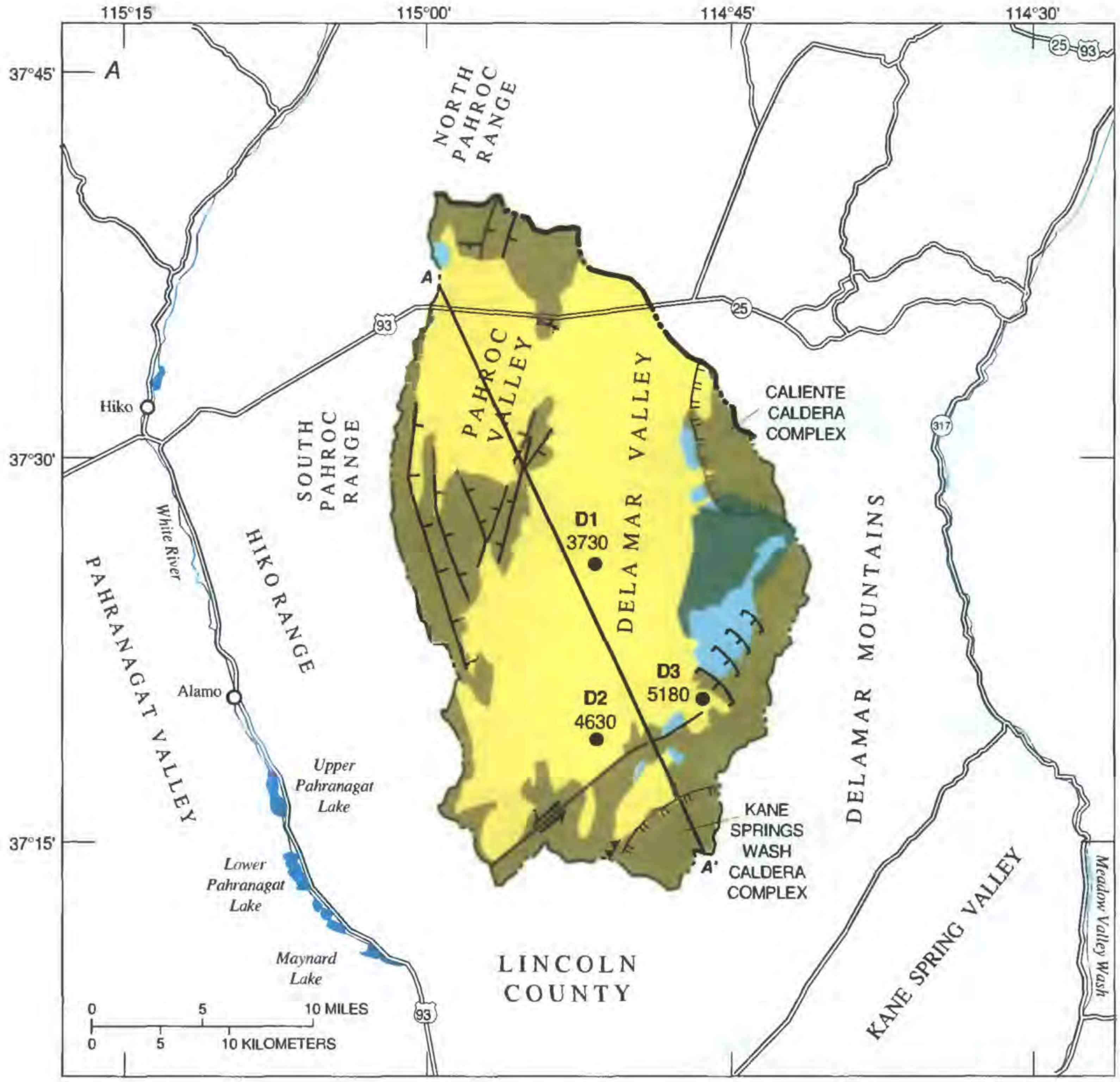
Hydrology

Although no wells penetrate the carbonate rocks beneath Delamar Valley, and only three wells (table 4) reach the water table, much has been inferred about ground-water flow beneath the valley. Local recharge from adjacent ranges has been estimated by Eakin (1963a) to be about 1,000 acre-ft/yr (table 5). Other investigators using this method have obtained estimates of recharge that differ slightly because of differing calibration processes (Welch and Thomas, 1984; Kirk, 1987; table 5). The remainder of the recharge to the valley is from subsurface inflow from Dry Lake Valley to the north. Virtually all discharge from Delamar Valley is by subsurface outflow to areas to the south and southwest, downgradient in the White River ground-water flow system.

The one available water-level measurement within the central part of Delamar Valley indicates that the water table is nearly 900 ft below the valley floor. The thickness of the basin fill and underlying volcanic rocks suggests that much of the subsurface flow probably moves through basin fill and Tertiary rocks rather than through carbonate rocks. Because the basin-fill deposits in valleys to the west and south are not nearly as thick as in Delamar Valley, it is likely that subsurface flow moves through basin-fill and volcanic rocks in Delamar Valley into carbonate rocks as flow moves downgradient within the White River ground-water flow system.

The quantity of subsurface flow beneath Delamar Valley was first estimated by Eakin (1966) to be 6,000 acre-ft/yr, equivalent to the recharge entering the ranges surrounding Dry Lake and Delamar Valleys (table 5). Kirk (1987) needed considerably more recharge from these areas to calibrate his isotopic model of the White River ground-water flow system. If additional underflow through Delamar Valley does occur, the source of water is probably from areas to the north and east of Dry Lake Valley and not from the local mountains. The total quantity of recharge contributed from these more northern areas is unknown and not sufficiently supported by field measurements, but Prudic and others (1993) indicate that it may be significant on the basis of a regional flow model.

The direction of subsurface outflow from Delamar Valley is not fully resolved. Eakin (1966) suggested on the basis of recharge and discharge estimates that the outflow from Delamar Valley enters Pahranagat Valley and may contribute to regional spring discharge there. Welch and Thomas (1984) developed an isotopic and geochemical model which indicates that the outflow from Delamar Valley enters Coyote Spring Valley to the south of Pahranagat Valley and does not contribute to spring discharge in Pahranagat Valley. Kirk (1987) concluded, on the basis of an isotope-mixing model, that most of the discharge from Delamar Valley enters Coyote Spring Valley, but a small quantity enters Pahranagat Valley.



EXPLANATION

- **Quaternary and Tertiary basin-fill deposits**—Chiefly alluvial deposits
- **Tertiary rocks**—Chiefly welded and nonwelded ash-flow tuffs. Locally includes ash-fall tuffs and sedimentary rocks
- **Paleozoic carbonate rocks**—Chiefly limestone and dolomite
- **Precambrian and Cambrian noncarbonate rocks**—Chiefly quartzite, siltstone, and shale with minor amounts of limestone and dolomite
- **Boundary of study area**
- **Boundary of hydrographic area**
- **Normal fault**—Hachures on downthrown side
- **Strike-slip fault**—Shows left-lateral movement associated with the Pahranagat shear zone. Dashed where approximately located
- **Thrust fault**—Sawteeth are on upper plate
- **Caldera rim**
- A——A' **Line of hydrogeologic section**
- D1 3730 **Well**—Penetrates water table, but does not reach carbonate rock beneath basin fill; upper number is well identifier, lower number is water-level altitude, in feet above sea level

Figure 6. Hydrogeologic map and generalized section through Delamar Valley. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, and water levels in basin fill which are considered equivalent to water levels in carbonate rocks in adjacent valleys (structural geology from Tschanz and Pampeyan, 1970, pl. 3; Ekren and others, 1977; hydrogeology from Thomas and others, 1986). *B*, Generalized hydrogeologic section through Delamar Valley (geology from Tschanz and Pampeyan, 1970; Ekren and others, 1977; Bedsun, 1980; Snyder, 1983).

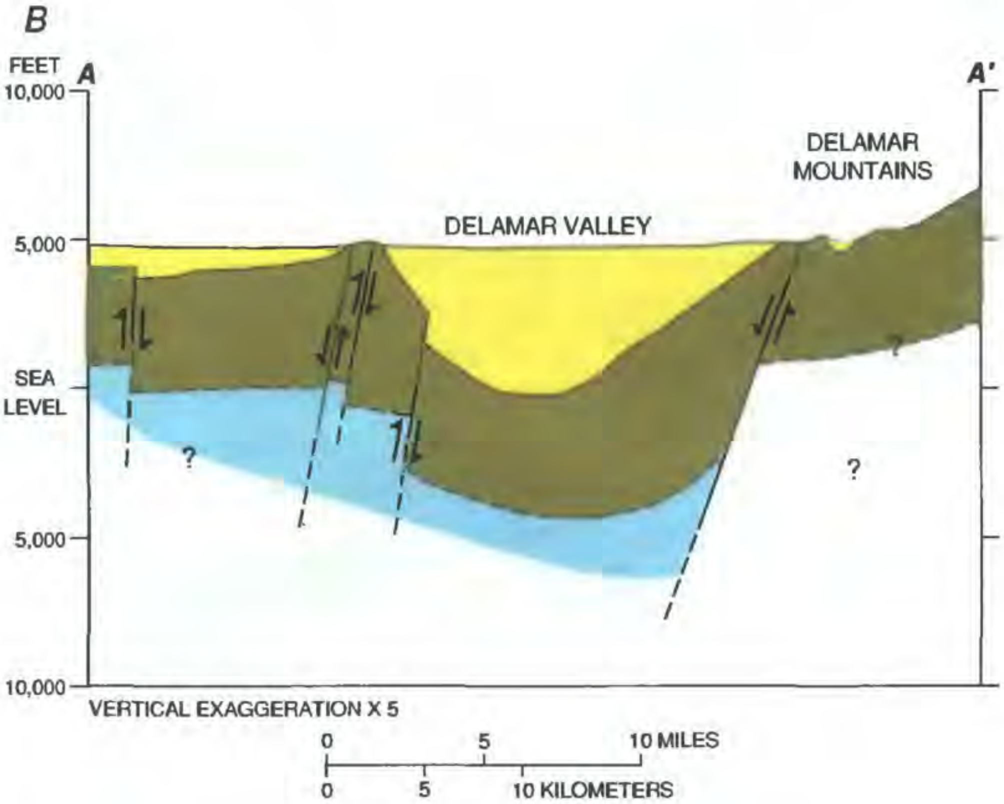


Figure 6. Continued.

There are not sufficient water-level data to determine an accurate water-level gradient that supports or refutes any of the above mentioned conclusions.

The quantity of storage within carbonate rocks beneath Delamar Valley is limited because depths to bedrock are likely to be impractical for development, except in the southeastern part of the valley. Storage for the entire area is estimated to be about 0.5 million acre-ft. Local storage (within the basin fill) is probably less than 0.3 million acre-ft.

Potential for Ground-Water Development

Delamar Valley has a low potential for development of ground water from the carbonate-rock aquifers. The depth to water in much of the valley is nearly 1,000 ft below land surface and the depth to carbonate rocks may be as much as 10,000 ft beneath the valley floor. Only in the southeast part of the valley are water levels moderately shallow; the depth to carbonate rocks there probably is considerably less than the 10,000 ft estimated near the center of the valley (Bedsun, 1980). Hence, potential for development is limited to a narrow area adjacent to the Delamar Mountains. However, even if development of the carbonate rocks

Table 4. Information on wells completed in basin fill in Delamar Valley

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations: D, domestic; N, not used; O, observation]

Number (fig. 6)	Owner	Total depth (feet)	Depth to water (feet below land surface)	Use
D1	USGS-MX Well	1,195	871	O
D2	Gulf Oil Corp.	265	220	N
D3	Private	95	63	D

Table 5. Recharge and discharge estimates for Delamar Valley

Component of recharge or discharge	Quantity (acre-feet per year)
Recharge	
Precipitation primarily in Delamar Range	
Eakin (1963a)	1,000
Welch and Thomas (1984)	1,000
Kirk (1987)	2,000
Subsurface inflow from Dry Lake Valley	
Eakin (1966)	5,000
Welch and Thomas (1984)	5,000
Kirk (1987)	7,000
Discharge	
Evapotranspiration from phreatophytes and bare soils; Eakin (1963a)	0
Springs issuing from carbonate rocks Eakin (1963a)	0
Subsurface outflow to Pahranagat and Coyote Spring Valleys	
Eakin (1966)	6,000
Welch and Thomas (1984)	6,000
Kirk (1987)	9,500
Total recharge (rounded)	6,000-9,000
Total discharge (rounded)	6,000-10,000

in southeastern Delamar Valley was possible, there is no indication that appreciable amounts of ground water flow into this area—either from recharge to the Delamar Mountains, which would be a small quantity, or as throughflow beneath the valley to downgradient areas within the White River ground-water flow system. In addition, the throughflow may not be easily recovered if the flow is deep.

Development of the basin-fill reservoir is a possibility, and effects on areas downgradient at spring discharge locations in Pahranagat Valley or in the Muddy River Springs area probably would not be fully realized for a long period—perhaps hundreds or even thousands of years. However, in order to capture the 6,000 acre-ft/yr of estimated throughflow beneath the valley, Eakin (1963a) indicated that pumping from a depth of at least 1,500 ft would be necessary.

Coyote Spring and Kane Springs Valleys and the Muddy River Springs Area

Hydrographic Setting

The Coyote Spring Valley, Kane Springs Valley, and Muddy River Springs hydrographic areas (1,025 mi^2) in southern Lincoln and northern Clark counties have been combined for this report because the areas are hydrologically related and topographically connected. Coyote Spring Valley contains the ephemeral diminutive channel and flood plain of the White River, which is continuous to Muddy River Springs (fig. 7). Kane Springs Wash is a major tributary to the White River drainage system. Only occasional flood waters flow in either of these streams. Drainage of the hydrographic areas is from the north (Pahranagat Valley) and northeast (Kane Springs Valley) to the south and southeast (Muddy River Springs Area). Ground-water flow likewise is generally in a south and southeast direction.

Ground water issuing from the Muddy River Springs forms the headwaters of the Muddy River that provides irrigation water to farms in the upper and lower parts of Moapa Valley. Coyote Spring and Kane Springs Valleys are used principally for livestock grazing, whereas the Muddy River Springs area has several dairy and other farming operations.

Geology

Tertiary volcanic rocks are dominant in the northern part of the hydrographic area, whereas Paleozoic carbonate rocks dominate the central and southern part of the area (fig. 7). Thick sequences of tuffaceous rocks are predominant throughout the Kane Springs Valley area. The Kane Springs Wash caldera complex, however, contains rhyolitic and basaltic flows that are likely to be many thousands of feet thick. A similar caldera complex at the Nevada Test Site (Blankennagel and Weir, 1973) contains at least 10,000 ft of volcanic rocks. Consequently, if any carbonate rocks are present beneath the complex they are probably at great depths. A rather sharp transition from volcanic to carbonate rocks occurs in the northern part of Coyote Spring Valley (fig. 7). Thicknesses of the dominant carbonate rock have been measured to be more than 10,000 ft in the Sheep Range (Guth, 1981). Basin fill directly overlies carbonate rocks in most areas, and thicknesses generally range from 500 to 1,000 ft throughout most of Coyote Spring Valley, but increase to more than 3,000 ft in the southeast part of the area including the Muddy River Springs area (fig. 7, pl. 1). Tertiary deposits containing evaporite minerals account for a large part of the basin-fill thickness. A sliver of Precambrian and Cambrian clastic rocks exposed adjacent to the Gass Peak thrust in the Sheep Range (fig. 7) probably extends thousands of feet beneath the range.

Thrust faulting and folding during the late Mesozoic deformed the region, especially along the Gass Peak and Dry Lake thrust faults (fig. 7). Along the Gass Peak thrust, Precambrian and Cambrian clastic rocks were thrust over nearly an entire section of Paleozoic carbonate rocks (D.L. Schmidt, U.S. Geological Survey, written commun., 1986). The northern extent of this fault and the thickness of these clastic rocks of low permeability beneath the western part of Coyote Spring Valley are not known, but clastic rocks probably restrict eastward flow from the Sheep Range.

Extensional forces were a major factor in modifying not only the landscape, but influencing the hydrology of the area as well. The central part of the region that includes Coyote Spring Valley and the Muddy River Springs area remained relatively intact (stable) during this time (Wernicke and others, 1984), but abundant intersecting high-angle normal faults probably provided good ground-water conduits toward the Muddy River Springs (D.L. Schmidt, U.S. Geological Survey, written commun., 1985). In contrast, highly extended terrane bounds this stable area to the west (west of the Sheep Range) and east (east of the Muddy River Springs and Meadow Valley Mountains). To the east, extensional faulting produced the deep Meadow Valley Wash basin between the Mormon Mountains to the east and the Muddy River Springs area to the west (H.R. Blank, U.S. Geological Survey, written commun., 1985). This basin is filled with Tertiary basin-fill deposits of low permeability (pl. 1) which are believed to dam regional flow in the thick carbonate-rock aquifer, causing an upward component of flow in the Muddy River Springs Area (M.D. Dettinger, U.S. Geological Survey, written commun., 1987).

The northern boundary of the hydrographic area along the Delamar Mountains consists of Tertiary volcanic rocks underlain by thick carbonate rocks. This area coincides with the southern extent of the Pahranagat shear zone (fig. 5). The Pahranagat shear zone along this northern boundary is probably a partial barrier to southward-trending ground-water flow.

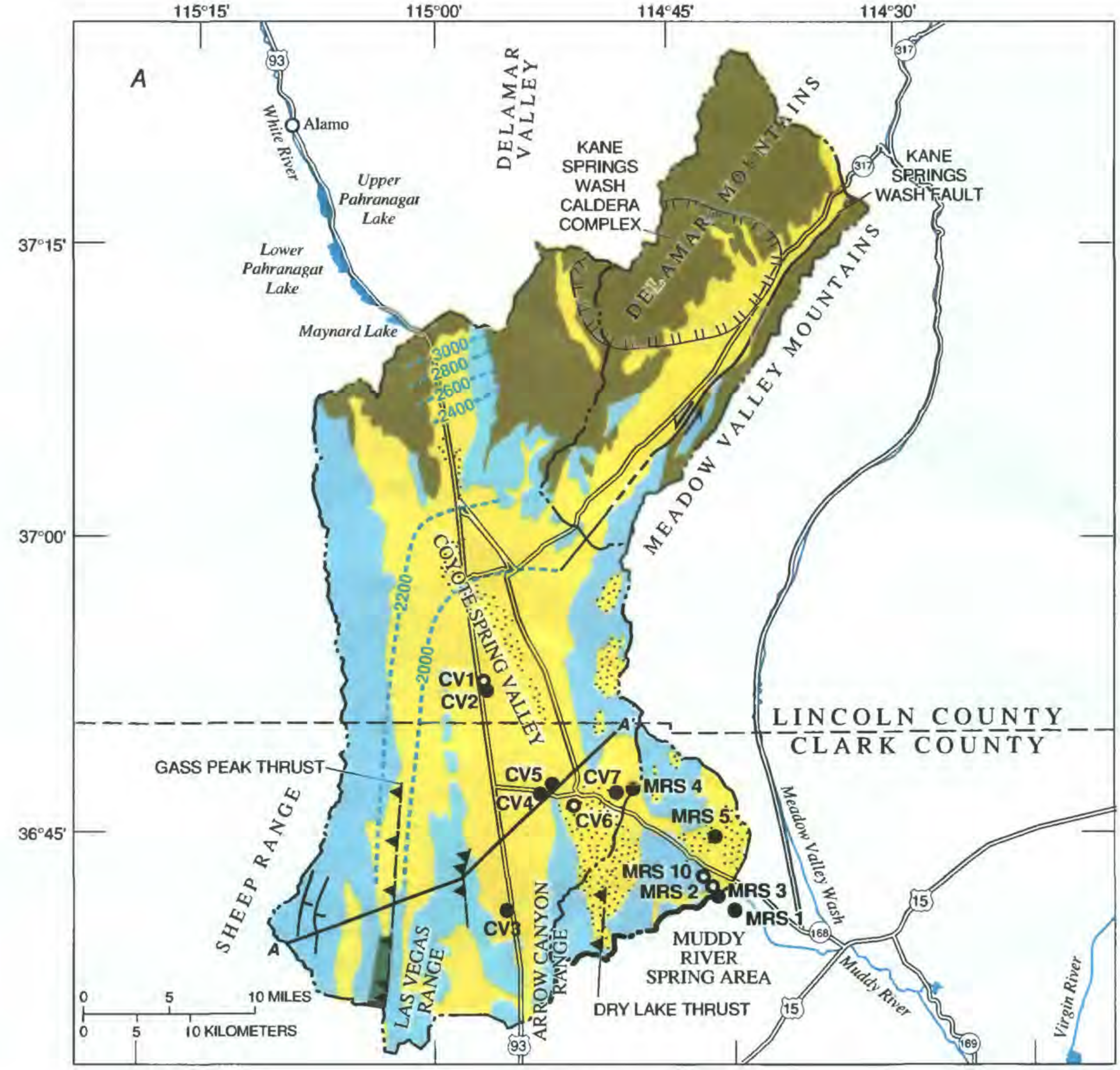
Hydrology

Local recharge in the three hydrographic areas was estimated by Eakin (1964) using empirical techniques to be 2,600 acre-ft/yr. Other investigators using the Maxey-Eakin method have adjusted their estimates of recharge based on geochemical techniques (Welch and Thomas, 1984) and isotopic modeling studies (Kirk, 1987) in this part of the White River ground-water flow system (table 6). More recent geochemical studies suggest that local recharge from the Sheep Range may be considerably larger than estimates obtained from traditional empirical techniques or previous geochemical and isotopic models (J.M. Thomas, U.S. Geological Survey, oral commun., 1988). This recharge is augmented by deep through-flowing water in carbonate rocks beneath Pahranagat and White River Valleys in the north, and possibly Dry Lake and Delamar Valleys in the northeast. An additional component of shallow inflow may come from Meadow Valley Wash to the east (Kirk, 1987; J.M. Thomas, U.S. Geological Survey, oral commun., 1988; table 6). Discharge from these areas is almost entirely by spring discharge at the Muddy River Springs and is 36,000 acre-ft/yr (Eakin and Moore, 1964).

Water levels beneath Coyote Spring Valley are considerably deeper than in Pahranagat Valley to the north (generally about 350-600 ft beneath the valley floor; Berger and others, 1988). The depth to water decreases toward the Muddy River Springs, which issues from basin fill overlying carbonate rocks. The discharge at the springs is probably entirely from carbonate rocks (Eakin, 1964).

Geochemical and isotopic studies (J.M. Thomas, U.S. Geological Survey, oral commun., 1988) suggest that at least one-half of the discharge at the Muddy River Springs is derived in southern Nevada from the Sheep Range and the Meadow Valley Wash ground-water flow system. The remainder of the discharge is throughflow from the White River ground-water flow system to the north. This suggests that recharge from the Sheep Range may be about 12,000-14,000 acre-ft/yr, slightly more than the 11,000 acre-ft/yr estimated as the total recharge from this mountain range, and five times more than the quantity estimated by Eakin (1966) to recharge Coyote Spring Valley. Throughflow from the Meadow Valley Wash area originates in the volcanic mountains south of Caliente (northeast of Kane Springs Wash [Emme, 1986]) and appears, on the basis of geochemical and isotopic data, to enter the area northeast of the deep carbonate wells located in Coyote Spring Valley. Ground water from the Meadow Valley Wash ground-water flow system probably flows beneath the Meadow Valley Mountains (fig. 7).

Estimates of stored water within the carbonate rocks beneath Coyote Spring Valley have been made on the basis of pumping tests (Bunch and Harrill, 1984; M.D. Dettinger, U.S. Geological Survey, written commun., 1988). Based on the assumptions described in this report, the estimated ground-water storage in carbonate rocks beneath the three areas is 8.7 million acre-ft. Of this total, about 80 percent occurs within the Coyote Spring hydrographic area; only small quantities of storage are likely to be present in the other two hydrographic areas. Local storage (beneath the basin fill) has been estimated at 5.0 million acre-ft for the three areas. The ground-water flow system beneath Coyote Spring Valley is probably not well connected with adjacent flow systems except to the east, with the ground-water flow system in the western part of the Lower Meadow Valley Wash area.



EXPLANATION

Quaternary and Tertiary basin-fill deposits—Chiefly alluvial, fluvial, and fan deposits, lake deposits of clay siltstone, and sandstone. Stippled areas are primarily tuffaceous sedimentary rocks, locally containing evaporative minerals (salt)

Tertiary rocks—Chiefly welded and nonwelded ash-flow tuffs. Locally includes ash-fall tuffs and sedimentary rocks

Paleozoic carbonate rocks—Chiefly limestone and dolomite

Precambrian and Cambrian noncarbonate rocks—Chiefly quartzite, sandstone, limestone, shale, and siltstone. Locally abundant metamorphic rocks

Boundary of study area

Boundary of hydrographic area

Normal fault—Hachures on downthrown side

Strike-slip fault—Shows left lateral movement. Dashed where approximately located

Thrust fault—Dashed where approximately located. Sawteeth on upper plate

Caldera rim

A——A' **Line of hydrogeologic section**

-- 3200 — **Water-level contour**—Shows altitude at which water level would stand in tightly cased wells developed in carbonate rocks. Dashed where approximately located. Contour interval, 200 feet. Datum is sea level

Data point and number—Site location where ground-water data are available:

CV1 ○ Completed in basin fill

CV2 ● Completed in carbonate rocks

Figure 7. Hydrogeologic map of Coyote Spring Valley, Kane Springs Valley, and Muddy River Springs area and generalized hydrogeologic section through southern Coyote Spring Valley. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, water levels in the carbonate rocks, and points where ground-water data are available for carbonate rocks (structural geology from D.L. Schmidt, U.S. Geological Survey, written commun., 1987; Ekren and others, 1977; hydrogeology from Thomas and others, 1986). *B*, generalized hydrogeologic section through the southern part of Coyote Spring Valley (geology from D.H. Schaefer, U.S. Geological Survey, written commun., 1988; D.L. Schmidt, U.S. Geological Survey, written commun., 1988).

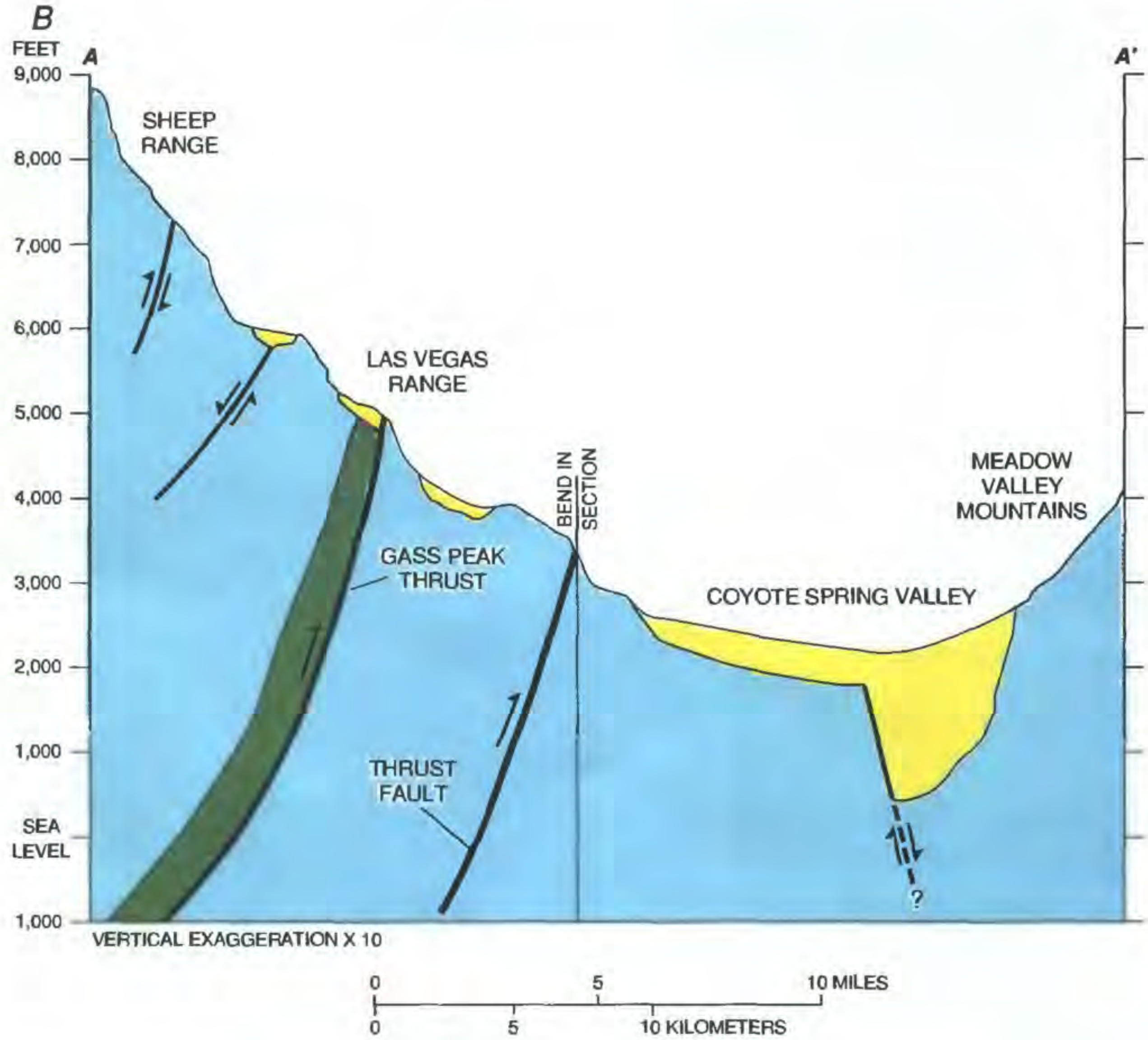


Figure 7. Continued.

Potential for Ground-Water Development

Much of Coyote Spring Valley and the Muddy River Springs area has the potential for development of the carbonate-rock aquifers on the basis of the criteria listed on plate 1. In contrast, Kane Springs Valley is probably not a favorable area for development because of the large depths to water (greater than 1,000 ft) and potentially large depths to carbonate rocks. Other important factors cannot be overlooked if these areas are to be developed because little, if any, water leaves the hydrographic areas as subsurface flow either to the south (to Hidden Valley) or east. The measured discharge at Muddy Springs may represent the entire recharge-plus-inflow to the area; hence, any pumping from the carbonate rocks within this area is likely to affect discharge at Muddy Springs. Well CV7 in carbonate rock (fig. 7) is used as a municipal supply during summer months when water demands are high, but the well has not yet been pumped enough to determine what effect this may have on discharge at Muddy Springs. The Muddy River Springs area contains lower quality water than upgradient areas because of the presence of evaporite minerals in the Tertiary deposits, but the quality (table 7, pl. 1) passes the criteria test developed earlier.

Lower Meadow Valley Wash

Hydrographic Setting

The Lower Meadow Valley Wash hydrographic area occupies approximately 979 mi^2 in eastern Lincoln and northeastern Clark Counties. Perennial streamflow in Meadow Valley Wash, supplied primarily by runoff from the Clover Mountains, brought ranchers to the area more than 120 years ago (Rush, 1964). Later, when the Union Pacific Railroad was built through the area, Caliente became a railroad division point and population center for the area (fig. 8). Today, the community of Caliente has about 1,000 residents.

Table 6. Recharge and discharge estimates for Coyote Spring Valley, Kane Springs Valley, and Muddy River Springs Area

[Symbols: --, no data; <, less than; >, greater than]

Component of recharge or discharge	Quantity (acre-feet per year)		
	Coyote Spring Valley	Kane Springs Valley	Muddy River Springs area
Recharge			
Precipitation in adjacent mountain blocks			
Eakin (1964)	2,100	500	0
Welch and Thomas (1984)	4,000	500	0
Kirk (1987)	2,700	1,000	0
Subsurface inflow			
Eakin (1966)	35,000	0	37,000
Welch and Thomas (1984)	24,000 [a]	0	36,000 [c]
Kirk (1987)	26,800 [b]	0	34,000 [d]
Discharge			
Evapotranspiration from phreatophytes and bare soils			
Eakin (1964)	<200	<200	0
Springs issuing from carbonate rocks			
Eakin and Moore (1964)	<200	<200	36,000 [e]
Pumpage from basin fill or carbonate rocks			
Eakin (1964)	0	0	3,000
Whipple [f]	<300	--	--
Subsurface outflow			
Eakin (1966)	37,000 [g]	500 [h]	<200
Welch and Thomas (1984)	28,000	500	0
Kirk (1987)	29,500	1,000	0
Total recharge (rounded)	26,000-39,000	500-1,000	34,000-37,000
Total discharge (rounded)	>28,000-37,000	>500-1,000	36,000-39,000

[a] Includes 5,000 acre-feet per year from Dry Lake Valley, 2,000 acre-feet per year from Delamar and Kane Springs Valleys, and 17,000 acre-feet per year from Pahranagat Valley.

[b] Includes 16,500 acre-feet per year from Pahranagat Valley, 9,300 acre-feet per year from Dry Lake and Delamar Valleys, and 1,000 acre-feet per year from Kane Springs Valley.

[c] Includes 8,000 acre-feet per year from Meadow Valley Wash.

[d] Includes 4,500 acre-feet per year from Meadow Valley Wash.

[e] 33,700 acre-feet per year leaves as streamflow to the Muddy River. Some diurnal and seasonal fluctuations in discharge occur due to local evapotranspiration.

[f] J. Whipple, Moapa Water District, oral commun., 1988.

[g] Subsurface outflow to Muddy River Springs area.

[h] Subsurface outflow to Coyote Spring Valley.

Table 7. *Information on wells completed in and springs issuing from carbonate rocks and basin fill in Coyote Spring Valley and Muddy River Springs area*

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations and symbols: D, domestic; I, irrigation; O, observation; --, no data; ~, approximate]

Number (fig. 7)	Source	Name	Depth to water (feet below land surface)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)	Use
CV1	well	VF1 [a]	543	230	--	O
CV2	well	VF2	604	470	33.8	O
CV3	well	CSV3	587	380	41.1	O
CV4	well	MX4 [b]	350	480	33.8	O
CV5	well	MX5	349	470	35.5	O
CV6	well	CSV1 [a]	344	320	15.5	O
CV7	well	MX6	457	560	33.3	D
MRS1	springs [c]	Muddy River [d]	0	610	32.2	I
MRS2	well	EH-4 [a]	--	~600	23.88	O
MRS3	well	EH-5	--	~600	28.88	O
MRS4	well	CSV2	391	590	27.2	O

[a] Well penetrates basin fill, but water level may reflect that of carbonate rocks below.

[b] Pump-test data at well CV4 indicate specific yield of 14 percent, with transmissivity of 1 million feet squared per day (Ertec, 1981).

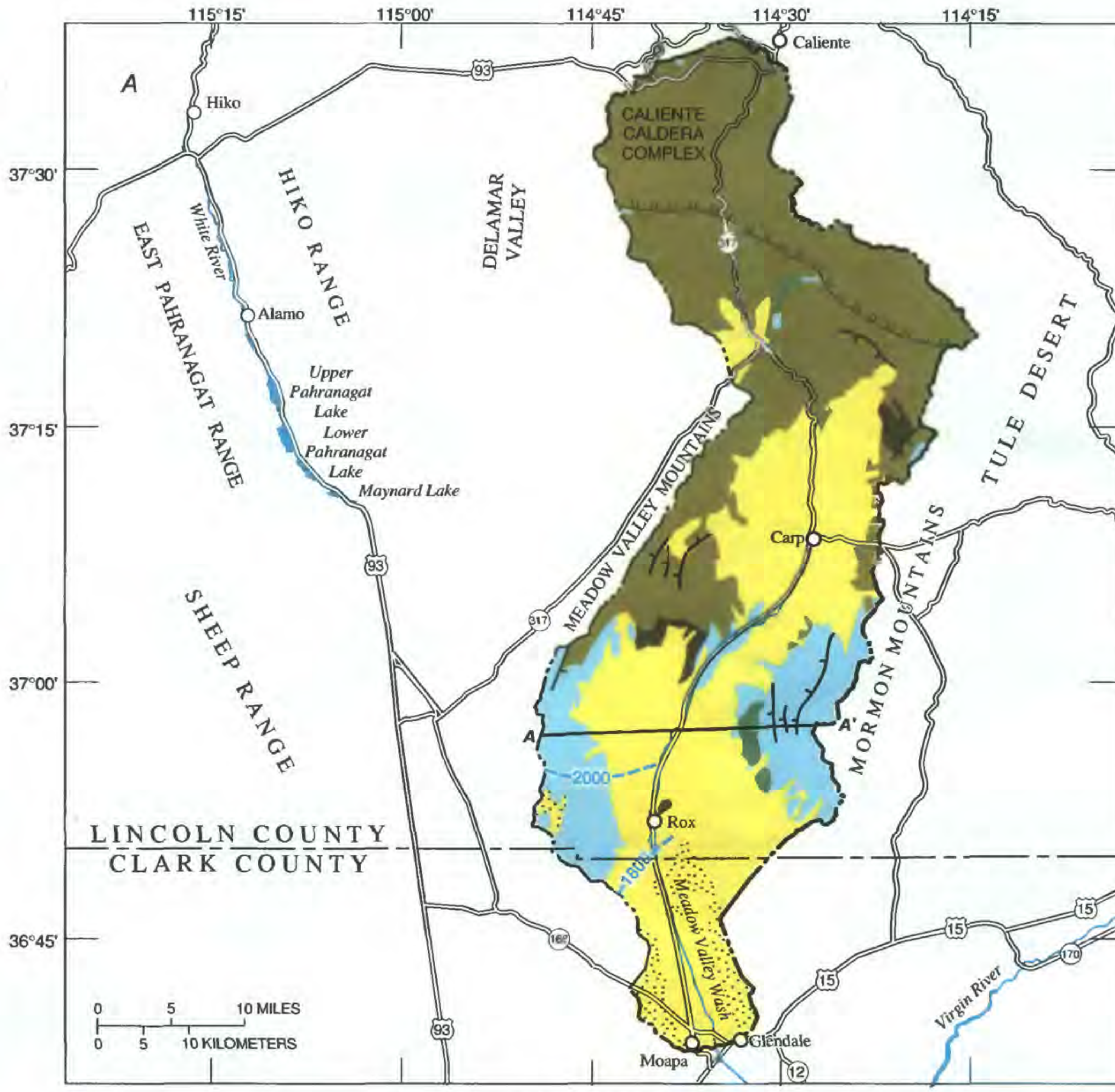
[c] Combined flow of several springs.

[d] Discharges 36,000 acre-ft/yr.

Meadow Valley Wash was incised through volcanic rocks in the northern part of the area and primarily through basin-fill deposits in the southern part of the area. The wash trends southward to the Muddy River (fig. 8), which drains into the Colorado River to the southeast. The wash south of about 37°N latitude is ephemeral due to pumping, evapotranspiration, and infiltration along its course.

Geology

The lower Meadow Valley Wash area has undergone an extremely complex geologic history that has only recently begun to be understood (Wernicke and others, 1985; Axen and others, 1987; G.J. Axen, Harvard University, written commun., 1988; Axen and others, 1988a; Axen and others 1988b). In general, the northern part of the Lower Meadow Valley Wash area consists predominantly of volcanic rocks, mostly tuffs, many of which erupted from the large Caliente caldera complex (Ekren and others, 1977) during the early Miocene. The total thickness of volcanic rocks in the caldera complex is unknown, but is believed to be at least several thousand feet. In the southern one-half of the area, exposed rocks are chiefly Paleozoic carbonates. The thickness of carbonate rocks may increase westward toward the miogeocline where much thicker deposits of carbonate rocks were deposited during the Paleozoic. Hence, the Meadow Valley Mountains may represent a much thicker sequence of carbonate rock than the Mormon Mountains. Thicknesses of carbonate rocks are generally only 1,000-3,000 ft in the



EXPLANATION

Quaternary and Tertiary basin-fill deposits—Chiefly alluvial, fluvial, and fan deposits, lake deposits of clay siltstone, and sandstone. Stippled areas are primarily tuffaceous sedimentary rocks, locally containing evaporative minerals (salt)

Tertiary rocks—Chiefly welded and nonwelded ash-flow tuffs. Locally includes ash-fall tuffs and sedimentary rocks

Upper Paleozoic carbonate rocks—Chiefly siltstone, claystone, and cherty limestone, with sparse conglomerate and gypsum

Paleozoic carbonate rocks—Chiefly limestone and dolomite

Precambrian and Tertiary basin-fill deposits—Chiefly quartzite, sandstone, limestone, shale, and siltstone. Locally abundant metamorphic rocks

Boundary of study area

Boundary of hydrographic area

Caldera rim

Normal fault—Hachures on downthrown side

A——A' **Line of hydrogeologic section**

--1800— **Water-level contour**—Shows altitude at which water level would stand in tightly cased wells developed in carbonate rocks. Dashed where approximately located. Contour interval, 200 feet. Datum is sea level

Figure 8. Hydrogeologic map and generalized section through Lower Meadow Valley Wash. *A*, Hydrographic area showing rock units and major structural features (structural geology from Ekren and others, 1977; Wernicke and others, 1985; Axen and others, 1987; and G.J. Axen, Harvard University, written commun., 1988; hydrogeology from Thomas and others, 1986; Emme, 1986). *B*, Generalized hydrogeologic section through the Lower Meadow Valley Wash (geology from P.L. Guth, Harvard University, written commun., 1988).

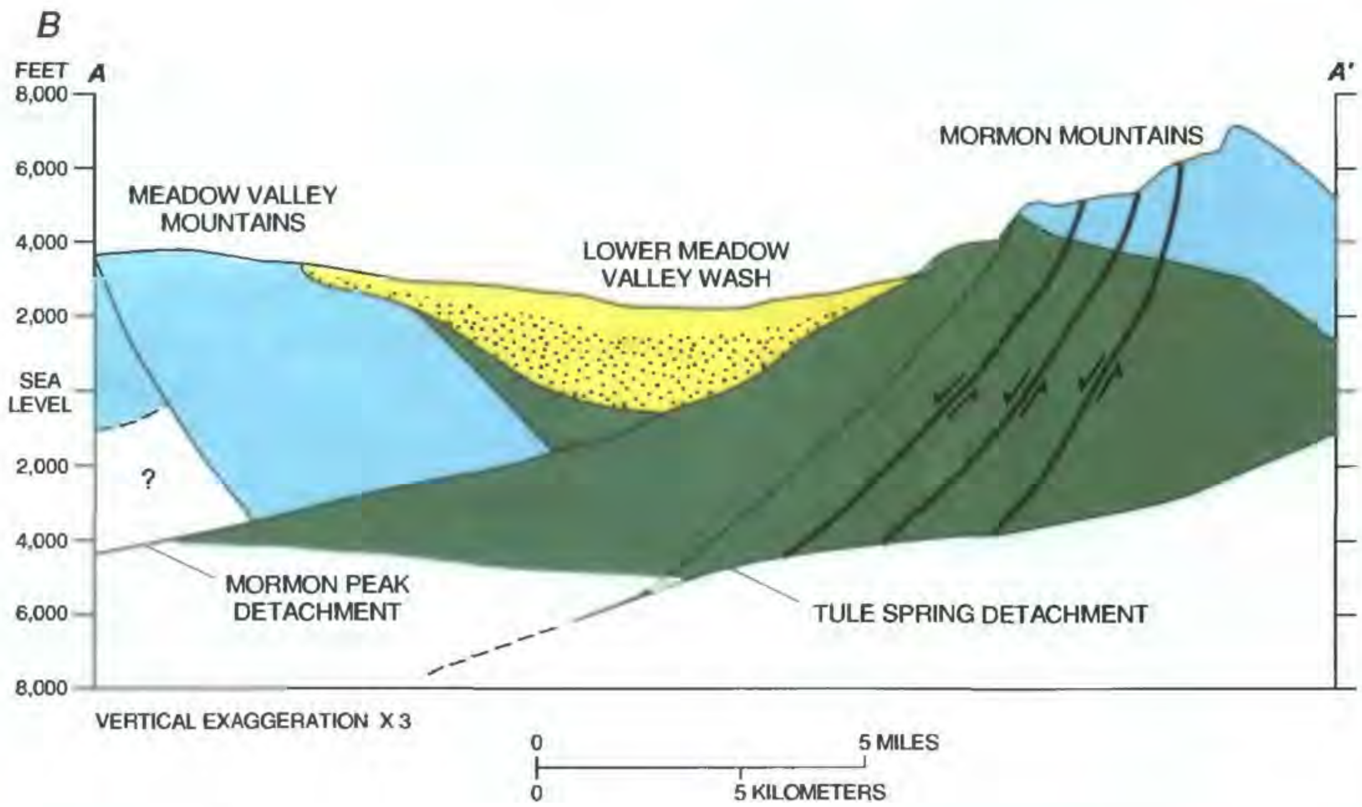


Figure 8. Continued.

Mormon Mountains and perhaps 5,000-6,000 ft in the Meadow Valley Mountains (fig. 8). Paleozoic rocks may be absent beneath much of the valley. A thick wedge of Tertiary deposits and Mesozoic sedimentary rocks occupies the basin between the ranges. Tertiary deposits thicken southward and may exceed 4,000 ft in the extreme southern part of the area (B.F. Lyles, Desert Research Institute, oral commun., 1988). Mesozoic sedimentary rocks containing evaporites may be abundant beneath the north-central part of the area (D.L. Schmidt, U.S. Geological Survey, oral commun., 1988) and may influence the quality of ground water. In the western part of the Mormon Mountains, exposures of Precambrian and Cambrian noncarbonate rocks, comprised mainly of quartzite, conglomerate and other clastic, and metamorphic rocks, are common. These rocks of low permeability probably act as a barrier to ground-water flow. These rocks become more predominant with depth, as schematically shown in figure 8.

Evidence for eastward thrusting and thickening of the Paleozoic section has been found in the Mormon Mountains (Wernicke and others, 1985). Later, in middle Tertiary time, extreme extension between the Mormon and Meadow Valley Mountains (fig. 8) has resulted in a highly complex, highly broken, faulted, and thin sequence of Paleozoic rocks overlying Cambrian clastic and Precambrian basement rocks in the Mormon Mountains (fig. 8). These highly broken carbonate rocks probably represent a large aquifer system where located below the water table. Extension greatly thinned the area between the Mormon and Meadow Valley Mountains (5-16 mi of extension likely, Wernicke and others, 1985). Thick sequences of Tertiary deposits overlie Mesozoic to Precambrian rocks beneath the basin between these ranges. Extension in this area probably postdates active volcanism in the northern part of the hydrographic area (Axen and others, 1987; Axen and others, 1988a); hence, many of the volcanic rocks are probably highly fractured and may transmit a significant amount of water locally. Extensional boundaries concomitant with stable or less extended areas often represent flow-system boundaries as well (Dettinger, 1987).

Hydrology

Recharge from surrounding mountain ranges, namely the Clover and Delamar Mountains to the north and the Mormon Mountains to the east, is estimated to be 1,300 acre-ft/yr (Rush, 1964). Recharge in the Meadow Valley Mountains (estimated by the Maxey-Eakin method to be about 1,000 acre-ft/yr) probably flows southward beneath the range to the Muddy River Springs area, and does not likely contribute significantly to the Lower Meadow Valley Wash hydrographic area. Additional water from surface flow within Meadow Valley Wash and subsurface inflow from areas to the north probably contribute most of the ground water in Meadow Valley Wash. Surface-water flow in Meadow Valley Wash south of Caliente averages about 8,800 acre-ft/yr (Frisbie and others, 1985). However, Rush (1964) concluded that the total surface-water contribution to ground-water flow in the wash is considerably less because pumping (water primarily from the river) and evapotranspiration account for an estimated 6,000 acre-ft/yr of this total. The amount of subsurface inflow from the north has not been estimated, but Emme (1986) suggests that the amount may be negligible on the basis of the isotopic and geochemical composition of ground water north of the area. The presumed absence of subsurface inflow may be attributed to the thick volcanic section in the northern part of the area.

No wells penetrate carbonate rocks in the area; consequently, water levels within the carbonate rocks are not known. Water levels within the basin fill are shallow throughout much of the area, but correlation between these water levels and those within the carbonate rocks is difficult to postulate—particularly in the southern part of the area where late Tertiary sediments are thick and may confine the water within the carbonate rocks. Perhaps only in the southwesternmost part of the area are basin-fill water levels representative of water levels in the underlying carbonate rocks.

Ground-water flow within the Lower Meadow Valley Wash area is generally from north to south in either the shallow alluvium or in Paleozoic carbonate rocks at depth along the west side of the valley (fig. 8) because the Tertiary and Mesozoic deposits have low permeability. Rush (1964) estimated that between 4,400 and 8,000 acre-ft/yr of ground water may leave the area as subsurface outflow near Glendale at the southernmost part of the valley (fig. 8). The amount of discharge surpasses the amount of estimated recharge; hence, the additional source of recharge to the area must be either (1) recharge from the volcanic rocks in the northern part of the hydrographic area, (2) surface water that infiltrates into the basin fill, or (3) subsurface inflow from outside the immediate hydrographic area boundary. The first of these three sources is the most plausible because, as stated earlier, the volcanic rocks may be highly fractured and may allow more infiltration of precipitation than previously thought. Subsurface inflow may also contribute additional ground water to the area (Prudic and others, 1993). Further studies are needed to accurately describe the quantity and origin of ground water recharged to and discharged from the area.

The structural geology of the area is such that two distinct flow systems may be present. The main flow system probably extends from the Clover and Delamar Mountains in the north to the south-southwest beneath the Meadow Valley Mountains where the carbonate rock section is thickest. J.M. Thomas (U.S. Geological Survey, oral commun., 1988) suggests that discharge from the Lower Meadow Valley Wash area supports spring discharge in the Muddy River Springs area (figs. 7 and 8). Ancient spring mounds (areas where springs once discharged) in the eastern Meadow Valley Mountains (D.L. Schmidt, U.S. Geological Survey, written commun., 1988) indicate that abundant ground water flowed during late Tertiary time beneath the Meadow Valley Mountains. This may indicate that the main flow path today is similarly located.

A second flow system within the area may be a narrow zone extending southward from the Mormon Mountains (Dettinger, 1987). Because Precambrian crystalline rock as well as Cambrian clastic rocks, Mesozoic sedimentary rocks, and upper Tertiary sediments occupy much of the area between the western Mormon Mountains and the Meadow Valley Mountains (fig. 8), it is unlikely that flow from these two areas mixes beneath the central part of the valley. Instead, recharge from the Mormon Mountains may feed Rogers and Blue Point Springs farther to the south (M.D. Dettinger, U.S. Geological Survey, oral commun., 1988).

The total quantity of storage in the carbonate rocks of the Lower Meadow Valley Wash area has been estimated, on the basis of the assumptions described earlier in this report, to be about 2.7 million acre-ft. This estimate is likely to be high as the thickness of saturated carbonate rock is limited beneath the Mormon Mountains. Local storage (within the basin fill) is limited to areas adjacent to the Meadow Valley Mountains (pl. 1) and has been estimated to be about 0.7 million acre-ft. This local storage reservoir is probably continuous with the carbonate-rock reservoir beneath the Coyote Spring Valley hydrographic area located to the west of the Meadow Valley Mountains.

Potential for Ground-Water Development

Parts of the Lower Meadow Valley Wash area may be favorable sites for development; however, further study is needed to accurately describe the hydrology of the area because no wells penetrate the underlying carbonate rocks. Geologic sections (G.J. Axen, Harvard University, written commun., 1988) indicate that the carbonate rocks along the western side of the valley (east of the Meadow Valley Mountains) are several thousand feet thick and relatively shallow beneath the basin fill (pl. 1). However, this is a questionable site for development until further investigations are made because of the uncertainty about the depth to water, the quantity of water, and the effects of development on discharge at Muddy River Springs.

The eastern part of the area, where carbonate rocks are known to be present, is not easily accessible except in the extreme south because Precambrian rocks are exposed in the western part of the Mormon Mountains, and the amount of flow is probably not more than several thousand acre-ft/yr. Thus, this area is also a questionable site for developing carbonate-rock aquifers.

Development potential in the northern part of the area is highly uncertain because a thick section of volcanic tuff covers most of the area and the thickness and distribution of carbonate rocks underlying the volcanic rock is uncertain, especially in the area of the caldera complex. Another disadvantage in developing the northern part of the area is that a thick sequence of evaporite-bearing Mesozoic sedimentary rocks intervenes at least in places between the volcanic rocks and the Paleozoic carbonate rocks (D.L. Schmidt, U.S. Geological Survey, written commun., 1988).

Hidden and Garnet Valleys

Hydrographic Setting

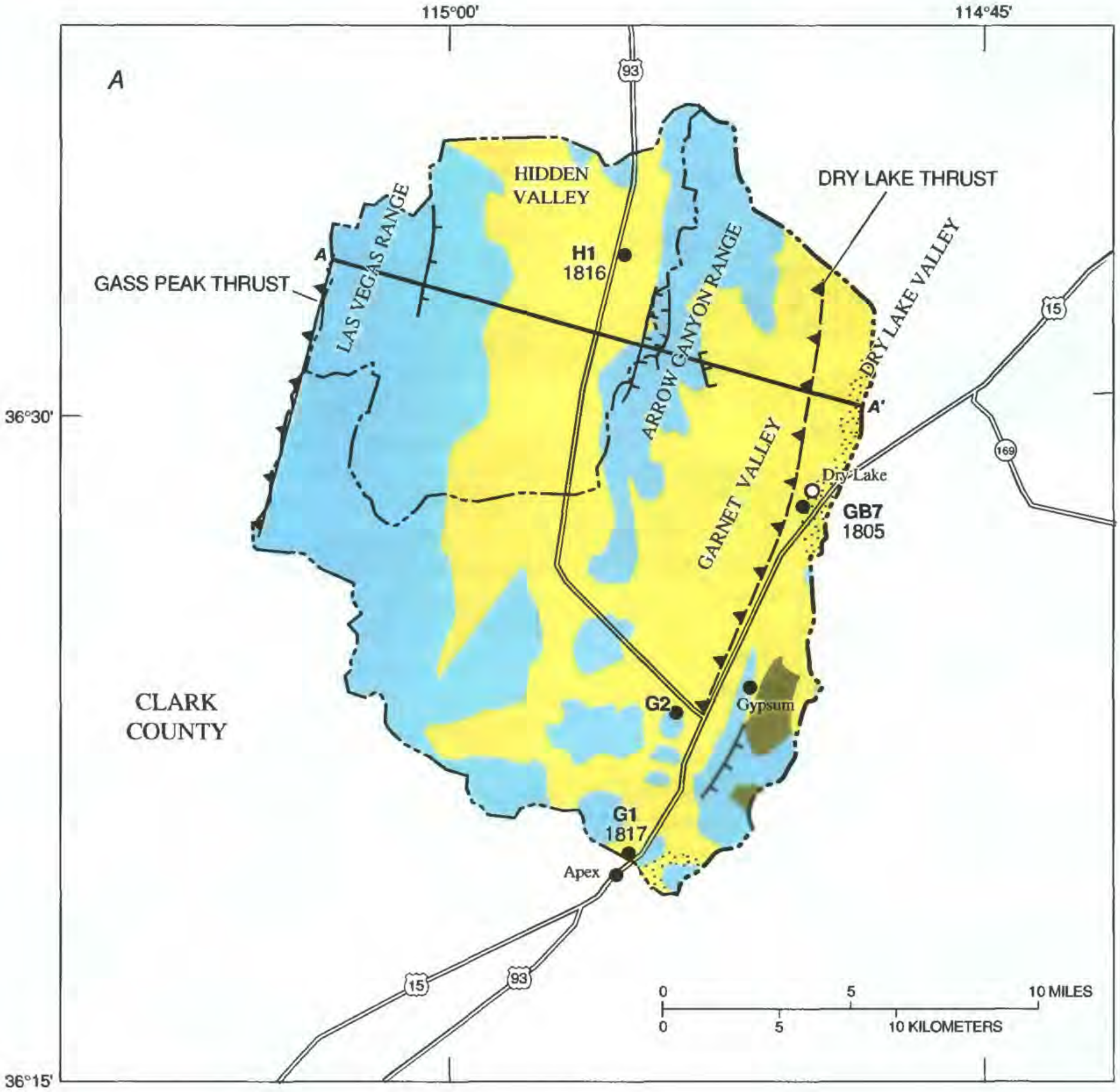
The Hidden and Garnet Valley hydrographic areas are the two smallest areas discussed in this report (fig. 9). Hidden Valley occupies only 80 mi^2, whereas Garnet Valley (more commonly referred to as Dry Lake Valley, but distinct from the earlier mentioned Dry Lake Valley north of Delamar Valley) encompasses about 156 mi^2. Both valleys are topographically closed and are bordered by small mountains or basin-fill topographic divides. Surface drainage in both valleys terminates in dry playas near the center of each valley (fig. 9). Hidden Valley is uninhabited, whereas the small community of Dry Lake in Garnet Valley is supported by a railroad that crosses the southeastern part of the valley. Lime and gypsum plants are also located along the railroad in southwestern Garnet Valley.

Geology

The Hidden and Garnet Valley areas are composed of mainly Paleozoic carbonate rock, both in the ranges surrounding the areas and beneath the valleys (fig. 9). Perhaps the thickest known section of carbonate rock in southern Nevada is beneath the Arrow Canyon Range where about 17,000 ft of limestone and dolomite were measured during exploration drilling (G2, fig. 9). Evaporite-bearing Mesozoic sedimentary rocks are exposed in the southern part of Garnet Valley, and these rocks may be present in between the basin fill and carbonate rocks beneath the valley. Quaternary and Tertiary basin fill may reach a thickness of 4,500 ft in Garnet Valley (D.L. Berger, U.S. Geological Survey, oral commun., 1988), whereas the basin fill in Hidden Valley is generally less than 500 ft thick and directly overlies carbonate rock (fig. 9). The Tertiary deposits, like the Mesozoic rocks, contain evaporites (mainly gypsum).

Compressional tectonics have had a dramatic impact on the area as evidenced by the thick carbonate-rock section that may contain three thrust sheets, according to drillers' logs. Of the three possible thrusts, only the Dry Lake thrust fault is exposed and can be inferred at depth (fig. 9). This fault is a potential barrier to ground water flowing out of Garnet Valley to the east. The Gass Peak thrust, which does not directly affect the area, is exposed along the western edge of the Hidden Valley hydrographic area and probably represents a hydrologic barrier because Precambrian and Cambrian clastic rocks lie between the carbonate rocks beneath Hidden Valley and carbonate rocks in areas to the west.

Extensional tectonics have not had a significant impact on the geology of the Hidden and Garnet Valley hydrographic areas, according to Wernicke and others (1984), because much of the Paleozoic section has retained its subhorizontal structure between the Gass Peak thrust fault to the west and the range-front fault on the west side of the Arrow Canyon Range to the east (fig. 9). The range-front fault zone contains prominent



EXPLANATION

Quaternary and Tertiary basin-fill deposits—Chiefly alluvial and fluvial sandstone, lakebed clay, siltstone and conglomerate. Stippled areas include gypsiferous sandstone and gypsum

Upper Paleozoic carbonate rocks—Chiefly siltstone, sandstone, cherty limestone, shale, and gypsum

Paleozoic carbonate rocks—Chiefly limestone and dolomite

Boundary of study area

Boundary of hydrographic area

Normal fault—Hachures on downthrown side

Thrust fault—Dashed where approximately located. Sawteeth on upper plate

A——A' **Line of hydrogeologic section**

G1 1817 ● **Well**—Completed in carbonate rocks. Upper number is well identifier; lower number is water-level altitude, in feet above sea level

Figure 9. Hydrogeologic map and generalized section through Hidden and Garnet Valleys. *A*, Hydrographic areas showing hydrogeologic rock units, major structural features, and wells completed in carbonate rocks (structural geology from D.L. Schmidt, written commun., 1988; D.L. Schmidt and G. Dixon, written commun., 1987; Langenheim, 1988; and Anderson and Jenkins, 1970; hydrogeology from Thomas and others, 1986). *B*, Generalized hydrogeologic section through Hidden and Garnet Valleys (geology from D.L. Schmidt, U.S. Geological Survey, written commun., 1988; Langenheim, 1988; Anderson and Jenkins, 1970; Hedlund and others, U.S. Geological Survey, written commun., 1966).

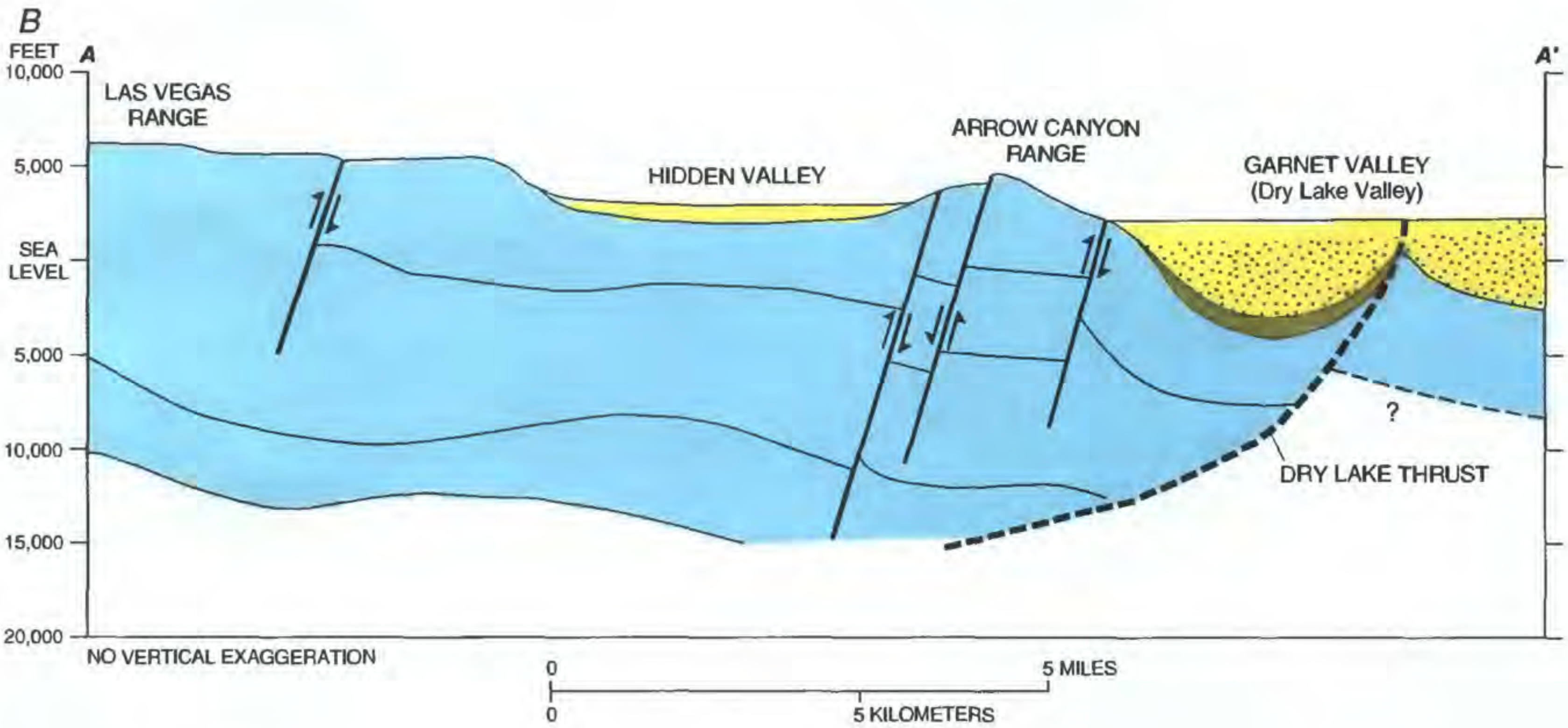


Figure 9. Continued.

vertical faults with vertical displacements of thousands of feet (Langenheim, 1988) and may compartmentalize ground-water flow locally. East of the range-front fault zone in the Arrow Canyon Range, Paleozoic carbonate rocks form a syncline (Anderson and Jenkins, 1970), as shown in figure 9.

Hydrology

Recharge to and discharge from Hidden and Garnet Valleys is small. Rush (1968a) estimated that 800 acre-ft/yr may recharge this area from local ranges; most of the recharge originates in the Las Vegas Range. A small amount of subsurface inflow from Coyote Spring Valley to the north may also enter the area. Discharge is either by subsurface outflow or pumping near the community of Dry Lake and at the lime and gypsum plants near Apex in southern Garnet Valley (fig. 9). Water levels are too deep for evapotranspiration of ground water or spring discharge. In Hidden Valley, depth to water is generally 800-900 ft below land surface. In Garnet Valley the altitude of the land surface is about 700 ft less than Hidden Valley; consequently, the depth to water is only 200-300 ft below the valley floor. At the town of Dry Lake, most wells penetrate the carbonate-rock aquifers because the Quaternary and Tertiary basin-fill deposits and Mesozoic sedimentary rocks are thin or not present at the margins of the valley (fig. 9).

Water-level gradients in the Hidden-Garnet Valley area are extremely flat (water-table altitude is approximately 1,800 ft above sea level in both areas; fig. 9). Geochemical and isotopic data from wells completed in carbonate rocks in the valleys (table 8) suggest that the area is both chemically and isotopically homogeneous (J.M. Thomas, U.S. Geological Survey, oral commun., 1988). Isotopic data also suggest that the water in this area is probably from the White River ground-water flow system with possibly some recharge from the Sheep Range or, more likely, the Las Vegas Range. Generally, ground-water flow into the area is negligible. Thus, the area probably represents the extreme southern end of the White River flow system, but is not dynamically connected to it because virtually all the ground-water flow in the White River system is discharged north of these valleys in the Muddy River Springs area. A small amount of ground water flows southeast from Hidden to Garnet Valley and a similarly small amount flows eastward from Garnet Valley beneath California Wash (Rush, 1968a).

Table 8. Information on wells completed in carbonate rocks in Hidden and Garnet Valleys

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations and symbol: D, domestic; I, industrial; O, observation; --, no data]

Number (fig. 9)	Name	Depth to water (feet below land surface)	Depth to carbonate rocks (feet below land surface)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)	Use
H1	SHV-1	833	250	470	23.8	O
G1	APEX	660	1,050	1,000	31.1	I
G2	Grace Petroleum	--	1,040	1,000	26.6	O
GB-7	Dry Lake Valley	260	532	960	28.8	D

The quantity of ground-water storage in carbonate aquifers beneath Hidden and Garnet Valleys is limited because of the small size of the area. Total storage in the two hydrographic areas, on the basis of assumptions discussed earlier in this report, is estimated to be about 2.8 million acre-ft. Local storage (within the basin fill) in the two areas represents about 1.4 million acre-ft, or about one-half of the total storage. This total falls within the range reported by Rush (1968a), who estimated that between 1,500 and 5,000 acre-ft/ft of water is stored in the carbonate rocks directly beneath the valley floors. Although the criteria for estimating storage uses a 2,000-ft thickness, there is potentially eight times this amount of saturated carbonate rocks beneath the area; hence, the actual quantity of ground-water storage may be much greater than presented here. The carbonate rocks constituting the storage reservoir of the area probably are hydrologically connected with the carbonate rocks beneath Coyote Spring Valley to the north. Continuity with carbonate rocks beneath Las Vegas Valley to the southwest may be restricted by the presence of the Las Vegas Valley shear zone, and water-level data suggest that a hydrologic divide is present between Las Vegas and Garnet Valleys (Thomas and others, 1986).

Potential for Ground-Water Development

Virtually all of the ground water that would be removed during development would come from storage within the carbonate rocks because only a small amount of water replenishes the aquifer in the area. Furthermore, development would initially not have significant impact on discharge to surrounding areas. Structural boundaries such as the Gass Peak thrust fault to the west, the possibility of rather shallow clastic rock to the north, and the Las Vegas Valley shear zone to the south also may favor development of the area and may limit the effects of ground-water withdrawal on nearby areas. Sites most suited for development are in east Hidden Valley where the depth to carbonate rock and water quality meet established criteria (pl. 1). How structural boundaries may aid in limiting effects of development is not known, but Hidden Valley probably represents a more favorable site for development than most other hydrographic areas in southern Nevada even though water levels are quite deep.

The factors that make Hidden Valley a favorable site also contribute to its disadvantage as a potential site. Almost all water pumped from the region would come from storage that is not readily replenishable. It could take thousands of years for these aquifers to be replenished if they are significantly developed. Long-term pumping would be limited due to the small area, although the thickness of the saturated carbonate-rock section is substantial (more than 10,000 ft). Ground-water quality is somewhat lower than in many other carbonate-rock settings in the study area because sulfate is at high concentrations in wells tapping carbonate rocks owing to the presence of evaporites in the thick Tertiary basin fill and Mesozoic sedimentary rocks in the Garnet Valley area.

Las Vegas Valley

Hydrographic Setting

Las Vegas Valley is the largest hydrographic area described in this report, covering 1,564 mi^2 in east-central Clark County (fig. 10). Metropolitan Las Vegas occupies much of the valley lowlands and is surrounded by long, gently sloping, piedmont surfaces that separate the lowlands from the mountain ranges (Bell, 1981). These piedmont surfaces, sometimes referred to as coalescing alluvial fans, reach lengths of 10 mi west of the city, but are generally about 2-5 mi long in much of the valley. The valley slopes gently to the east and southeast and is drained by Las Vegas Wash, which discharges into Lake Mead. Las Vegas Wash was ephemeral, but has become perennial as a result of urban-induced discharges, especially treated effluent.

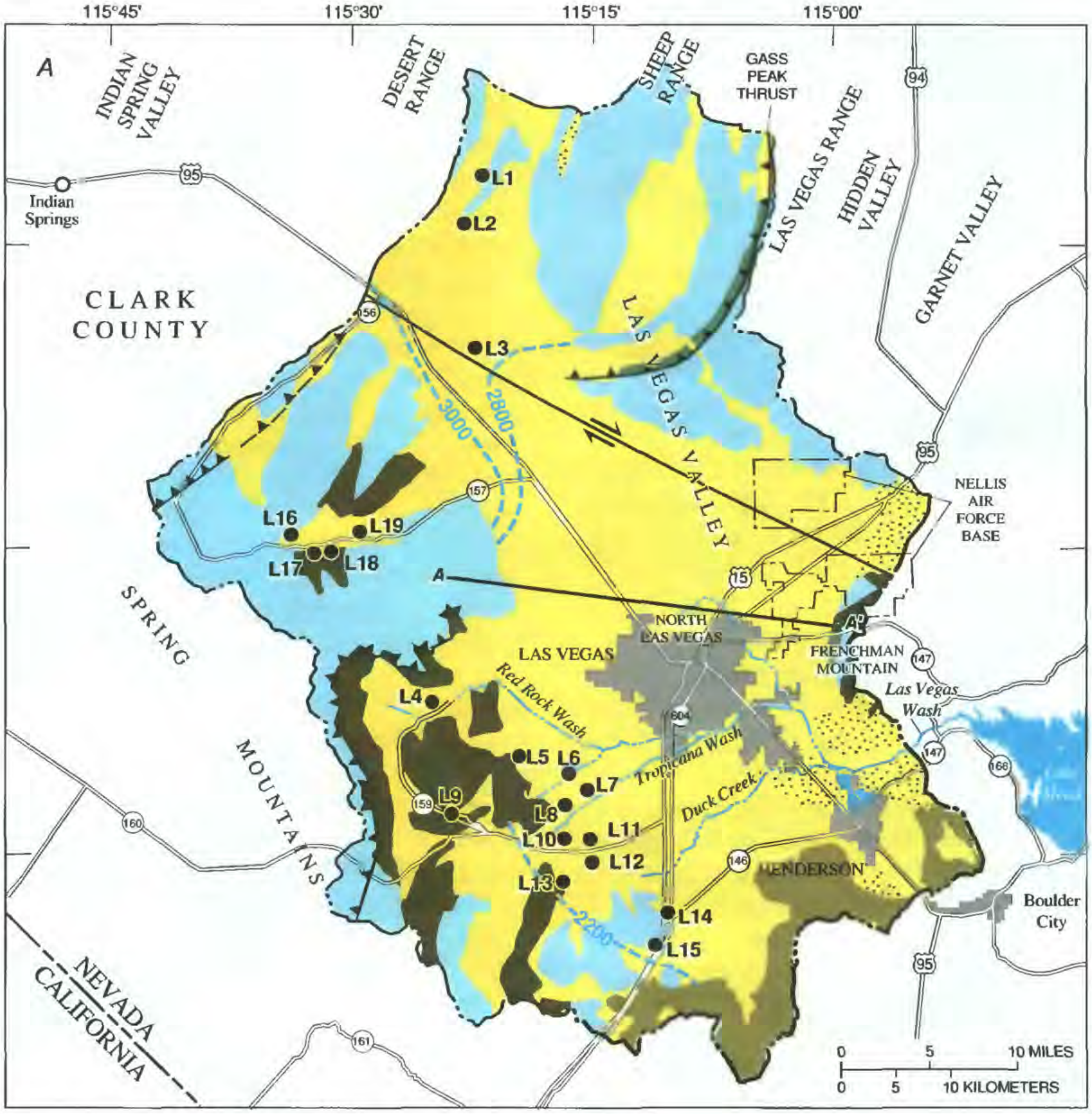
Las Vegas Valley, the population center of the entire study area, had approximately 630,000 residents as of 1987, living in three principal communities—Las Vegas, North Las Vegas, and Henderson. The Las Vegas area was probably first inhabited by settlers because of springs in the area. During the mid-1800's, the area was settled by Mormon missionaries and after 1905 became a community supported by railroads that ran through the area. During and after World War II, gaming and tourism began to thrive, accompanied by an increasing population. Las Vegas and vicinity remains one of the fastest growing areas in the country and has undergone a 3,000-percent increase in population since 1946 when the area had only 21,000 residents (Maxey and Jameson, 1948). Today, Las Vegas is not only a major tourist attraction but also is one of the world's largest convention centers. In addition, Nellis Air Force Base is in the east part of the valley (pl. 1).

The rapid growth of metropolitan Las Vegas has led to an overdraft of aquifers, resulting in depleted ground-water storage and locally severe land-subsidence problems (Bell, 1981; Harrill, 1976). Water imported from Lake Mead surpassed that obtained from pumping in 1975. In 1990, imported surface water represented approximately 75 percent of the total consumptive use in the valley; this figure is likely to increase as water demands increase.

Geology

The Las Vegas Valley hydrographic area contains all five hydrogeologic rock units defined in this study. Precambrian and Cambrian noncarbonate rocks are exposed along the Gass Peak thrust fault and extend at depth along the fault plane. A small wedge of these noncarbonate rocks is also exposed in Frenchman Mountain east of Las Vegas (fig. 10). Paleozoic carbonate rocks are the most prevalent unit in the mountainous areas because most of the ranges north of the valley contain thick sections of limestone and dolomite. The carbonate-rock section in the Sheep Range contains up to 26,000 ft of Paleozoic and Mesozoic rocks (Longwell and others, 1965). It is not known to what depth carbonate rocks extend beneath the Spring Mountains, but carbonate rocks beneath the western part of the valley are at least several thousand feet thick (fig. 10). Upper Paleozoic and Mesozoic sedimentary rocks are widespread in the western part of the area and may also be thousands of feet thick. Although these sedimentary rocks may locally contain a significant amount of limestone, they also contain abundant evaporite deposits. Tertiary volcanic rocks are limited, in general, to the southern part of the area. They predominate in the southeastern part of Las Vegas Valley, where thicknesses of basaltic and andesitic flows may reach 17,000 ft (Anderson, 1971), and directly overlie mostly Precambrian rock (Smith and others, 1987b); hence, these volcanic rocks mark the southern extent of the carbonate-rock province. Quaternary and Tertiary basin fill has accumulated to thicknesses of as much as 5,000 ft in the center of the valley beneath Las Vegas (Plume, 1989; fig. 10). A second thick section of Quaternary and Tertiary basin fill is in the northern part of the area between the Sheep and Desert Ranges (fig. 10), where as much as 2,500 ft of these deposits may have accumulated (Guth, 1981).

Recent studies report both compressional and extensional tectonic deformation in the vicinity of Las Vegas Valley. The geology and structure of the Desert, Sheep, Las Vegas, and Arrow Canyon Ranges north of the valley are discussed by Guth (1987), Wernicke and others (1984), Guth (1981), and D.L. Schmidt (U.S. Geological Survey, written commun., 1987); of the Spring Mountains to the west by Axen (1984), Wernicke and others (1982), Burchfiel and others (1974), and Wright and Troxel (1973); and of the area



EXPLANATION

- **Quaternary and Tertiary basin-fill**—Chiefly alluvial, tuffaceous sedimentary rocks, lake deposits, sandstone and siltstone. Stippled pattern represents Muddy Creek or Horse Spring Formations that include evaporite deposits, particularly gypsum
- **Tertiary rocks**—Chiefly andesite and basalt flows with locally significant rhyolite flows and intusive rocks
- **Upper Paleozoic and Mesozoic sedimentary rocks**—Chiefly siltstone, sandstone, limestone, and gypsum with sparse dolomite, shale, and conglomerate
- **Paleozoic carbonate rocks**—Chiefly limestone and dolomite
- **Precambrian and Cambrian noncarbonate rocks**—Chiefly quartzite and clastic rocks, with minor amounts of metamorphic rocks
- **Boundary of study area**
- **Boundary of hydrographic area**
- **Strike-slip fault**—Shows right-lateral movement associated with Las Vegas Valley Shear Zone
- **Thrust fault**—Dashed where approximately located. Sawteeth on upper plate
- A——A' **Line of hydrogeologic section**
- --2800-- **Water-level contour**—Shows altitude at which water level would stand in tightly cased wells developed in carbonate rocks. Contour interval, 200 feet. Datum is sea level
- ●L2 **Well**—Completed in carbonate rocks. Number is well identifier

Figure 10. Hydrogeologic map and generalized section through Las Vegas Valley. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, and water levels in the carbonate rocks (structural geology from Burchfiel and others, 1974; Plume, 1989; hydrogeology from Thomas and others, 1986; Harrill, 1976; Morgan and Dettinger, 1994). *B*, Generalized hydrogeologic section through Las Vegas Valley (geology from Plume, 1989).

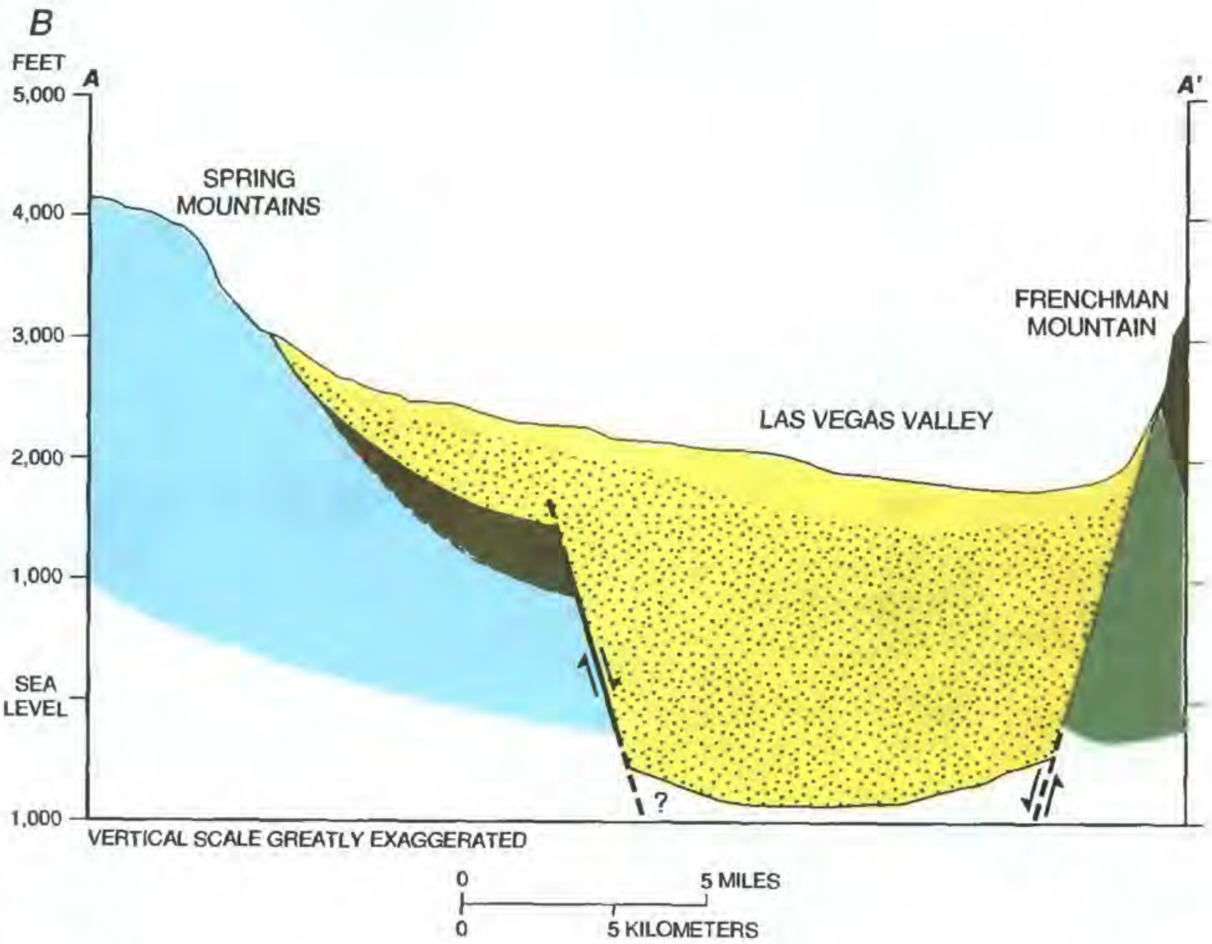


Figure 10. Continued.

to the south and east by Smith and others (1987a, b) and Anderson (1971). Together, these reports, among many others, characterize the geology and tectonic deformation of the carbonate-rock province in the vicinity of the Las Vegas Valley hydrographic area.

Numerous thrust faults in the Spring Mountains suggest that compressional tectonic deformation was extensive in the western part of the area. The Gass Peak thrust is the most prominent thrust in the northern part of the area, where compression was great and little extension occurred (Wernicke and others, 1982). Extension was significant in the northwest part of the area—west of the Sheep Range where a deep extensional basin formed as a result of faulting associated with stretching of the crust (Guth and others, 1988; Guth, 1981). This extensional basin may represent an isolated aquifer system separate from the aquifer system beneath the floor of Las Vegas Valley (Dettinger, 1987). Extension was much less severe south of the Las Vegas Valley shear zone—a vertical fault boundary and ground-water flow barrier having about 45 mi of lateral displacement in response to differential rates of extension on either side (Fleck, 1970; Wernicke and others, 1982). The shear zone produced the bowl-shaped trough beneath Las Vegas Valley, which is bounded to the east and west by steeply dipping faults (fig. 10) and to the north by the Las Vegas Valley shear zone. This large trough, filled with Tertiary and Quaternary sediments, contains the major aquifers beneath Las Vegas Valley.

Hydrology

Recharge to Las Vegas Valley is by precipitation in the adjacent ranges, particularly the Spring Mountains to the west. Recharge totals about 30,000 acre-ft/yr, although the estimated amount differs somewhat from author to author (table 9). Recharge from precipitation, however, is not adequate to meet the growing demand for water by metropolitan Las Vegas. Furthermore, little or no subsurface inflow from surrounding hydrographic areas has been reported. Consequently, the percentage of imported water from Lake Mead has continued to increase over the past several decades (table 9) while the natural ground-water discharge in the valley has decreased. Heavy pumping from the basin-fill aquifers within the valley has dried up the springs that once flowed naturally. Natural evapotranspiration has also diminished greatly in the western part of the valley, although evapotranspiration rates remain high in the southeast part of the valley north of Henderson. Ground-water withdrawals

Table 9. Recharge and discharge estimates for Las Vegas Valley

[Symbols: --, no data; >, greater than]

Component of recharge or discharge	Year for which estimate was made	Quantity (acre-feet per year)
Recharge		
Precipitation primarily in Spring Mountains		
Maxey and Jameson (1948)	1944	30,000-35,000
Malmberg (1965)	1955	25,000
Harrill (1976)	1972	30,000
Morgan and Dettinger (1994)	1981	32,000
Imported surface water from Lake Mead		
Maxey and Jameson (1948)	1944	0
Malmberg (1965)	1955	5,000
Harrill (1976)	1972	75,000
Morgan and Dettinger (1994)	1981	>112,000
Discharge		
Evapotranspiration from phreatophytes and bare soils		
Maxey and Jameson (1948)	1944	5,000-8,000
Malmberg (1965)	1955	24,000
Harrill (1976)	1972	--
Morgan and Dettinger (1994)	1981	10,000
Springs issuing from basin fill		
Maxey and Jameson (1948)	1944	6,000
Malmberg (1965)	1955	2,000
Harrill (1976)	1972	minor
Morgan and Dettinger (1994)	1981	0
Pumpage from basin fill		
Maxey and Jameson (1948)	1944	15,000
Malmberg (1965)	1955	39,000
Harrill (1976)	1972	63,000
Morgan and Dettinger (1994)	1981	71,000
Subsurface outflow and leakage to washes		
Maxey and Jameson (1948)	1944	0
Malmberg (1965)	1955	0
Harrill (1976)	1972	1,200
Morgan and Dettinger (1994)	1981	12,000

by pumping are the main source of discharge from the aquifers beneath the valley as even leakage to washes results from return flow of pumped or imported water (table 9).

Water-level data from wells drilled into carbonate rocks are restricted to the northwestern and southwestern parts of the valley (fig. 10, table 10), and indicate a southeastward and eastward flow of ground water. A possible exception to this flow pattern occurs in the northwest part of the area where recent drilling indicates that ground-water flow may be northwestward. The thick sequence of basin-fill sediments in the central part of the valley makes it difficult to determine whether or not the basin fill and carbonate rocks are hydraulically connected. The chemical and isotopic composition of several springs in Las Vegas Valley indicates that ground water discharges from the carbonate-rock aquifer through the basin-fill deposits in some areas, particularly in the west and west-central parts of the valley (J.M. Thomas, U.S. Geological Survey, written commun., 1989). Conversely, water levels in the basin fill may not reflect water levels in the carbonate rocks in the central and eastern parts of

Table 10. Information on Com Creek Spring (discharge, 200 acre-feet per year) and selected wells completed in carbonate rocks in Las Vegas Valley

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987; and Lyles, 1987a. Abbreviations and symbol: D, domestic; I, irrigation; N, not used; NA, not applicable; O, observation; Z, other; --, no data]

Number (fig. 10)	Source	Name	Total depth (feet)	Depth to water (feet below land surface)	Depth to carbonate rocks (feet below land surface)	Use
L1	well	Cow Camp	1,403	1,334	350	O
L2	well	SBH No. 1	694	581	60	O
L3	spring	Corn Creek	NA	0	NA	D,I
L4	well	none	158	149	153	D
L5	oil well	BD No. 1	6,220	--	0	O
L6	well	none	778	302	765	D
L7	well	none	600	530	545	D
L8	well	none	905	650	650	D
L9	well	none	570	230	200	D
L10	well	none	835	437	500	D
L11	oil well	LOG No. 1	6,800	--	750	O
L12	well	none	500	426	350	D
L13	well	none	385	--	225	D
L14	well	none	755	345	500	D
L15	well	none	670	520	589	D
L16	well	MaryJane	261	219	210	N
L17	well	Mt Charleston	377	272	240	Z
L18	well	Kramer	290	213	250	N
L19	well	Kingston	650	458	280	N

the valley. This may be especially true in areas of heavy pumping because local flow directions may be toward major well fields. In the western part of the valley, however, the thickness of basin-fill deposits is less than 1,500 ft (fig. 10, pl. 1). Plume (1989) suggests that ground water may flow from carbonate rocks to the basin fill. Weaver (1982) analyzed the chemistry of water from pumped wells in west-central Las Vegas Valley and concluded that some of the pumped water originated from carbonate rocks beneath the basin fill. Lyles (1987b) also suggested that deeper ground water from carbonate rocks mixes with shallow basin-fill water along the Las Vegas Valley shear zone in the northwest part of the valley. The geometry and extent of this hydraulic connection in the structurally deeper parts of the basin is not known.

Continual pumping of the basin-fill aquifers has significantly depleted ground-water storage of the basin-fill aquifer in the west-central part of the valley (Harrill, 1976; Morgan and Dettinger, 1994). Storage depletion within the basin fill was estimated to be nearly 1.5 million acre-ft/yr as of 1983 (Morgan and Dettinger, 1994; earlier estimates were reported by Malmberg, 1965, and Harrill, 1976). Ground-water overdraft has led to water-level declines of as much as 5 ft/yr at some localities in the western part of the valley. Land subsidence caused by overdraft of the basin-fill aquifers was between 0.6 and 1.0 ft from 1972 to 1981 (Morgan and Dettinger, 1994). Bell (1981) reported a maximum land subsidence of between 2.5 and 3.0 ft from 1963 to 1980.

In 1987, the Las Vegas Valley Water District initiated an artificial recharge program (Katzer and Brothers, 1989; Brothers and Katzer, 1990) that, as of 1995, has recharged over 100,000 acre-ft into the ground-water system (Zikmund and Cole, 1996). This recharge has reduced the net pumpage in the west and northwest parts of the valley and has slowed, and locally may have reversed, the decline of ground-water levels.

Although water levels in basin-fill aquifers have been drawn down by development, ground-water storage within the carbonate rocks of the Las Vegas Valley hydrographic area has probably not been greatly affected by pumping and the amount of storage within these rocks may be large. Total storage in carbonate rocks, on the basis of assumptions described earlier in this report, is estimated to be about 14 million acre-ft, whereas local storage (beneath the basin-fill areas) is estimated to be about 9 million acre-ft. The area north of the Las Vegas Valley shear zone and west of the Gass Peak thrust fault may represent a storage reservoir different from that beneath the city of Las Vegas south of the shear zone (M.D. Dettinger, U.S. Geological Survey, oral commun., 1988).

Potential for Ground-Water Development

Too few data are available for the carbonate rocks beneath Las Vegas Valley to adequately evaluate the potential for development from these rocks. However, the limited quantity of recharge to the Las Vegas hydrographic area indicates that ground-water development from the carbonate rocks in the area would possibly result in either a direct decline in water levels in the basin-fill aquifers, or a storage depletion within the carbonate rocks, or both.

The criteria used to evaluate potential development sites are met in the southwestern third of the valley (pl. 1). Because the carbonate rocks in this area probably have a close hydraulic connection with the basin fill, development would likely affect water levels within the basin-fill aquifers.

Water quality within the carbonate rocks varies both laterally and with depth. Several wells in the southwest part of the valley intersected zones of saline water. Ground-water quality generally decreases toward the southeast along the flowpath because evaporite minerals are common in the fine-grained Tertiary basin fill. In the southwest part of the valley, the Mesozoic sedimentary rocks also contain evaporites. In the carbonate rocks, no water-quality pattern can be identified; hence, the area of average or high ground-water quality, shown on plate 1, was limited to the northwest part of the valley where the quality of the ground water is known.

Overall, development of the carbonate-rock aquifers in Las Vegas Valley is constrained by limited recharge and a high probability that any development in areas meeting proposed criteria would have immediate effects on currently used basin-fill aquifers.

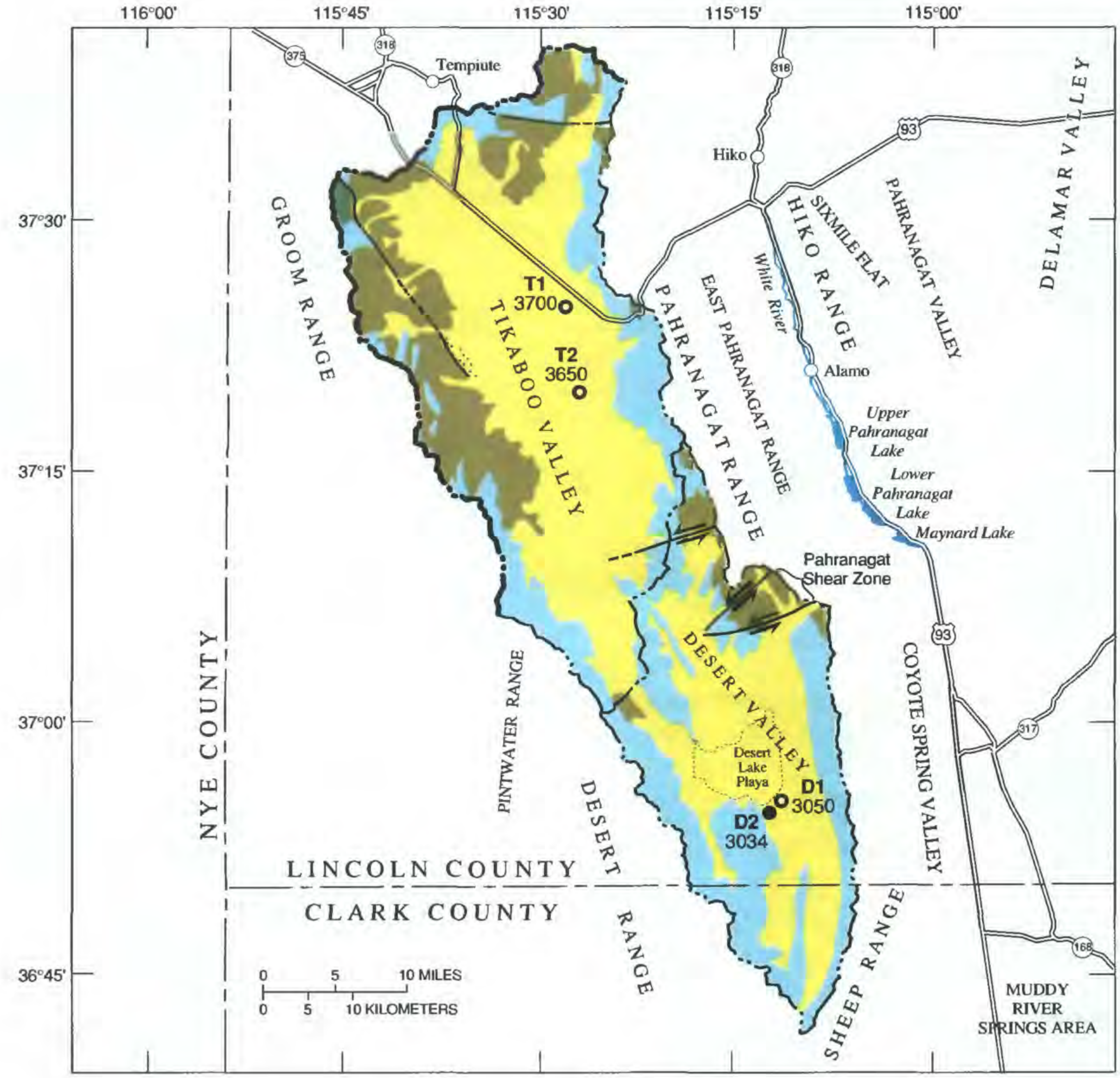
Tikaboo Valley

Hydrographic Setting

The Tikaboo Valley hydrographic area in southwestern Lincoln County consists of a northern part encompassing Tikaboo Valley (627 mi^2), and a southern part encompassing Desert Valley (380 mi^2; fig. 11). The area is topographically closed, with surface drainage mostly in a southward direction to Desert Lake playa along a gradient of 51 ft/mi. Drainage from Tikaboo Valley enters Desert Valley through a narrow divide between exposures of carbonate rock that separate the two valleys. Much of the central and southern part of the Tikaboo Valley hydrographic area is part of the Nellis Bombing Range and the Desert National Wildlife Range (pl. 1); hence, much of the area is restricted to public access and is off limits for development. Consequently, little or no hydrologic data exist for the Tikaboo Valley area.

Geology

The oldest rocks exposed in the area are Precambrian and Cambrian clastic rocks in the extreme northwestern corner of the area (fig. 11). Otherwise, the area is predominately composed of Paleozoic carbonate rocks that are exposed in the Pahranagat, Sheep, and Desert Ranges, where stratigraphic thicknesses of as much as 20,000 ft have been reported by Guth (1981) for the Sheep Range and by Dolgoff (1963) for the Pahranagat Range. The thickness of carbonate rock in the Desert Range, however, is probably only several thousand feet (Guth, 1981). Tertiary deposits composed primarily of welded and nonwelded tuffs and rhyolite and andesite flows are predominately in the northern half of the area, especially the Groom Range (fig. 11). Geophysical studies indicate that the basin beneath Tikaboo Valley contains more than 5,000 ft of Quaternary and Tertiary basin-fill deposits and Tertiary volcanic rocks overlying Paleozoic carbonate rocks (Bedsun, 1980). In Desert Valley, thicknesses of Quaternary and Tertiary basin-fill deposits are more than 3,000 ft in the vicinity of Desert Lake playa where there are few or no Tertiary volcanic rocks present (H.A. Pierce, U.S. Geological Survey, written commun., 1988).



EXPLANATION

Quaternary and Tertiary basin fill—Chiefly alluvial, fluvial lake, and mud-flow deposits. Stippled areas include minor amount of tuffaceous sedimentary deposits

Tertiary rocks—Chiefly welded and nonwelded ash-flow tuffs. Locally includes rhyolitic and andesitic flows and shallow intrusives

Paleozoic carbonate rocks—Chiefly limestone and dolomite

Precambrian and Cambrian noncarbonate rocks—Chiefly quartzite and clastic rocks, with minor amounts of metamorphic rocks, siltstone, shale, and conglomerate

Boundary of study area

Boundary of hydrographic area

Normal fault—Dashed where approximately located

Strike-slip fault—Shows left-lateral movement associated with the Pahranagat shear zone. Dashed where approximately located

Well—Upper number is well identifier; lower number is water-level altitude, in feet above sea level

T1 3700 Completed in basin fill

D2 3034 Completed in carbonate rocks

Figure 11. Hydrogeologic map of Tikaboo Valley (modified from Plume and Carlton, 1988).

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Mesozoic thrust faults in both the Pahranagat Range and the eastern part of the Sheep Range (figs. 7 and 10) indicate that the Paleozoic section (both carbonate and clastic rocks) was thickened during the Mesozoic era when compressional forces were active. Evidence for extreme extension during the Tertiary period (large-scale thinning of the Paleozoic rocks) has been reported by Wernicke and others (1984) and Guth (1981) along the western margin of the Sheep Range and the area to the west (Desert Valley and Desert Range). The extent to which this large-scale "pulling-apart" has affected the Tikaboo Valley area in the north is not known. The Pahranagat shear zone, which has differential rates of extension between the two areas, divides the known highly extended area to the south from the Tikaboo Valley area to the north (fig. 11). Large extension west of Tikaboo Valley appears likely, however, as structures in the Groom Range are similar to structures in the Desert Range (Humphrey, 1945). Tikaboo Valley represents a structurally deep basin similar to Desert Valley and is characteristic of extended terranes. Therefore, carbonate-rock aquifers within the study area are likely to be either extremely thin or located at great depths beneath the valleys such that most ground-water flow would be through basin-fill deposits.

Hydrology

Empirical techniques (Maxey-Eakin method; Eakin and Maxey, 1951) used to estimate recharge in the mountains of the hydrographic area indicate that 2,600 acre-ft/yr recharges Tikaboo Valley mostly from the Pahranagat Range, and that 3,400 acre-ft/yr recharges Desert Valley, mostly from the Sheep Range. Estimated recharge to Desert Valley may be high because most of the recharge to the Sheep Range is believed to flow eastward to Coyote Spring Valley (J. M. Thomas, U.S. Geological Survey, oral commun., 1988). Ground-water recharge is discharged solely by subsurface outflow because neither springs nor evapotranspiration discharge ground water from the Tikaboo Valley hydrographic area.

Only one well is completed in carbonate rock and three wells in the basin fill (two of which are dry) for the entire hydrographic area (table 11). The depth to water in the carbonate well and nearby basin-fill well is about 160-220 ft below land surface near the southeastern edge of Desert Lake playa (fig. 11). Basin-fill water levels in Tikaboo Valley are greater than 750 ft below the valley floor (Winograd and Thordarson, 1975, pl. 1).

Ground-water flow within the carbonate rocks is difficult to estimate. In addition to the 6,000 acre-ft/yr of local recharge, Winograd and Thordarson (1975) estimated that as much as 6,000 acre-ft/yr of ground water flows beneath the Tikaboo Valley hydrographic area from Pahranagat Valley toward Ash Meadows near Death Valley (pl. 1). If this is an accurate estimate, a probable route for ground-water flow in the carbonate-rock aquifers is southwestward parallel to the Pahranagat shear zone between the Groom and Desert Ranges and across the north end of the Pintwater Range. The ground-water gradient is large from Pahranagat Valley to Frenchman Flat (pl. 1) and similar to the gradient across the Pahranagat shear zone between Pahranagat Valley and Coyote Spring Valley (fig. 11; pl. 1) and the gradient in the basin-fill deposits

Table 11. Information on observation wells in Tikaboo Valley

[Data modified from J.M. Thomas, U.S. Geological Survey, written commun., 1987. Symbols: >, greater than; --, no data]

Number (fig. 11)	Name	Depth to water (feet below land surface)	Depth to carbonate rocks (feet below land surface)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)
T1	none	dry	--	--	--
T2	none	dry	--	--	--
D1	DDL-1	160	>160	300	18.8
D2	DDL-2	216	6	--	--

southwest of the Groom Range. Therefore, because of the large hydraulic gradient and presence of carbonate rocks along this proposed flow path, ground water in the carbonate-rock aquifers beneath the Tikaboo Valley area is believed to flow westward toward Ash Meadows (pl. 1; Winograd and Thordarson, 1975, p. 85-90; Winograd and Pearson, 1976; Winograd and Friedman, 1972).

Prudic and others (1993) suggested, on the basis of conceptual simulations, that a ground-water divide occurs west of Tikaboo Valley, and flow in the valley is north to south rather than east to west as proposed by Winograd and Thordarson (1975). Therefore, much additional information is needed to determine the flow direction beneath Tikaboo Valley.

Estimates of ground-water storage in the Tikaboo hydrographic area are based on the assumptions described earlier in this report. Because the thickness and extent of carbonate rocks beneath Tikaboo Valley are unknown, a satisfactory estimate cannot be made. Nonetheless, a total storage for the area has been estimated to be 5.3 million acre-ft. This large value reflects the large area of the two valleys and the high percentage of carbonate-rock-dominated mountains. Local storage (beneath the basin fill) is considerably less than the total storage. A local storage value of 1.8 million acre-ft has been estimated for the southern part of the area. No estimate was made for the northern part of the area because depths to carbonate rocks are assumed to be too deep to incorporate into the storage estimates.

Potential for Ground-Water Development

The current geologic and hydrologic data preclude determination of the overall potential for development. The hydraulic connectivity throughout the carbonate rocks at depth beneath the Tikaboo Valley area is not known, but may not be sufficient if the area has been highly extended. The thickness of carbonate rocks beneath Tikaboo Valley (northern one-half of the hydrographic area) is not known and the depth to carbonate rocks may be prohibitive to future development except possibly near the margins of the valley. In the southern one-half of the area (Desert Valley), however, high permeabilities may prevail in the vicinity of the Pahranagat shear zone (Winograd and Thordarson, 1975, p. 92). The few available water-level measurements (160-220 ft below land surface) may not reflect the general depth to water throughout Desert Valley (especially to the north). Water quality within carbonate rocks beneath Tikaboo Valley is probably high on the basis of the quality of adjacent areas.

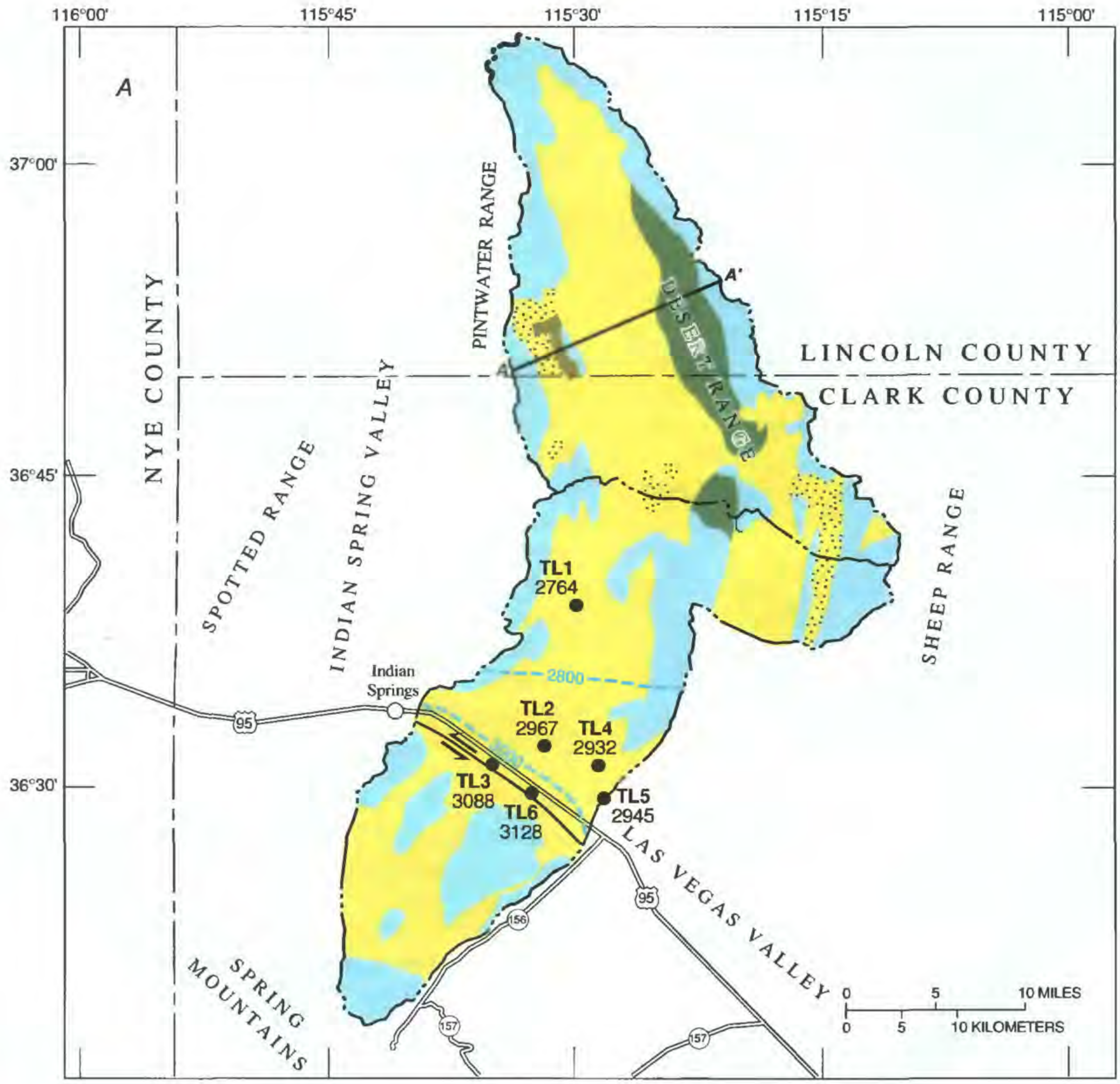
Three Lakes Valley

Hydrographic Setting

Three Lakes Valley is divided into two distinct hydrographic areas—a northern area covering 298 mi^2 in northwestern Clark and southern Lincoln Counties, and a southern area covering 311 mi^2 in northwestern Clark County (fig. 12). Although these two hydrographic areas belong to different drainage systems, according to Rush (1974), they are not hydrologically distinct and are therefore discussed as a single hydrographic area. The northern and southern parts of Three Lakes Valley each contain a playa which represents the terminus of surface drainage from surrounding ranges; the southern playa is about 500 ft lower in altitude than the northern playa. A major highway (U.S. Highway 95) connecting Las Vegas with the northern part of the state crosses the southern part of the area (fig. 12). All of the hydrographic area north of the highway is part of the Nellis Bombing Range (pl. 1) and is currently restricted. Consequently, available data and understanding of the geology and hydrology of the area are greatly limited. Most of the hydrographic area is also part of the Desert National Wildlife Range (pl. 1) where development is limited. A maximum security penitentiary is located in southern Three Lakes Valley.

Geology

Ranges made up of Paleozoic carbonate rock encompass most of the Three Lakes Valley hydrographic area. The thickness of carbonate rocks in the Desert Range is several thousand feet (Guth, 1981) and in the northern part of the area decreases westward to the center of the valley where few or no carbonate rocks are at depth (fig. 12; P.L. Guth, Harvard University, written commun., 1988). A thick section of carbonate rocks extends beneath the Pintwater Range and beneath most of the western and probably southern parts of the area. Precambrian and Cambrian noncarbonate rocks are exposed in the Desert Range and extend beneath the eastern one-half of the valley, probably to great depths (fig. 12). Tertiary volcanic rocks are not abundant in the area (Ekren and others,



EXPLANATION

Quaternary and Tertiary basin fill—Chiefly alluvial, fluvial, lake, and mudflow deposits. Stippled areas include minor amount of tuffaceous sedimentary deposits and older clastic rocks

Tertiary rocks—Chiefly welded and nonwelded ash-flow tuffs

Paleozoic carbonate rocks—Chiefly limestone and dolomite

Precambrian and Cambrian noncarbonate rocks—Chiefly quartzite, limestone, dolomite, siltstone, and shale, with minor conglomerate

Boundary of study area

Boundary of hydrographic area

Strike-slip fault—Shows left-lateral movement associated with the Las Vegas Valley shear zone

3000 **Water-level contour**—Shows altitude at which water level would stand in tightly cased wells developed in carbonate rocks. Dashed where approximately located. Contour level, 200 feet. Datum is sea level

A——A' **Line of hydrogeologic section**

TL4 ● 2932 **Well**—Completed in basin-fill deposits (from Winograd and Thordarson, 1975; and Lyles and Hess, 1988). Upper number is well identifier; lower number is water-level altitude, in feet above sea level

Figure 12. Hydrogeologic map of the northern and southern Three Lakes Valley areas and generalized hydrogeologic section through northern Three Lakes Valley. *A*, Hydrographic areas showing hydrogeologic rock units, major structural features, water levels in the carbonate rocks, and wells completed in basin-fill deposits (structural geology from Longwell and others, 1965; Tschanz and Pampeyan, 1970; Ekren and others, 1977; Wernicke and other, 1984; Guth, 1987; and P.L. Guth, Harvard University, written commun., 1988; hydrogeology from Thomas and others, 1986, and Lyles and Hess, 1988). *B*, Generalized hydrogeologic section through the northern part of the Three Lakes Valley (geology from Longwell and others, 1965; Tschanz and Pampeyan, 1970; Ekren and others, 1977; Guth, 1981; Wernicke and others, 1984; Guth, 1987; and P.L. Guth, Harvard University, written commun., 1988).

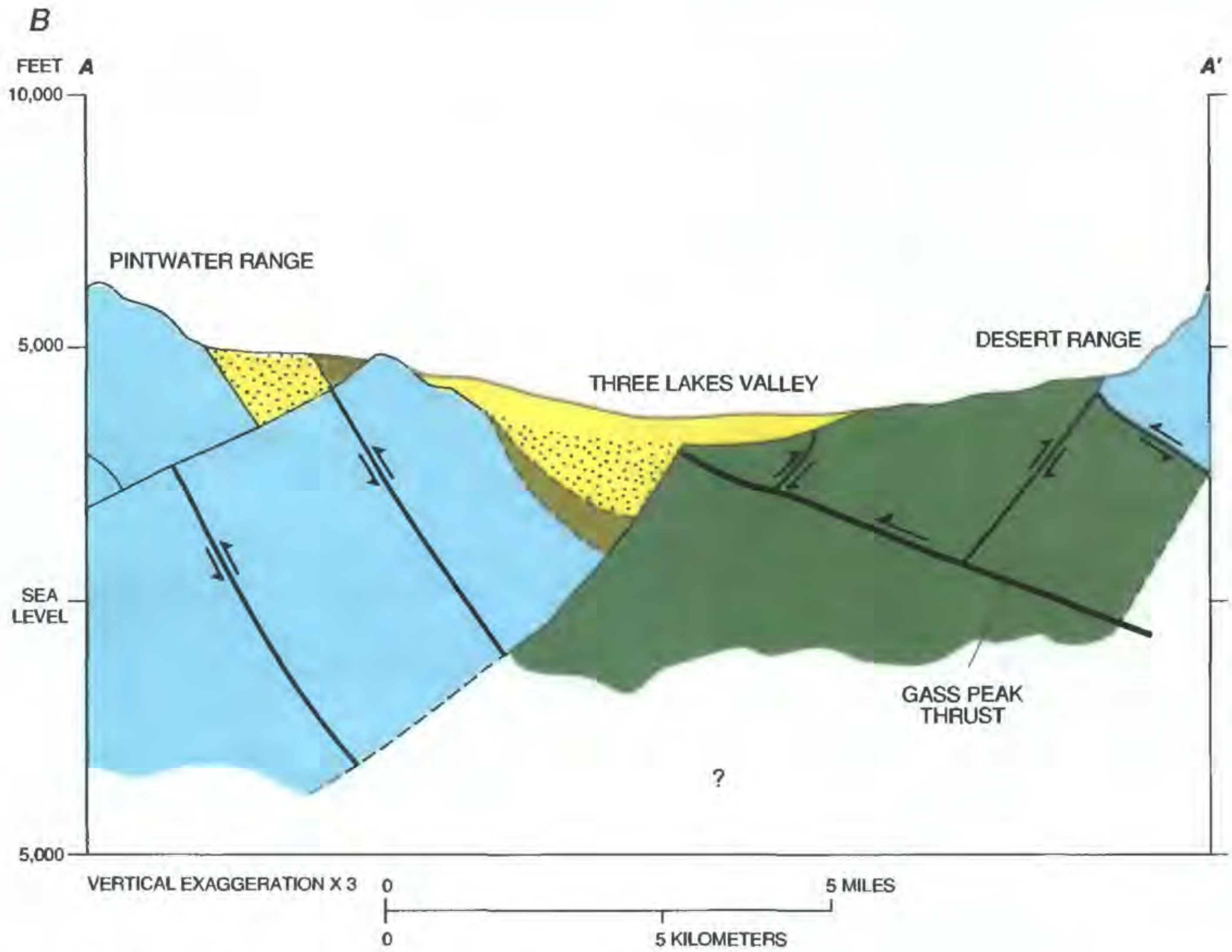


Figure 12. Continued.

1977), but may underlie the basin-fill deposits in the northern part of the area. Quaternary and Tertiary basin-fill deposits overlie Precambrian and Cambrian noncarbonate rocks west of the Desert Range, and Paleozoic carbonate or Tertiary volcanic rocks elsewhere. Basin-fill thicknesses generally range from 1,000 ft in the south to more than 3,000 ft in the northwest (P. L. Guth, Harvard University, written commun., 1988; D.H. Schaefer, U.S. Geological Survey, oral commun., 1988).

The Three Lakes Valley area was probably greatly thickened during Mesozoic time by compressional deformation because major thrust faults are exposed in the Sheep and Pintwater Ranges. Late Tertiary extension greatly thinned the area west of the Sheep Range resulting in faulting, tilting, rotation, and breakage of large rock masses. This extension also initiated movement along older thrust faults (Guth, 1988; Guth, 1987; Wernicke and others, 1984; Guth, 1981). Extensional thinning and subsequent erosion has exposed the large area of Cambrian clastic rocks (Precambrian and Cambrian noncarbonate rock unit) in the central Desert Range (fig. 12). In the Pintwater Range, extensional faulting has rotated a thick section of carbonate rock into the subsurface that has been preserved. This same fault probably greatly deepened the basin and consequently thickened the basin-fill deposits in the western one-half of Three Lakes Valley. Erosion removed most of the Tertiary volcanic rocks, although volcanism was probably not significant in the area (Guth, 1987; fig. 12).

The Las Vegas Valley shear zone, possibly representing the boundary between two regions with differential Tertiary extension (Wernicke and others, 1984) extends northwestward across the southern part of the area. The depth and characteristics of this fault zone beneath the basin fill are not known.

Hydrology

About 75 percent of the estimated 8,000 acre-ft/yr of mountain-block recharge in the Three Lakes Valley hydrographic area is supplied by precipitation on the Spring Mountains in the southern part of the area (Rush, 1970). Additional recharge as subsurface inflow from Pahranagat Valley (6,000 acre-ft/yr; Winograd and Friedman, 1972) and Tikaboo Valley (6,000 acre-ft/yr; Rush, 1970) may flow through the northern part of Three Lakes Valley westward into the Indian Springs Valley hydrographic area.

The estimated amount of inflow from Tikaboo Valley may be excessive because most of the recharge to Tikaboo Valley (Rush, 1970) originates in the Sheep Range. J.M. Thomas (U.S. Geological Survey, oral commun., 1988) suggests that most of, if not all, the recharge in the Sheep Range flows east toward the Muddy River Springs area. No regional springs or evapotranspiration of regional ground water are thought to occur in Three Lakes Valley because water levels are assumed to be deep throughout the area, as indicated by depths to water of 100 to 200 ft in southern Three Lakes Valley. Therefore, discharge from the area is inferred to be exclusively by subsurface outflow. The precise direction of subsurface flow beneath the valley, however, is not known because there are no water-level data for the carbonate rocks beneath the basin fill. Only six wells intercept the basin-fill aquifer in the southern part of the valley (table 12). No water-level data are available for the northern part of the valley.

If basin-fill water levels reflect water levels in the carbonate rocks at depth, the general direction of flow, according to Thomas and others (1986), is northward toward the northern part of the area and then probably west toward Ash Meadows. A ground-water divide may lie along the southern part of the valley, which may cause some recharge in southern Three Lakes Valley from the Spring Mountains to flow southeastward toward Las Vegas Valley (Lyles, 1987b). Recent drilling (Lyles and Hess, 1988) in Three Lakes Valley (Wells TL4 and TL5, fig. 12) and in nearby Las Vegas Valley suggests that a northward component of flow may be prevalent near the highway in the southeast part of the area. However, further drilling is necessary because interpretations of regional flow gradients are based on water levels in the basin-fill deposits and not on water levels in the deeper carbonate rocks.

The amount of ground-water storage beneath Three Lakes Valley is difficult to estimate without knowing the vertical extent of carbonate rocks in the area. However, based on assumptions used in this report for estimating storage, the total ground-water storage in the Three Lakes Valley hydrographic area is 6.0 million acre-ft. About 4.3 million acre-ft of the total is present in the southern part of the area. Local storage is somewhat limited and is confined to areas adjacent to the Pintwater Range (pl. 1). An estimated 3.5 million acre-ft of local storage is available in the area, most of which is in the southern half of Three Lakes Valley.

Potential for Ground-Water Development

Potential for development of the Three Lakes Valley area is uncertain due to the absence of available data on the thickness and extent of carbonate rocks and water levels beneath the valley. Much of the valley is currently part of a military reservation, making access for the public difficult in areas north of the highway. The southern part of Three Lakes Valley may have a potential for development because water levels generally are shallow and basin-fill deposits are thin (about 200 ft thick). Carbonate-rock aquifers in the southern part of the area also may be laterally continuous with

Table 12. Information on wells completed in basin fill in Three Lakes Valley

[Data modified from J.M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations and symbol: D, domestic; O, observation; --, no data]

Number (fig. 12)	Name	Depth to water (feet below land surface)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)	Use
TL1	none	301	--	--	O
TL2	none	54	--	--	O
TL3	Point Bravo	118	200	25	O
TL4	Old Dry	125	200	22.7	O
TL5	Divide	131	200	20.5	O
TL6	Prison	222	200	22.7	D

carbonate-rock aquifers beneath northwestern Las Vegas Valley, although the extent of carbonate rocks beneath the southern Desert Range is uncertain. Further exploration of the area would be beneficial to help determine the direction of deep flow and to provide information on the extent of carbonate rocks beneath the basin fill. If the Las Vegas Valley shear zone is a barrier to ground-water flow, the part of Three Lakes Valley north of the shear zone may have potential for development because the effects of pumping would be limited to areas north of the zone. However, areas to the west (Indian Springs Valley) may be adversely affected by development if a significant amount of water is withdrawn from the valley. If ground water flows toward Ash Meadows (pl. 1), spring discharge in Ash Meadows would eventually decline, although hundreds or thousands of years may pass before spring flows decline.

Indian Springs Valley

Hydrographic Setting

The Indian Springs hydrographic area occupies 655 mi^2 in northwestern Clark, southwestern Lincoln, and southeastern Nye Counties (fig. 13). All the area, except for a small part that extends into Nye County, is part of the Desert National Wildlife Range. The northern two-thirds of the area (generally north of U.S. Highway 95) is part of the Nellis Bombing Range (pl. 1) and is closed to the public; hence, hydrogeologic information in this part of the valley is extremely limited.

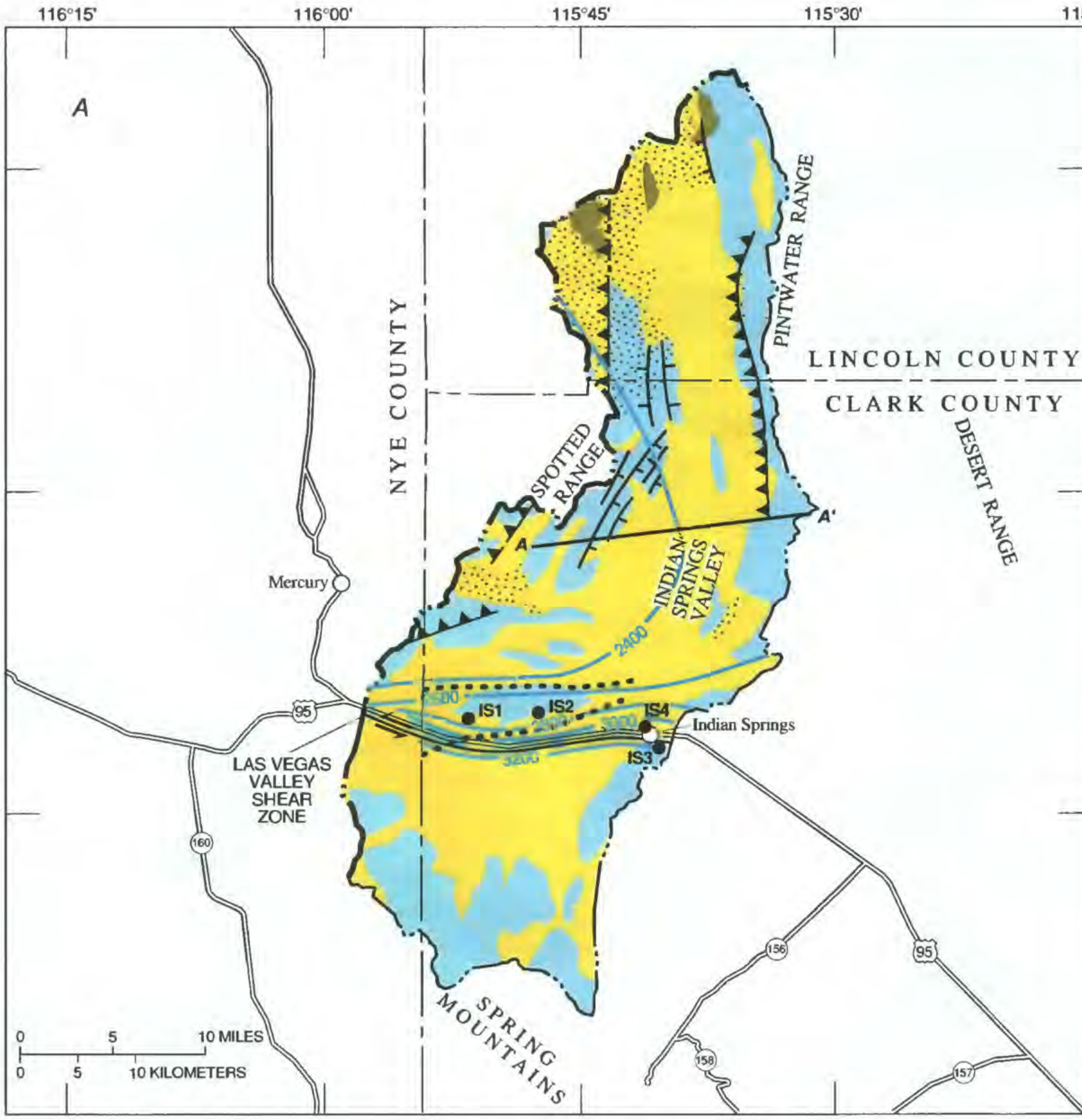
Surface drainage is northward from the Spring Mountains in the south, eastward from the Spotted Range to the west, and westward from the Pintwater Range to the east, and converges at a playa in the center of the valley. Except for several perennial reaches in and adjacent to the Spring Mountains, no streams in the area are perennial. Surface water occurs only during torrential storms or spring snowmelt (Maxey and Robinson, 1947). Most of the runoff rapidly infiltrates the highly fractured carbonate rocks of the Spring Mountains, Spotted and Pintwater Ranges, and the coarse basin-fill deposits of the alluvial fans adjacent to these ranges so that surface runoff rarely reaches the valley floor.

Indian Springs Air Force Base is located near the small community of Indian Springs (population 900) along U.S. Highway 95, which is the major highway connecting Las Vegas with the northern part of Nevada.

Geology

The ranges encompassing Indian Springs Valley consist primarily of Paleozoic carbonate rocks. These rocks extend to depths of more than 5,000 ft in the ranges and beneath the valley (P. L. Guth, Harvard University, written commun., 1988; fig. 13). A locally significant clastic-rock section within the Paleozoic carbonate unit is exposed in the Spotted Range and may restrict ground-water flow, particularly to the west of the Spotted Range (shown as stippled pattern in the Paleozoic carbonate-rock unit in fig. 13) where the clastic section thickens abruptly. Precambrian and Cambrian clastic rocks brought to the surface during thrusting are exposed in the Spring Mountains to the south and may extend to depths of thousands of feet. Tertiary volcanic rocks, mainly tuffs, crop out in the extreme northern part of the area, but their effect on ground-water flow is negligible. Quaternary and Tertiary basin-fill deposits are generally less than 500 ft thick, although south of the playa their thickness may increase to as much as 1,000 ft (D.H. Schaefer, U.S. Geological Survey, oral commun., 1988; fig. 13).

No detailed studies have thoroughly described the structural geology in the Indian Springs Valley hydrographic area; however, several regional studies have included the area (Guth, 1988; Guth, 1987; Wernicke and others, 1984; Barnes and others, 1982; Longwell and others, 1965). Thickening of the Paleozoic carbonate section resulting from Mesozoic compressional forces has occurred in the Spring Mountains (Burchfiel and others, 1974; Axen, 1984), and in the Spotted and Pintwater Ranges (Guth, 1988; see thrust faults in fig. 13). Tertiary extensional deformation resulted in extensive faulting and thinning of the carbonate-rock section (Guth, 1987), but the section remained fairly thick in the Indian Springs Valley area (P. L. Guth, Harvard University, written commun., 1988); it is possible that the carbonate rocks beneath the valley may have retained their subhorizontal position (fig. 13). In the Spotted Range west of Indian Springs Valley, extensional forces have produced highly broken west-dipping fault blocks (Guth, 1988).



EXPLANATION

Quaternary and Tertiary basin-fill deposits—Chiefly alluvial, fluvial, lake, and mud-flow deposits. Stippled areas include minor amount of tuffaceous sedimentary deposits and older clastic rocks

Tertiary rocks—Chiefly welded and nonwelded ash-flow tuffs

Paleozoic carbonate rocks—Chiefly limestone and dolomite, with locally thick sequences of clastic rocks including shale, sandstone, and conglomerate. Stippled areas include clastic unit comprised primarily of argillite, quartzite, and conglomerate

Boundary of study area

Boundary of hydrographic area

Normal fault—Hachures on downthrown side

Strike-slip fault—Shows left-lateral movement associated with the Las Vegas shear zone

Thrust fault—Dashed where approximately located. Sawteeth on upper plate

3000 **Water-level contour**—Shows altitude at which water level would stand in tightly cased wells developed in carbonate rocks. Dashed where approximately located. Contour interval, 200 feet. Datum is sea level

Inferred ground-water barrier—As postulated by Winograd and Thordarson (1968, 1975)

A——A' **Line of hydrogeologic section**

IS4 **Well or spring**—Completed in or discharging from carbonate rocks. Number is well or spring identifier

Figure 13. Hydrogeologic map of Indian Springs Valley and generalized section through northern Indian Springs Valley. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, water levels in the carbonate rocks, wells completed in carbonate rocks, and springs issuing from carbonate rocks (structural geology from Longwell and others, 1965; Winograd and Thordarson, 1968; Tschanz and Pampeyan, 1970; Wernicke and others, 1984; Barnes and others, 1982; hydrogeology from Winograd and Thordarson, 1975, and Thomas and others, 1986). *B*, Generalized hydrogeologic section through northern Indian Springs Valley (geology from Anderson and Jenkins, 1970; Guth, 1987; P.L. Guth, Harvard University, written commun., 1988).

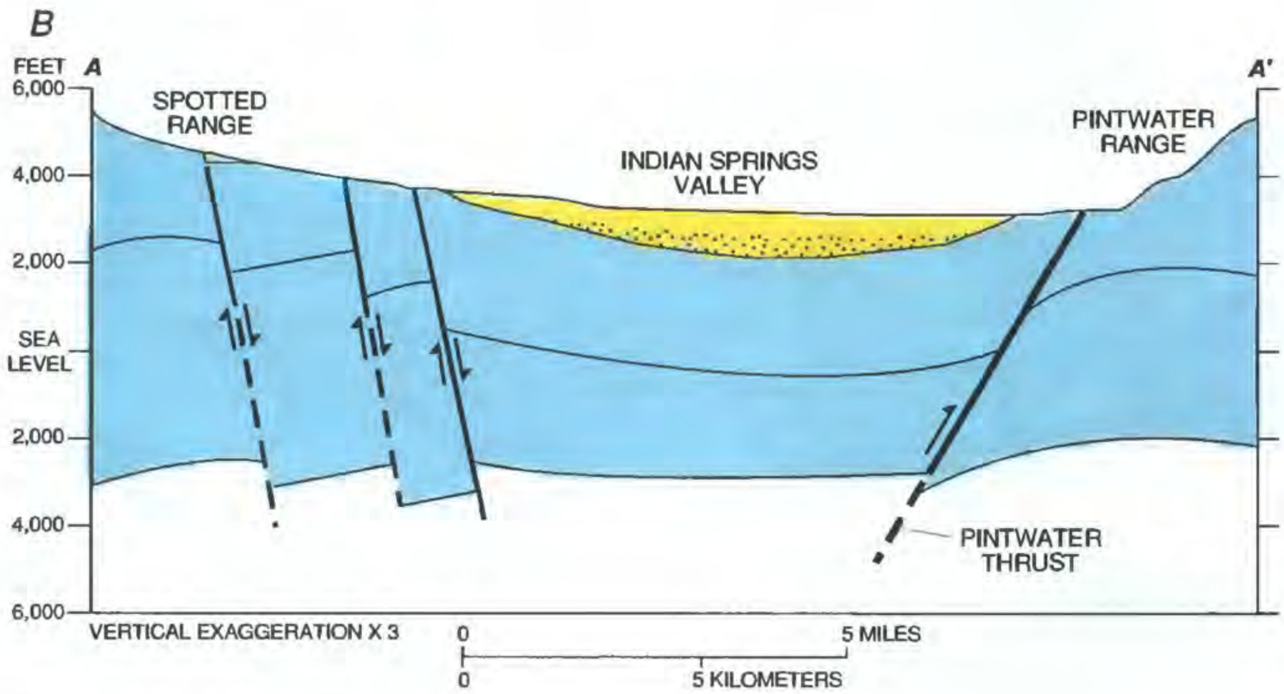


Figure 13. Continued.

The Las Vegas Valley shear zone, which nearly parallels the highway (fig. 13), marks the boundary between two regions of differential Tertiary extension (Wernicke and others, 1984). Correlation of stratigraphic and structural features across the shear zone indicates displacements ranging from 24 to 40 mi (Longwell, 1974; Stewart, 1967; Burchfiel, 1965). Winograd and Thordarson (1968, 1975) suggest that fault gouge (finely crushed rock) along the shear zone may act as a barrier to ground-water flow (see next section).

Hydrology

Nearly all the estimated 10,000 acre-ft/yr of recharge derived from precipitation in Indian Springs Valley originates in the Spring Mountains (Rush, 1970; fig. 13). Near the community of Indian Springs, ground water is discharged from springs and by evapotranspiration. This discharge is small (5 percent) in comparison with the estimated subsurface outflow. Ground water originating as recharge in the Spring Mountains flowing beneath Indian Springs Valley may supply more than 50 percent of the spring discharge at Ash Meadows in the Amargosa Desert (J.M. Thomas, U.S. Geological Survey, oral commun., 1988).

Water levels decrease abruptly from the Spring Mountains toward the playa in the center of the valley. Water levels south of the highway near Indian Springs are generally less than 100 ft below land surface, but they decrease to a depth greater than 800 ft north of the highway toward the playa (fig. 13). Winograd and Thordarson (1968, 1975) suggested that two ground-water barriers are responsible for the lowering of water levels to the north; these authors believe that the barriers create a step-like, water-level pattern. The southernmost ground-water barrier almost coincides with the inferred position of the Las Vegas Valley shear zone (Longwell and others, 1965). The northern barrier may result from shallow Cambrian and Precambrian clastic rocks penetrating into the aquifer from below. Winograd and Thordarson (1968) suspect these barriers are responsible for the location of Indian Springs (IS3, fig. 13; table 13) located just south of the Las Vegas Valley shear zone. Between the two inferred barriers, according to these observers, is a gentle westward-trending hydraulic gradient. The two inferred ground-water flow barriers may not be significant in the carbonate-rock aquifers, but may merely reflect the steep hydraulic gradient in the Spring Mountains recharge area (Lyles, 1987b; and J.M. Thomas, U.S. Geological Survey, oral commun., 1988). More water-level data are needed to accurately determine flow directions in this part of Indian Springs Valley. Meanwhile, no water-level data are available for the northern part of the valley (fig. 13, table 13).

Table 13. Information on wells completed in and a spring issuing from carbonate rocks in Indian Springs Valley

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations and symbols: D, domestic; O, observation; --, no data; <, less than]

Number (fig. 13)	Source	Name	Depth to water (feet below land surface)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)	Use
IS1	well	none	840	<500	--	O
IS2	well	none	740	<500	25.5	O
IS3	spring [a]	Indian	0	200	25	D
IS4	well	none	75	<500	--	O

[a] Discharges 645 acre-ft/yr

The quantity of subsurface inflow from Three Lakes Valley to the east and from Emigrant Valley to the north is not known. Estimates have been reported to be 22,000 acre-ft/yr, and probably include underflow originating from Pahranagat Valley (Scott and others, 1971). Coupled with the 10,000 acre-ft/yr recharging the valley from precipitation, the total quantity of subsurface outflow toward Ash Meadows (pl. 1) is estimated to be 32,000 acre-ft/yr. This quantity appears too large on the basis of discharge measurements at Ash Meadows and is based on the assumption that all water from the Sheep Range flows toward Ash Meadows. If all, or most, recharge in the Sheep Range flows eastward, then the total outflow from Indian Springs Valley would be on the order of 21,000 acre-ft/yr. Ground-water flow through carbonate rocks is expected to flow northward from the Spring Mountains and then westward toward Ash Meadows. Exactly where beneath Indian Springs Valley this change of direction may occur is not known, although the scant water-level data indicate that this westward flow may begin in southern Indian Springs Valley (fig. 13).

The quantity of ground water stored in carbonate rocks within the Indian Springs hydrographic area has been estimated, on the basis of assumptions described earlier in this report, to be about 7 million acre-ft. Local storage (within the basin fill) represents an estimated 4.1 million acre-ft, or about 58 percent of the total storage.

Potential for Ground-Water Development

Water-level data indicate that the best area for development is south of the highway (south of the Las Vegas Valley shear zone) in the Indian Springs area where water levels are generally less than 100 ft below land surface and where the basin fill is relatively thin. As reported earlier, an estimated 10,000 acre-ft/yr may flow from the Spring Mountains northward then westward toward Ash Meadows. Development in this area could have dramatic short-term effects on wells at the Indian Springs Air Force Base and on discharge from Indian Springs. However, it could take several hundred years for the effect of pumping in this area to cause significant declines in spring discharge at Ash Meadows and the water level at Devils Hole where the environmentally protected Pupfish live. The area north of U.S. Highway 95 is restricted to public access, so even if this area proved to be a potential site for development on the basis of the criteria described in this report, it would be difficult to gain access for further data collection and development.

Amargosa Desert

Hydrographic Setting

The Amargosa Desert hydrographic area occupies about 896 mi^2 in western Nye County, Nevada, and 468 mi^2 in eastern Inyo County, California (fig. 14). The area is part of the much larger Death Valley drainage basin (Walker and Eakin, 1963;

Winograd and Thordarson, 1975). Because of its proximity to the Nevada Test Site (northeast of Amargosa Desert) and its prominent regional springs and Devils Hole, the hydrogeology of Ash Meadows in south-central Amargosa Desert has been investigated extensively during the past few decades (Eakin and others, 1963; Winograd and Eakin, 1965; Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Winograd and Pearson, 1976; Claassen, 1983; and Kilroy, 1991).

The hydrographic area is surrounded by mountain ranges, the most prominent being the Funeral Mountains to the west. Part of the northeastern boundary through Lathrop Wells is not bounded by mountains and is arbitrarily drawn along U.S. Highway 95 (fig. 14). Intermittent surface water drains to the Amargosa River, which flows southeastward through the central part of the area. The Amargosa River enters the northwestern part of the area at Beatty where the altitude is about 5,000 ft. The river leaves the area south of Death Valley Junction where its altitude is 1,900 ft. Surface water entering the Amargosa River mostly infiltrates into the basin fill; hence, the river is dry along most of its course, except during rain storms. Amargosa Flat and Alkali Flat are two prominent playas occupying the southeast and southern parts of the area, respectively (fig. 14).

Few people live in the area. A large farm, located in the north-central part of the area, supports farmers and ranchers who have attempted to grow various crops including alfalfa and pistachios, but declining water levels caused by extensive irrigation have disrupted production. Devils Hole, a national monument where an endangered species of Pupfish are protected, is located in Ash Meadows in the south-central part of the area (A5, fig. 14). Consequently, pumpage has been greatly reduced in the Ash Meadows area in an effort to preserve the Pupfish habitat.

Geology

Precambrian and Cambrian noncarbonate rocks are widespread and abundant. The northern Funeral Mountains consist primarily of metamorphic rocks that likely extend to significant depths and act as a barrier to ground-water flow. Precambrian and Cambrian quartzites and clastic rocks are common in Bare Mountain in the northern part of the area and in the Montgomery Mountains along the eastern border of the area. In the Montgomery Mountains, 3,000 ft of quartzite of low permeability overlies Paleozoic carbonate rocks (Burchfiel and others, 1983a). More than 16,000 ft of Paleozoic carbonate rocks crop out in the Specter Range in the northeastern part of the area (Burchfiel, 1965). Carbonate rocks are also common in the Montgomery Mountains, but are not as thick as exposed sections in the Specter Range (Burchfiel and others, 1983a, fig. 3), and in the southern Funeral Mountains. The thickness and extent of carbonate rocks beneath Amargosa Desert is not known, but they probably are limited mostly to the southeastern part of the area. Several thousand feet of Tertiary volcanic rocks comprised chiefly of tuffs are exposed in the Bullfrog Hills in the northern part of the area. Thick sequences of basalt, andesite, and rhyolite constitute the Greenwater Range in the southwestern part of the area. Thicknesses of Quaternary and Tertiary basin fill vary greatly within the Amargosa Desert. In the northern part of the area, the basin-fill deposits may be as thick as 2,300-3,500 ft (Healey and Miller, 1971), but they thin to about 1,400 ft toward the central part of the area southwest of Lathrop Wells (fig. 14). In Amargosa Flat and southwest of Ash Meadows, basin-fill thicknesses may exceed 5,000 ft locally (fig. 14), and generally are at least 3,500 ft. In the extreme southwest part of the area, the thickness of basin fill generally ranges from 2,000 to 3,500 ft.

Within the Amargosa Desert hydrographic area, compressional deformation has produced at least three thrust faults (fig. 14) and has thickened the upper Precambrian and Paleozoic sections beneath Amargosa Flat in the northeastern part of the area (Winograd and Thordarson, 1975, p. 75). The lateral extent of the carbonate rocks beneath the southern part of Amargosa Desert extending northwest to the center of the desert is not known because extreme extension may have removed the thick Paleozoic carbonate section except beneath Amargosa Flat. Greenhaus and Zablocki (1982) suggest, on the basis of geophysical data, that Paleozoic carbonate or Precambrian clastic rocks underlie much of southern Amargosa Desert, where Tertiary volcanic rocks are generally sparse or not present. Figure 14 shows a thin section of Paleozoic rock at depth southwest of Alkali Flat, but more information is needed to adequately describe the hydrogeologic rock units at depth.

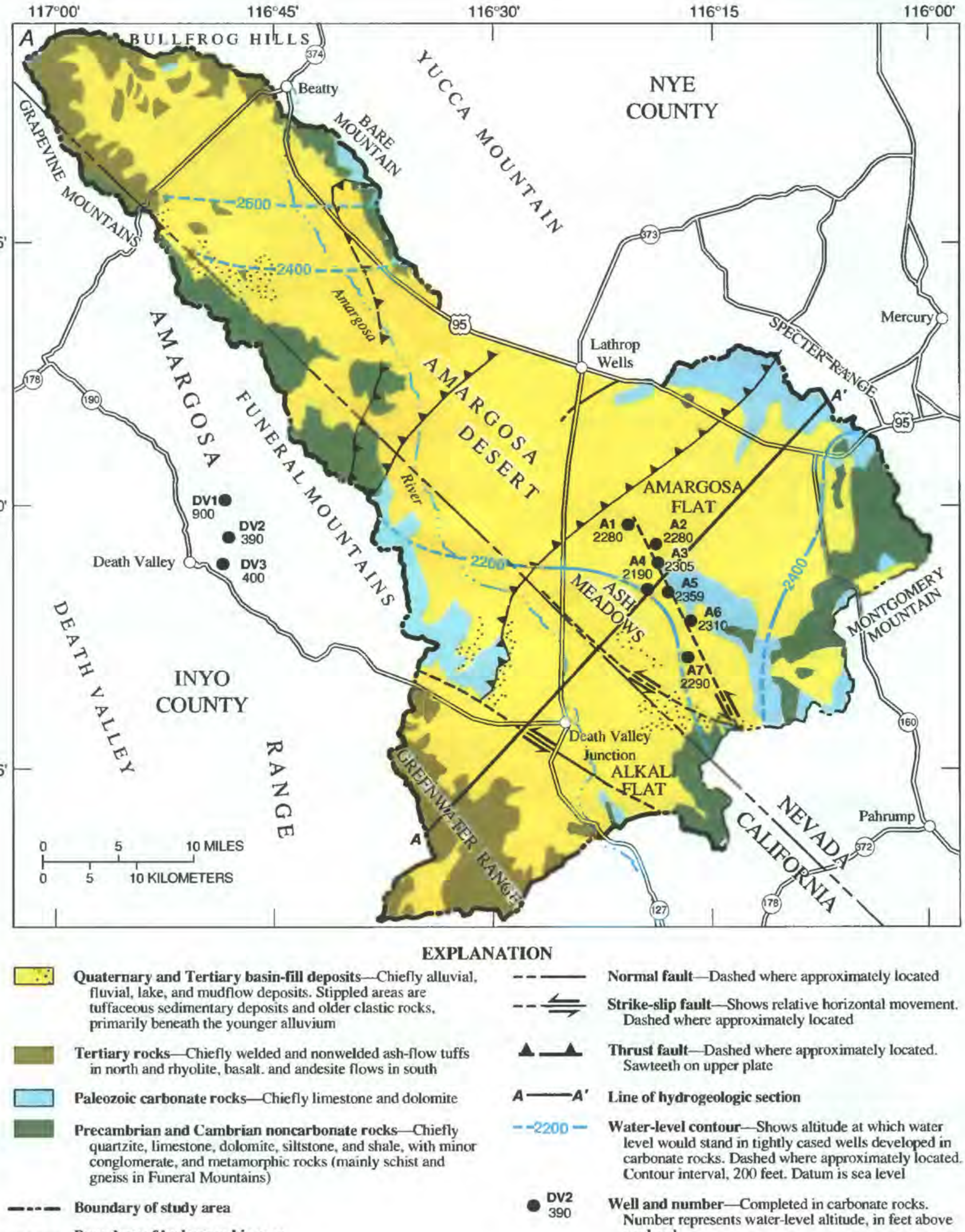


Figure 14. Hydrogeologic map and generalized section through Amargosa Desert. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, and water levels in the carbonate rocks (structural geology from Winograd and Thordarson, 1975; Carr and Monsen, 1988; Burchfiel and others 1983a; Wernicke and others, 1988b; hydrogeology from Thomas and others, 1986, and Kilroy, 1991). *B*, Generalized hydrogeologic section through the Amargosa Desert (geology from Winograd and Thordarson, 1975, and Wright and Troxel, 1967).

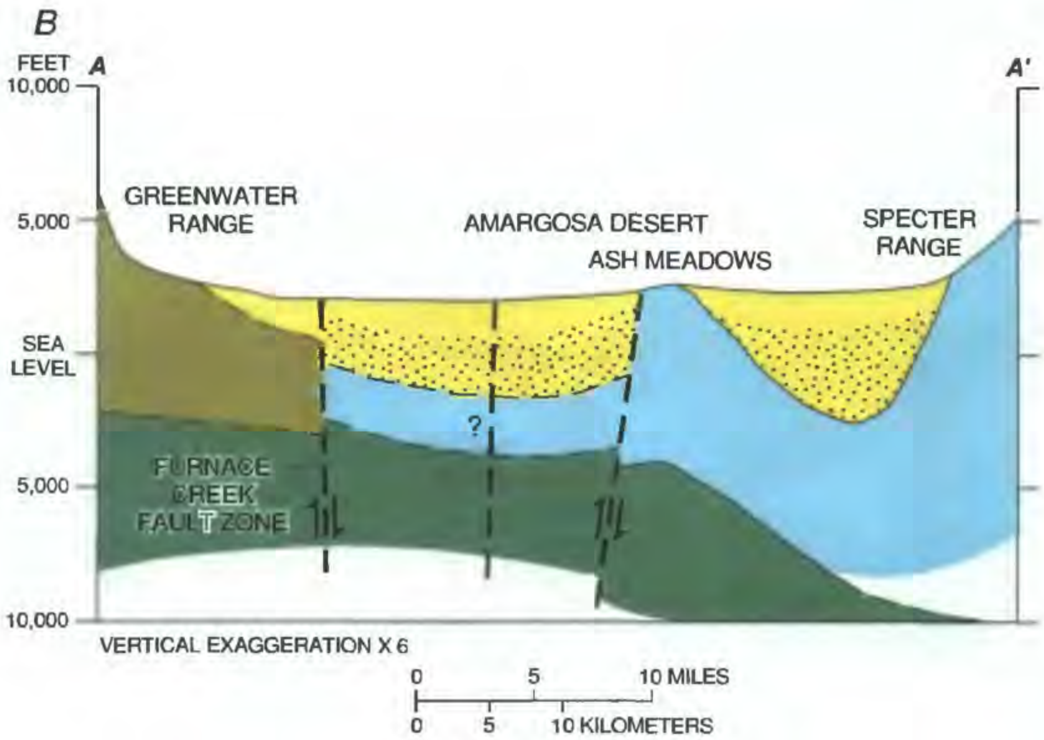


Figure 14. Continued.

Extensional faults are found throughout the area. Large Late Tertiary faults are exposed at Bare Mountain in the northwestern part of the area where a westward-trending highly extended area has been mapped on the west side of the mountain (Carr and Monsen, 1988; Robinson, 1985). Extreme thinning of the Paleozoic carbonate rocks in the Bull Frog Hills has all but eliminated the carbonate-rock section so that thick, Late Tertiary volcanic rocks mostly overlie Precambrian basement rock (Maldonado, 1988). Other important extensional faults are in the south and south-central Amargosa Desert where strike-slip and normal faults may have juxtaposed carbonate rocks against low-permeability clastic rocks or basin-fill deposits, perhaps greatly affecting the hydrogeology of the area. Most of the faults are buried by basin fill and their significance is not well understood. However, a high-angle normal fault trending north-northwest through the springs in Ash Meadows strongly suggests juxtaposition of highly permeable Paleozoic carbonate rocks against low-permeability Tertiary basin-fill deposits because many springs emerge from either carbonate rocks or basin fill along a line coinciding with this fault. Figure 14 shows the inferred geologic section through this fault at Ash Meadows.

Hydrology

Numerous hydrologic investigations of south-central Nevada have focused, at least in part, on the Amargosa Desert and particularly Ash Meadows (Eakin and others, 1963; Walker and Eakin, 1963; Winograd and Friedman, 1972; Naff and others, 1974; Winograd and Thordarson, 1975; Winograd and Pearson, 1976; Waddell, 1982; Claassen, 1983; Waddell and others, 1984; and Czarnecki, 1985). Recharge from infiltration of precipitation in surrounding mountain blocks is probably small (Walker and Eakin, 1963) compared with water that enters the area as subsurface inflow (Winograd and Friedman, 1972; Winograd and Thordarson, 1975; Waddell, 1982; Claassen, 1983) primarily through thick sequences of carbonate rocks beneath the Specter Range (table 14). Subsurface inflow from carbonate rocks in this area supports springflow at Ash Meadows and at Death Valley (fig. 14, table 14) and may exceed 21,000 acre-ft/yr. The ground water entering Amargosa Desert through the Specter Range is not local, but originates from several distant sources. According to Winograd and Friedman (1972) and Winograd and Thordarson (1975), sources of recharge include the Spring Mountains, the Sheep Range, and Pahranagat Valley nearly 100 mi to the northeast of Ash Meadows. J.M. Thomas and M.D. Dettinger (U.S. Geological Survey,

Table 14. Recharge and discharge estimates for Amargosa Desert

[Symbol: <, less than]

Component of recharge or discharge	Quantity (acre-feet per year)
Recharge	
Precipitation in adjacent mountain blocks (Walker and Eakin, 1963)	1,200
Subsurface inflow from:	
Spring Mountains and Jackass Flats beneath Specter Range (Walker and Eakin, 1963)	19,000
Spring Mountains, Sheep Range, and Pahranagat Valley (Winograd and Thordarson, 1975)	21,000
Spring Mountains, Sheep Range, Pahranagat Valley, Jackass Flats, and Oasis Valley (Waddell and others, 1984)	34,000
Discharge	
Evapotranspiration from phreatophytes, bare soils, and springs issuing from carbonate rocks for:	
Ash Meadows and Alkali Flat (Walker and Eakin, 1963)	24,000
Ash Meadows (Winograd and Thordarson, (1975)	17,000
Pumpage for:	
1962 (Walker and Eakin, 1963)	3,000
1985 (Kilroy, 1991)	10,000
Subsurface outflow to Death Valley	
Walker and Eakin (1963)	<3,000
Winograd and Thordarson (1975)	4,000-5,000
Waddell and others (1984)	5,000
Total recharge (rounded)	20,000-35,000
Total discharge (rounded)	21,000-27,000

oral commun., 1988) exclude the Sheep Range as a source of water for the springs in Ash Meadows on the basis of recent geologic, hydrologic, and geochemical evidence that indicates eastward flow from the Sheep Range. Additional recharge from Oasis Valley to the northwest and Jackass Flats to the northeast enters the area primarily through basin-fill deposits and possibly welded-tuff aquifers of the Nevada Test Site. The amount of recharge or subsurface flow from these sources may be large (Walker and Eakin, 1963; Waddell and others, 1984; table 14).

Ground water within the hydrographic area, as already mentioned, discharges primarily as springflow along a northwest-trending line of springs in Ash Meadows (fig. 14). The location and emergence of these springs is believed to be related to the high-angle normal fault that coincides with the line of springs (fig. 14, table 15). Evapotranspiration in Ash Meadows probably results from spring discharge and local subsurface flow from carbonate rocks rather than from inflow through basin-fill deposits north of Ash Meadows (Winograd and Thordarson, 1975; Claassen, 1983). Farther south, in Alkali Flat, evapotranspiration may be significant because of shallow water levels (Waddell and others, 1984). Some throughflow beneath Amargosa Desert through carbonate rocks or basin fill toward Death Valley is likely because springs in Death Valley (fig. 14) have similar geochemical and isotopic characteristics to springs emerging at Ash Meadows. Furthermore, discharge of these Death Valley springs near the terminus of carbonate rocks exposed in the southern Funeral Mountains strongly indicates regional flow through carbonate rocks.

Water-level data indicate that ground-water flow within basin-fill deposits is generally northwest to southeast along the course of the Amargosa River in the northern part of the area, but southwestward in the southern part of the area. Similar ground-water flow directions are inferred in carbonate rocks at depth in the southern part of the area. Overall, the depth to water is generally shallow throughout the Amargosa Desert except in the extreme northern and southwestern parts of the hydrographic area where depths to water may reach 500 ft or more (Kilroy, 1991).

Ground-water storage within the carbonate rocks beneath the Amargosa Desert has been estimated at about 3.6 million acre-ft, according to the assumptions outlined in this report. Local ground-water storage (within basin fill) has been estimated at 2.3 million acre-ft.

Potential for Ground-Water Development

Amargosa Desert is an unlikely site for potential development of carbonate-rock aquifers for two reasons. First is the U.S. Supreme Court's mandate that pumping in the vicinity of Ash Meadows be greatly reduced to protect the Pupfish habitat in Devils Hole, which greatly reduces, if not excludes, the potential area where carbonate rocks can be practically and economically penetrated. Pumping anywhere upgradient from or in the vicinity of the springs would eventually affect water levels in the area, particularly at Devils Hole (A5, fig. 14). Second, the absence of hydrogeologic data in areas downgradient of Ash Meadows precludes comprehensive evaluation of

Table 15. Information on major springs issuing from carbonate rocks in Amargosa Desert and adjacent parts of Death Valley

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations and symbol: D, domestic; U, unused; <, less than]

Number (fig. 14)	Name	Discharge (acre-feet per year)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)	Use
A1	Fairbanks	2,900	420	27.2	U
A2	Rogers	1,200	<500	27.7	U
A3	Longstreet	1,700	<500	27.2	U
A4	Crystal Pool	4,700	450	31.1	U
A5	Devils Hole	0	430	32.7	U
A6	Point-of-Rock	2,500	<500	32.7	U
A7	Big	1,700	490	27.2	U
DV1	Nevares	260	630	33.8	D
DV2	Texas	360	610	32.7	D
DV3	Travertine	490	660	33.8	D

development potential. Although evidence suggests that carbonate rocks may underlie the basin fill in this area, the depth to and thickness of the carbonate-rock sequences and the quantity of flow are not known. Winograd and Thordarson (1975) suggest that the quantity of flow beneath the area is equivalent to the quantity of spring discharge at Death Valley (between 4,000 and 5,000 acre-ft/yr). Therefore, development in this area would probably affect spring discharge at Death Valley, which is used for domestic purposes.

In the northwestern half of the Amargosa Desert area, the presence of carbonate rocks at depth is unknown. Further study of this area is needed to make even a reconnaissance appraisal of development potential.

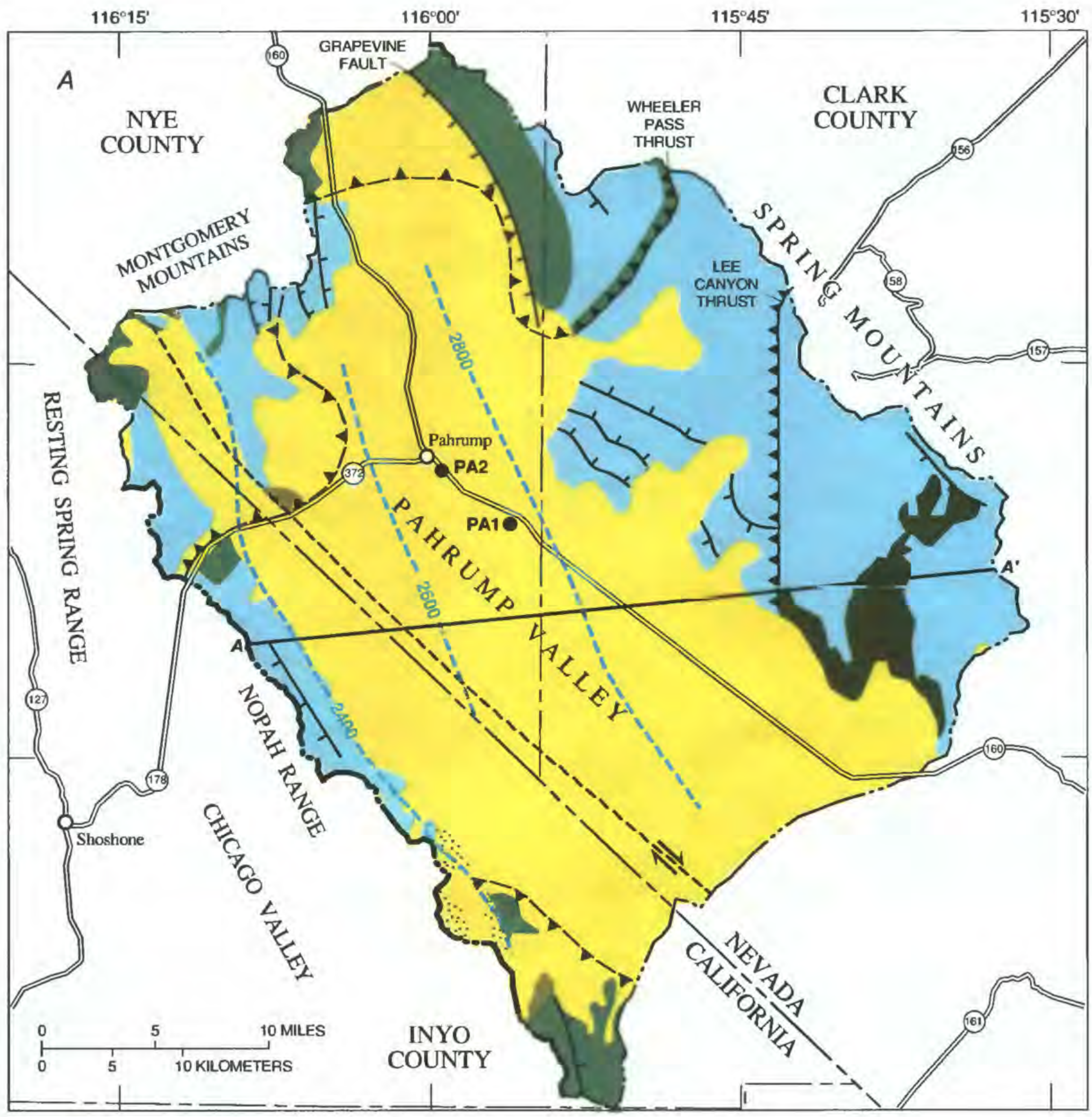
Pahrump Valley

Hydrographic Setting

The Pahrump Valley hydrographic area encompasses about 1,050 mi^2 in Nye and Clark Counties in southern Nevada, and Inyo County in southeastern California (fig. 15). Approximately 80 percent of the area is in Nevada. Pahrump Valley is a topographically closed basin with surface drainage generally from northeast to southwest (Malmberg, 1967). The Spring Mountains on the northeast side of the area are the source of recharge for the valley and greatly influence the direction and magnitude of ground-water flow throughout the area. Large alluvial fans, extending southwestward from the Spring Mountains, have a surface gradient of between 200 and 400 ft/mi. Historically, two major springs discharged near the foot of the fans until pumping for irrigation eventually lowered the water table to where the springs no longer flow (Harrill, 1986). More recently, water levels have slightly risen as a result of decreased pumping in the vicinity of the springs. The southwestern part of the valley is gently sloping with typical gradients of 15 to 30 ft/mi in a southwest direction. The Pahrump area is one of the chief areas for growing alfalfa, cotton, and grains in southern Nevada, and is currently being developed for residential purposes. The town of Pahrump is the major community in the area. All water for domestic and irrigation purposes is obtained from wells; no perennial streams flow in Pahrump Valley.

Geology

The Spring Mountains, the largest range in southern Nevada, are composed largely of thick sections of Paleozoic carbonate rocks and contain locally interlayered units of Precambrian and Cambrian noncarbonate rocks. Paleozoic carbonate rocks are also widespread in the Nopah Range to the west and may exceed 10,000 ft in thickness (Burchfiel and others, 1983a,



EXPLANATION

Quaternary and Tertiary basin-fill deposits—Chiefly alluvium, lake deposits, sandstone, and siltstone. Stippled areas include minor amounts of tuffaceous sedimentary rocks and older clastic rocks

Tertiary rocks—Chiefly ash-fall and ash-flow tuffs, with locally significant basalt flows

Upper Paleozoic and Mesozoic sedimentary rocks—Chiefly siltstone, sandstone, limestone, and gypsum, with sparse dolomite, shale, and conglomerate

Paleozoic carbonate rocks—Chiefly limestone and dolomite

Precambrian and Cambrian noncarbonate rocks—Chiefly quartzite, sandstone, siltstone, and shale

Boundary of study area

Boundary of hydrographic area

Normal fault—Hachures on downthrown side

Strike-slip fault—Dashed where approximately located

Thrust fault—Dashed where approximately located. Sawteeth on upper plate

A——A' **Line of hydrogeologic section**

2800 **Water-level contour**—Shows altitude at which water level would stand in tightly cased wells developed in carbonate rocks. Dashed where approximately located. Contour interval, 200 feet. Datum is sea level

PA1 ● **Spring and number**—Discharges from alluvial deposits, but source is believed to be carbonate-rock aquifer

Figure 15. Hydrogeologic map and generalized section through Pahrump Valley. *A*, Hydrographic area showing hydrogeologic rock units, major structural features, water levels in the carbonate rocks, and springs discharging (or previously discharging) from carbonate rocks (structural geology from Cornwall, 1972; Burchfiel and others, 1974; Wright and others, 1981; Wernicke and others, 1988b; hydrogeology from Thomas and others, 1986, and Harrill, 1986). *B*, Generalized hydrogeologic section through Pahrump Valley (geology from Malmberg, 1967; Burchfiel and others, 1974; Wright and others, 1981; and Harrill, 1986).

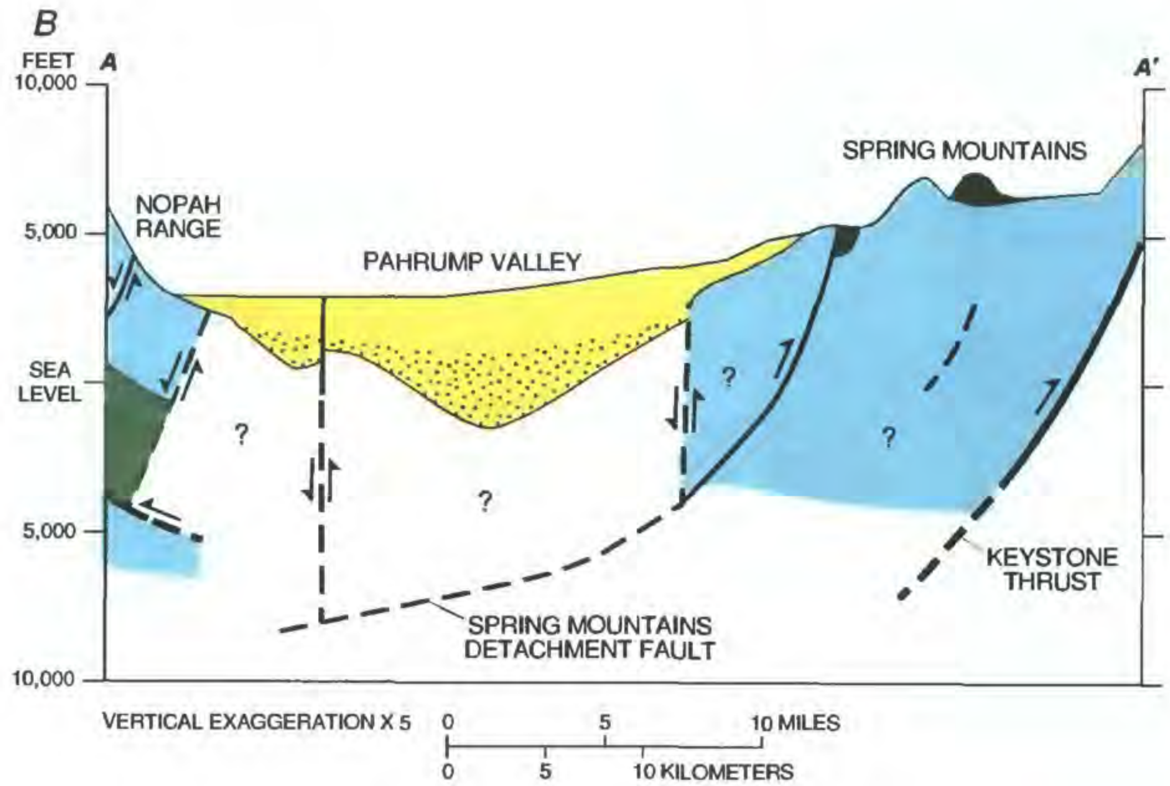


Figure 15. Continued.

fig. 3). Precambrian and Cambrian noncarbonate rocks are prevalent in the northern part of the Spring Mountains, in the Montgomery Mountains, and in the Kingston Range (fig. 15). Thicknesses of this unit generally exceed 3,000 ft (Burchfiel and others, 1983b; Burchfiel and others, 1974). A thick wedge of Mesozoic sedimentary rocks is exposed in the Spring Mountains in the eastern part of the area (fig. 15). Quaternary and Tertiary basin-fill deposits are thin near the margins of the valley, but may exceed 4,000 ft near the center of the valley (Harrill, 1986). Because no wells penetrate the rocks underlying the basin fill, the hydrologic rock units beneath the valley are not known.

Widespread evidence of compressional tectonics can be seen in the Spring Mountains where thick sequences of Paleozoic carbonate rocks and Cambrian and Precambrian clastic rocks have been thickened by thrusting. The westernmost thrust fault in the Pahrump Valley area, the Wheeler Pass thrust, brought a thick sequence of Precambrian clastic rocks over much of the younger Paleozoic carbonate rocks. Pahrump Valley and the Resting Springs Range to the southwest are results of extreme extensional deformation, which has resulted in high-angle block and normal faulting as the area was "pulled apart" (Burchfiel and others, 1983b; fig. 15). The geology beneath Pahrump Valley is probably highly complex. It is not known whether thick sequences of Precambrian and Cambrian clastic rocks were transported eastward (beneath the valley) during thrusting, or whether Paleozoic carbonate rocks or older clastic rocks still remain after being greatly extended.

Hydrology

Pahrump Valley is recharged almost exclusively from the infiltration of precipitation atop the abundantly exposed carbonate rocks of Spring Mountains, the largest area of recharge in southern Nevada. Malmberg (1967) estimated that about 22,000 acre-ft/yr is recharged to Pahrump Valley from the Spring Mountains, whereas Harrill (1986) estimated that as much as 37,000 acre-ft/yr may recharge the valley, on the basis of computer simulations. Of the 37,000 acre-ft/yr estimated by Harrill, approximately 18,000 acre-ft/yr recharges the carbonate rocks at depth while the remaining 19,000 acre-ft/yr recharges the basin fill. Prior to extensive pumping for irrigation, ground water within Pahrump Valley was discharged by evapotranspiration, springs (Manse and Bennets Springs, fig. 15, table 17), and subsurface outflow. Table 16 shows the natural recharge and discharge estimates (prior to pumping) made by previous investigators.

Table 16. Recharge and discharge estimates for Pahrump Valley prior to development

Component of recharge or discharge	Quantity (acre-feet per year)
Recharge	
Precipitation in Spring Mountains	
Malmberg (1967)	22,000
Harrill (1986)[a]	37,000
Recirculated discharge from Manse and Bennet Springs	
Harrill (1986)[a]	4,600
Discharge	
Evapotranspiration from phreatophytes	
Malmberg (1967)	10,000 [b]
Harrill (1986)	14,000 [c]
Springs issuing from carbonate rocks and basin fill	
Maxey and Jameson (1948)	9,700
Subsurface outflow to Shoshone, Tecopa, and possibly Death Valley	
Malmberg (1967)	12,000 [d]
Harrill (1986)	18,000
Total recharge (rounded)	22,000-42,000
Total discharge (rounded)	22,000-42,000

[a] Results from simulation of steady-state ground-water flow model. Amount of spring discharge recirculated back into flow model.

[b] Represents spring discharge consumed by evapotranspiration.

[c] Does not include direct evapotranspiration of 5,200 acre-feet per year of spring discharge not recirculated back to ground water.

[d] Represents 2,000 acre-feet per year through the basin fill and 10,000 acre-feet per year through carbonate rocks.

Water levels in the basin fill were within 50 ft of land surface in much of the valley prior to development. Several wells near the springs had artesian flow caused by high water pressures at depth. Subsequently, water-level declines of 100 ft have been measured for 60 years following the onset of pumping (Harrill, 1986). Water levels have recovered on the order of 5 to 10 ft since the mid-1970's because of decreased pumping. Most wells within the valley, however, are shallow because the water levels are shallow. The deepest wells extend to about 1,000 ft below land surface, but are still well within the basin fill, which may be as thick as 4,000 ft. No water-level data are available for carbonate rocks beneath Pahrump Valley.

The hydrologic character of Pahrump Valley shows evidence of structural influences at depth. Prior to development of the valley, both Manse and Bennets Springs issued from the base of the large alluvial fans sloping up to the Spring Mountains. These springs originate from ground water in carbonate rocks, on the basis of geochemistry (J.M. Thomas, U.S. Geological Survey, oral commun., 1988), but evidence suggests that ground-water circulation is relatively shallow because the temperature of the springs is less than 27°C (table 17). The present location of the springs may be the result of extensional faults that have juxtaposed highly permeable Paleozoic carbonate rocks with Tertiary basin fill of low permeability near where the springs discharge (fig. 15), or more simply due to the break in slope at the toe of the alluvial fans. As pumping began and water levels declined within the valley, these springs dried up because of the shallow source of ground-water flow and the close hydraulic connection between the carbonate rocks and adjacent basin fill.

Table 17. Information on springs assumed to be fed by carbonate-rock aquifer and used for irrigation in Pahrump Valley [a]

[Data modified from James M. Thomas, U.S. Geological Survey, written commun., 1987.]

Number (fig. 15)	Name	Discharge [b] (acre-feet per year)	Dissolved solids (milligrams per liter)	Temperature (degrees Celsius)
PA1	Manse	4,400	230	22
PA2	Bennets	5,400	240	25

[a] Water-quality data were obtained from wells adjacent to springs before pumping began.

[b] Discharge rate prior to development.

Spring discharge at Shoshone and Tecopa (south of Shoshone) southwest of the Resting Spring Range (fig. 15 and pl. 1) originates from recharge to the carbonate rocks within the Spring Mountains. Model simulations by Harrill (1986) indicate that pumping centers in Pahrump Valley have little short-term influence on spring discharge or evapotranspiration at Shoshone and Tecopa; rather, pumping tends to extract stored water in the basin fill or perhaps the shallow underlying carbonate rocks. How long-term pumping in Pahrump Valley would affect discharge at Shoshone and Tecopa depends (1) on the difference in altitude between water in the wells at the pumping center and the water level at the downgradient discharge areas, which is currently about 1,000 ft below the altitude of the pumping wells, and (2) on the amount of flow the pumping wells could capture. Furthermore, the influence of possible low-permeability clastic rocks beneath Pahrump Valley on long-term pumping and downgradient discharge is not known.

Because much of the Pahrump Valley area has exposed carbonate rocks, the estimated ground-water storage within the area is quite high. About 10 million acre-ft of storage has been estimated for the area, according to the assumptions outlined in this report; of this total, about 6.7 million acre-ft represents local storage (within the basin fill). Both total (carbonate rock and basin-fill storage) and local storage estimates may be high if extension has thinned or moved the carbonate rocks from beneath Pahrump Valley.

Potential for Ground-Water Development

Pahrump Valley has many positive attributes that make it a potential site for future development: shallow water levels, potentially thick sequences of carbonate rocks at depth, high water quality (pl. 1), and, most importantly, a source of water (10,000-18,000 acre-ft/yr) that under natural conditions leaves the valley. However, much of the valley is filled with thick basin-fill deposits and the underflow leaving the basin may be prohibitively deep (greater than 2,500 ft), especially if Precambrian clastic rocks overlie Paleozoic carbonate-rock aquifers as a result of thrust faulting. Conversely, basin-fill deposits may be hydraulically connected to the underlying carbonate rocks so that development of the basin-fill aquifers may capture deeper carbonate-rock ground-water flow. The possibility of deep flow paths beneath the valley is supported by the temperature of discharging water at Tecopa (108°F) and Shoshone (92°F) Springs, southwest of and downgradient from Pahrump Valley. The possibility of deep flow also is supported by the estimated age of the water (approximately 16,000 years, according to corrected carbon-14 ages; J.M. Thomas, U.S. Geological Survey, written commun., 1990) discharging at Shoshone Spring; the water is believed to flow beneath Pahrump Valley from the Spring Mountains.

If most of the throughflow beneath Pahrump Valley is recharged through carbonate rocks in the Spring Mountains, then development on the alluvial fans adjacent to the Spring Mountains, and perhaps southeast of the currently active pumping areas, may be feasible. The thickness of basin fill is not excessive on the fans (fig. 15) and carbonate rocks may be thick. In addition, ground-water quality does not seem to be impaired by the presence of Mesozoic sedimentary rocks in the Pahrump Valley area (fig. 15), although further study is needed to verify this conclusion.

Mesquite and Ivanpah Valleys

Hydrographic Setting

Two hydrographic areas, Mesquite Valley and Ivanpah Valley, are combined in this report into a composite area because both areas are small in size. Mesquite Valley occupies 456 mi^2; 236 mi^2 are in extreme southern Nevada and 220 mi^2 are in the southeastern part of California (fig. 16). Ivanpah Valley is located across the southern Spring Mountains to the east of Mesquite Valley and occupies 235 mi^2. Both valleys have ephemeral streams that originate in the Spring Mountains to the north, which rapidly evaporate or infiltrate into the basin fill before reaching the lower parts of the valleys. In Mesquite Valley, surface drainage is southeastward toward Mesquite Lake, a dry playa fringed by vigorously growing phreatophytes. In Ivanpah Valley, surface drainage is generally southward toward Roach Lake, a dry playa. In addition to the Spring Mountains, the Kingston and Clark Ranges encompass Mesquite Valley. The McCullough Range borders Ivanpah Valley to the east (fig. 16).

Mesquite Valley is sparsely populated with isolated farms and ranches located along the lower parts of the valley. Some livestock grazing is also associated with ranching but, for the most part, Mesquite Valley does not have a local economy. Interstate 15 connecting Los Angeles and Las Vegas bisects Ivanpah Valley. The high volume of traffic has led to the recent buildup of gaming facilities at Jean and at the State line. Gaming and tourism represent the major part of the economy in Ivanpah Valley, which supports about 200 residents who live primarily in Jean and Goodsprings (fig. 16), but the transient tourist population is much larger (and growing) and the demand for domestic water is likewise increasing.

Geology

The southern Spring Mountains, separating Mesquite and Ivanpah Valleys, contain more than 10,000 ft of Paleozoic carbonate rocks (fig. 16), but the carbonate rocks thin to about 2,000 ft in the Clark Mountains south of the Spring Mountains (Burchfiel and Davis, 1971; Burchfiel, 1988). In general, the carbonate rocks become thicker relative to Precambrian and Cambrian noncarbonate rocks toward the east. To the west, in the Kingston Range, Precambrian crystalline and Cambrian clastic rocks are the thickest and most abundant of the exposed hydrologic units (fig. 16). In the eastern part of the area, Precambrian and Cambrian non-carbonate rocks, composed primarily of granitic and metamorphic rocks, predominate in the McCullough Range, representing the southeast boundary of the carbonate-rock province. Small exposures of Tertiary volcanic rocks are found in the southern Spring Mountains and in the McCullough Range. A larger volcanic area is in the Kingston Range to the west where Tertiary granitic rocks form the central core of the range. Mesozoic sedimentary rocks have only limited exposure in the area, yet they may be more extensive at depth beneath the overthrusted Paleozoic carbonate rocks (fig. 16). Quaternary and Tertiary basin-fill deposits form an extremely thick basin in Mesquite Valley where geophysical (gravity) studies indicate as much as 10,000 ft of basin fill may overlie Paleozoic carbonate rocks (MIT Field Geophysics Course, 1985). In Ivanpah Valley, basin fill is generally several thousand feet thick (Bates, 1967) and overlies primarily carbonate rocks (Glancy, 1968; fig. 16).

The Mesquite-Ivanpah area marks the southeasternmost extent of the Cordilleran miogeosyncline (Hewett, 1956). In the southern Spring Mountains, three separate episodes of thrust faulting are recognized that greatly thickened the carbonate-rock section in this area (Carr, 1983). Farther to the south in the Clark Mountains, Burchfiel and Davis (1971) and Burchfiel (1988) recognized three distinct episodes of thrusting as well. The amount of Tertiary extension is still uncertain. Extreme extension occurred in the Kingston Range to the west (McMackin, 1988; Burchfiel and others, 1983b) and in the McCullough Range to the east (Smith and others, 1986). Evidence favors significant extension within the area because of the extremely deep basin beneath Mesquite Valley, and the presence of abundant low-angle faults superimposed on thrust faults in Ivanpah Valley (Burchfiel and Davis, 1988; fig. 16).

Hydrology

Mesquite and Ivanpah Valleys receive virtually all their recharge from the southern Spring Mountains. Of the 1,500 acre-ft/yr estimated to recharge Mesquite Valley from precipitation on the adjacent ranges, 1,400 acre-ft/yr originates from the Spring Mountains (Glancy, 1968). In Ivanpah Valley, all 700 acre-ft/yr recharging the valley from precipitation originates in the Spring Mountains (Glancy, 1968). Mesquite Valley may receive an additional estimated 700 acre-ft/yr of underflow from the carbonate-rock aquifers beneath Pahrump Valley to the northwest (Glancy, 1968). Ivanpah Valley may receive an additional 800 acre-ft/yr of subsurface inflow from California through both carbonate rocks and basin fill, according to Glancy (1968).

Discharge from the area is generally by evapotranspiration or subsurface outflow. In Mesquite Valley, virtually all of the recharge entering the valley is discharged as evapotranspiration from phreatophytes surrounding Mesquite Lake playa. Some minor quantities of ground water may be lost to irrigation. Increased pumping in Ivanpah Valley may capture much of the subsurface outflow inferred by Glancy (1968) to be flowing toward Las Vegas Valley to the northeast. The growing tourist industry will lead to an estimated increase in ground-water pumping that will be currently twice the estimated recharge to the valley (Katzer and others, 1988).

Water levels within the carbonate rocks beneath Mesquite and Ivanpah Valleys are unknown in most areas as only a few wells penetrate the thick basin-fill cover in these areas. Basin-fill water levels in Mesquite Valley are generally less than 100 ft below land surface and decrease to less than 30 ft near the playa. Because of the thick basin-fill cover, it is not known whether water levels in the carbonate rocks are similar, but large differences are probably unlikely. The depth to water generally increases to the northeast. In Ivanpah Valley, basin-fill water levels are generally greater than 100 ft below land surface and may deepen to more than 500 ft. One well in the center of the valley that penetrates carbonate rocks has a water level greater than 800 ft below land surface (well I1; fig. 16, table 18). The inferred direction of ground-water flow (Glancy, 1968) is northward toward Las Vegas Valley from Ivanpah Valley. In Mesquite Valley, deep ground-water flow directions are not known except for possible flow from Pahrump to Mesquite Valley. The shallow flow within the basin fill is toward the playa in the southeastern part of the valley.

Ground-water quality in the basin fill is generally poor because evaporite minerals are common in these deposits. Within the carbonate rocks at depth, however, water quality probably improves significantly (Katzer and others, 1988). Evidence for this is based on data from wells penetrating basin fill near recharge areas where only a thin basin-fill cover exists. At these sites, water quality is greatly improved in comparison to wells where thick basin-fill deposits are known to be present, especially areas far from sources of recharge in the Spring Mountains.

Ground-water storage within the Mesquite and Ivanpah hydrographic areas is estimated to be about 3.4 and 2.4 million acre-ft, respectively, based on assumptions discussed earlier in this report. Most storage within these areas is local storage (beneath basin fill). In Mesquite Valley, local storage has been estimated to be 2.1 million acre-ft, or 62 percent of the total storage; in Ivanpah Valley, local storage has been estimated to be 1.7 million acre-ft, or 71 percent of the total storage.

Potential for Ground-Water Development

Little recharge from precipitation occurs within the area; hence any development of the carbonate-rock aquifers must depend heavily upon storage reservoirs within the carbonate rocks. Because the basin fill in both valleys is thick (pl. 1), and because poor-quality ground water is commonly associated with these areas, particularly in Ivanpah Valley, development would have to be confined to areas near the Spring Mountains where basin fill is not thick and water quality may be generally satisfactory. Also, because the carbonate-rock section in the Spring Mountains is thick, the quantity of available ground water from storage is probably significant. Development in northern Mesquite Valley may capture ground water consumed by phreatophytes around Mesquite Lake, although this is a small quantity (2,200 acre-ft/yr, according to Glancy, 1968).

Long-term effects of development are difficult to evaluate. In Ivanpah Valley, intensive pumping may lower water levels below most domestic wells as the hydraulic connection is probably good between basin fill and the underlying carbonate rocks. Difficulty in obtaining ground water of good quality in most parts of Ivanpah Valley, thus, may limit development (table 18). Further information is needed to accurately assess the long-term effects of development in this area.

SUMMARY AND CONCLUSIONS

The geology and hydrology of selected hydrographic areas in southern Nevada was summarized and each area was assessed for its potential for development of the carbonate-rock aquifers underlying the valley floor. Geologic and hydrologic information for each site was compiled and used to evaluate potential

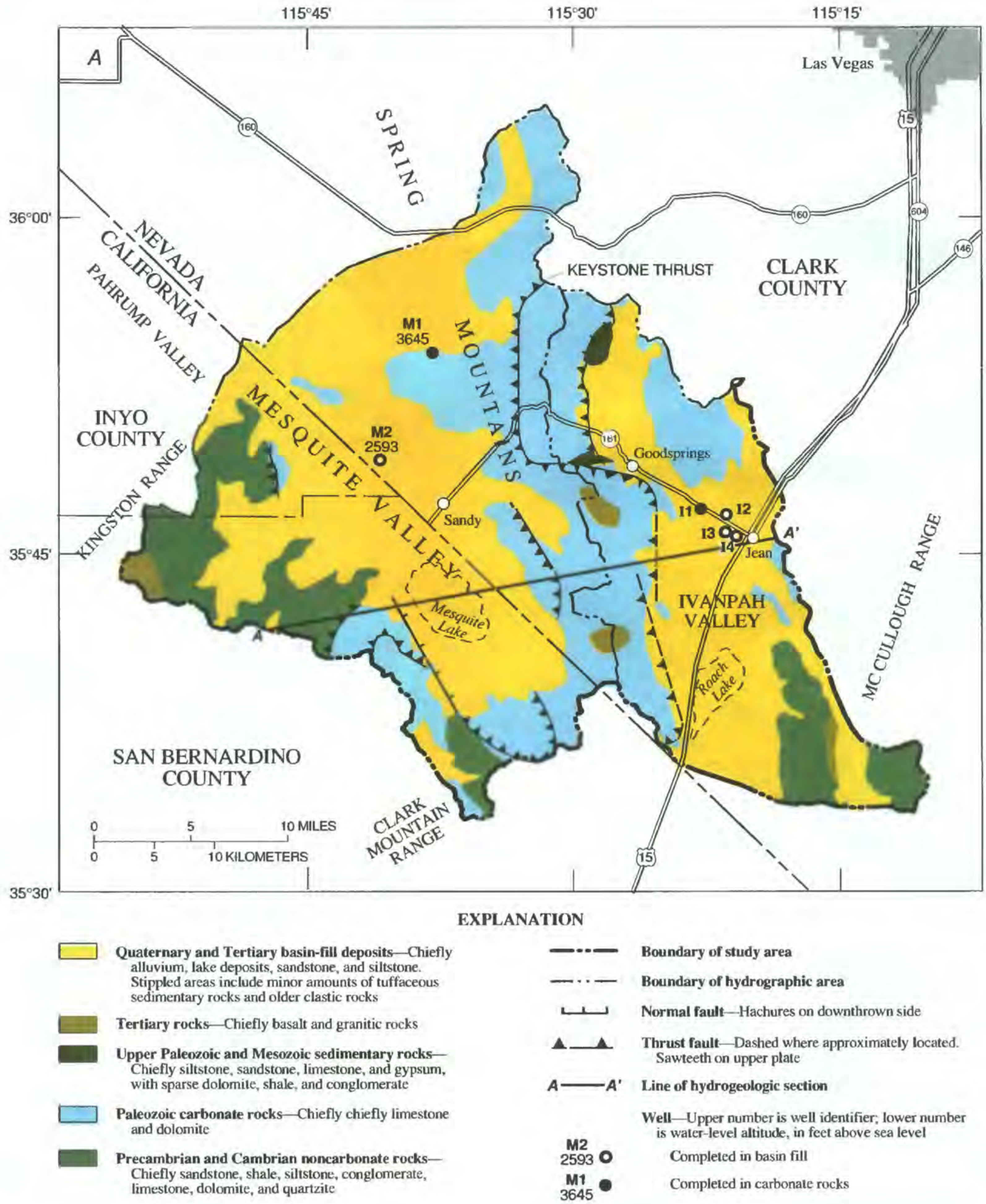


Figure 16. Hydrogeologic map and generalized section through Mesquite and Ivanpah Valleys. *A*, Hydrographic areas showing hydrogeologic rock units, major structural features, and points where ground-water data are available from carbonate rocks (structural geology from Longwell and others, 1965; Burchfiel and Davis, 1971; Carr, 1983; MIT field geophysics course, 1985; Burchfiel and Davis, 1988; and McMackin, 1988; hydrogeology from Thomas and others, 1986). *B*, Generalized hydrogeologic section through Mesquite and Ivanpah Valleys (geology from Burchfiel and others, 1974; Burchfiel and Davis, 1971; Carr, 1983; MIT field geophysics course, 1985; and Burchfiel, 1988).

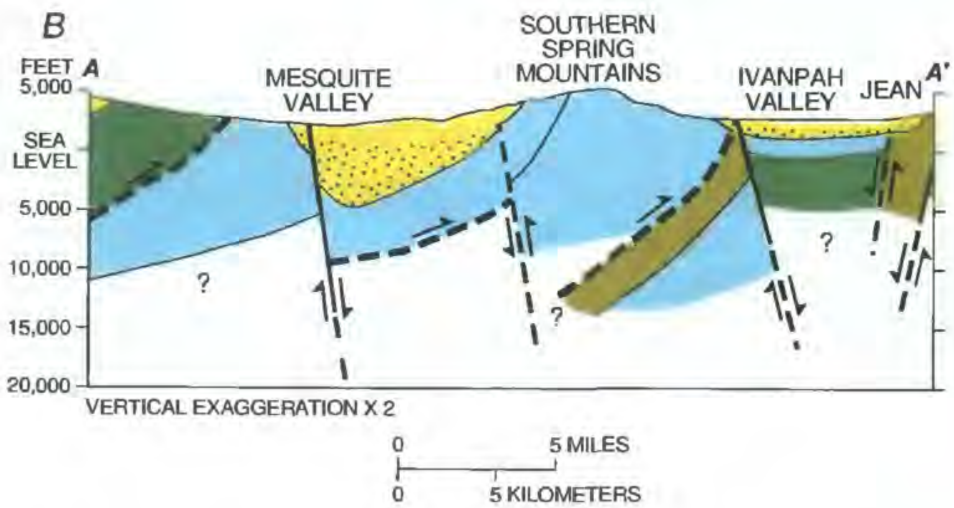


Figure 16. Continued.

Table 18. Information on wells completed in carbonate rocks and basin fill in Mesquite Valley and Ivanpah Valley

[Data modified from J.M. Thomas, U.S. Geological Survey, written commun., 1987. Abbreviations and symbols: D, domestic; M, municipal; O, observation; --, no data; <, less than; >, greater than]

Number (fig. 16)	Name	Total depth (feet)	Depth to water (feet below land surface)	Depth to carbonate rocks (feet below land surface)	Dissolved solids (milligrams per liter)	Use
M1	none	800	355	33	<500	D
M2	none	925	62	>925	--	D
I1	A3-1	939	840	909	920	O
I2	A3-9	800	630	>800	800	O
I3	A3-11	785	585	>785	350	O
I4	Gold Strike	1,281	570	>1,281	620	M

areas for development on the basis of three major criteria: (1) depth to water, (2) depth to and thickness of carbonate rocks, and (3) water quality. Other factors, such as short and long-term effects of development and accessibility, were also taken into consideration.

Geologic data indicate that much of the central part of southern Nevada is underlain by thick sequences of carbonate rock, although overall thicknesses may be highly variable locally. Less desirable areas for potential ground-water development include those where little or no carbonate rock is present at depth; such areas include Lower Meadow Valley Wash, northern Three Lakes Valley, northern Amargosa Desert, and possibly eastern Las Vegas Valley. In these areas, structural patterns indicate that clastic and crystalline rock of Precambrian age underlie the unconsolidated deposits. Other factors that limit the potential for development include areas where the carbonate rock is present, but where there are less than 2,000 ft of carbonate rock in the uppermost 5,000 ft of depth; examples of such areas include southern Amargosa Desert, central Mesquite and Pahrump Valleys, Delamar Valley, Garnet Valley, Three Lakes Valley, and possibly Tikaboo Valley. These areas generally possess trough-like basins filled with thick sedimentary deposits of Quaternary and Tertiary age. Several areas contain at least 2,000 ft of carbonate rocks in the uppermost 5,000 ft of rock and overlapping sediments, but they are not potential areas for development because the depth to carbonate rocks is greater than 1,500 ft; examples of such areas include parts of Ivanpah Valley, western Pahranagat Valley, and west-central Las Vegas Valley. Many of the remaining areas may provide favorable sites for development of the carbonate-rock aquifers on the basis of geologic data, assuming that the carbonate rocks are well enough fractured to allow adequate ground-water flow. The potentially favorable areas include eastern Pahranagat and Coyote Spring Valleys, southernmost Delamar Valley, eastern Lower Meadow Valley Wash, Hidden Valley, northwest Las Vegas Valley, southern Indian Springs Valley, northern Mesquite Valley, and eastern Pahrump Valley.

The extent of favorable areas for ground-water development is further limited when available hydrologic data are used to assess potential areas. For example, hydraulic continuity of carbonate-rock aquifers from area to area, particularly if regional springs are present, indicates that development of one area may affect the quantity of flow or spring discharge in an adjacent area. Examples of such areas include eastern Pahranagat Valley, southern Delamar Valley, and Coyote Spring Valley, which are all part of the White River ground-water flow system terminating at the Muddy River Springs area. Development in any one of these areas may eventually affect spring discharge. Similarly, development in southern Indian Springs Valley may eventually affect discharge at springs in Ash Meadows because a large amount of ground water flows from the Spring Mountains beneath Indian Springs Valley to Ash Meadows. Further limitations caused by conditions of poor water quality in the easternmost part of the area must also be considered in selecting potential sites. These areas include Lower Meadow Valley Wash, eastern Las Vegas Valley, and Ivanpah Valley.

Favorable areas for ground-water development that meet the three major criteria are further classified as one of two types: (1) areas that have plentiful, but underdeveloped ground water, and (2) areas that have isolated ground-water storage reservoirs. Northern Mesquite Valley is a favorable area on the basis of the first classification. It has an adequate supply of recharge (Spring Mountains) and a large amount of the recharge is lost to phreatophytes within the hydrographic area. Eastern Pahrump Valley may also be a favorable area based on the first classification; however, existing development in basin-fill deposits in the western part of the valley has already created a basin-wide overdraft. This condition needs to be taken into consideration when evaluating any additional development because development in the carbonate rocks may affect water levels in overlying basin-fill deposits, if the two are hydraulically well connected.

Potential favorable areas, on the basis of the second classification, include northwest Las Vegas Valley and southern Tikaboo Valley, because of potential ground-water flow barriers in the Desert and Sheep Ranges formed by thick sequences of Precambrian and Cambrian clastic rock, and along the Las Vegas Valley shear zone. These barriers may compartmentalize flow in carbonate-rock aquifers and inhibit the undesirable effects of aquifer development. The extremely thick carbonate-rock aquifers beneath Hidden and Garnet Valleys may represent potential areas for development. The carbonate-rock aquifers may be compartmentalized by hydraulic barriers to the west in the Sheep Range, because of thick sequences of Precambrian and Cambrian clastic rock, and by the Las Vegas Valley shear zone to the south; these features may reduce undesirable effects of development. However, a possible hydraulic connection between aquifers in Hidden and Garnet Valleys and Coyote Spring Valley to the north should be considered because of the possible effect on discharge at Muddy River Springs. Development in areas bounded by flow barriers and not significantly recharged by adjacent ranges, such as Hidden and Garnet Valleys, provides a one-time source of ground water. Thousands of years may be required for these aquifers to be replenished if they are extensively developed.

More information is needed to adequately evaluate the potential for ground-water development within each of the hydrographic areas. The area-by-area evaluations described herein are only preliminary, but provide information relevant to the selection of sites for further detailed assessment.

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GLOSSARY

The definitions presented in this glossary have been modified from Bates and Jackson (1987), Fiero (1986), and Lohman and others (1972).

Accretion—process by which the continents increased in size by addition of an island arc—a chain of islands margined by a deep trench and a deep sea basin.

Anticline—a fold in rocks in which the strata dip outward from both sides, away from the axis. An anticline is convex.

Aquifer—a permeable geologic unit that can transmit significant quantities of water.

Block fault—a high-angle normal fault in which a block is downfaulted relative to adjacent blocks.

Broken terrane—region of severe extension, characterized by imbricate faults (domino-style faulting), rotated blocks, and gravity slides (slumping of large rock masses under the influence of gravity).

Clastic rocks—consolidated sedimentary rocks (such as sandstone and shale) composed of transported fragments of older rock.

Compressional tectonics—mountain-building process resulting from collision of two crustal plates and characterized by large low-angle faults (thrust faults) causing a thickening of the crust.

Confining unit—a body of relatively impermeable material stratigraphically adjacent to one or more aquifers.

Detachment—a low-angle normal fault that usually comprises the lower boundary of an extensional rock mass.

Dry playa—a flat-lying dry lakebed located within a desert basin representing the terminus of drainage from surrounding areas.

Evaporite—a salt-rich sedimentary deposit resulting from evaporation of saline water.

Extensional tectonics—large scale spreading or "pulling-apart" of the Earth's crust, resulting in areas of broken terrane and thinning of the crust.

Fracture porosity—the fraction of the total porosity that results from fractures, joints, and solution cavities; also called secondary porosity.

Ground-water storage—the volume of water that a unit volume of aquifer releases under a unit decline in water level. In confined aquifers, storage represents the quantity of water released due to compaction of the aquifer and expansion of the water. In unconfined aquifers, the quantity of storage also includes the water obtained from gravity drainage of the aquifer.

Hydraulic gradient—the change in water level over a specified distance along a flow path.

Interstitial porosity—a ratio representing the volume of voids within the matrix of the porous medium to the total volume of porous medium.

Island arc—a chain of volcanic islands separated from the continental margin by a deep submarine trench.

Miogeocline—a large linear trough that subsided deeply over a long period of time during which thick deposits of sedimentary rocks accumulated.

Permeability—the ability of a porous medium (aquifer) to transmit water.

Piedmont—the sloping area transitional between the valley lowlands and the mountain block.

Potentiometric surface—a surface that represents the static hydraulic head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells within a specific aquifer or stratum.

Shear zone—a strike-slip fault or series of faults (faulting that represents lateral movement) in which the rocks along the fault have been sheared or crushed.

Specific yield—a ratio of the volume of water a porous medium yields by gravity, after being saturated, to the total volume of porous medium. The value is usually given as a percentage.

Stable terrane—large rock mass that has been only slightly or moderately extended relative to adjacent rock mass; characterized by thick, coherent sequences of rock.

Syncline—a fold in rocks in which the strata dip inward from both sides toward the axis. A syncline is concave.

Thrust fault—a low-angle (less than 45°) fault in which the mass of rock above the fault plane has moved upward relative to the mass of rock beneath the fault plane.

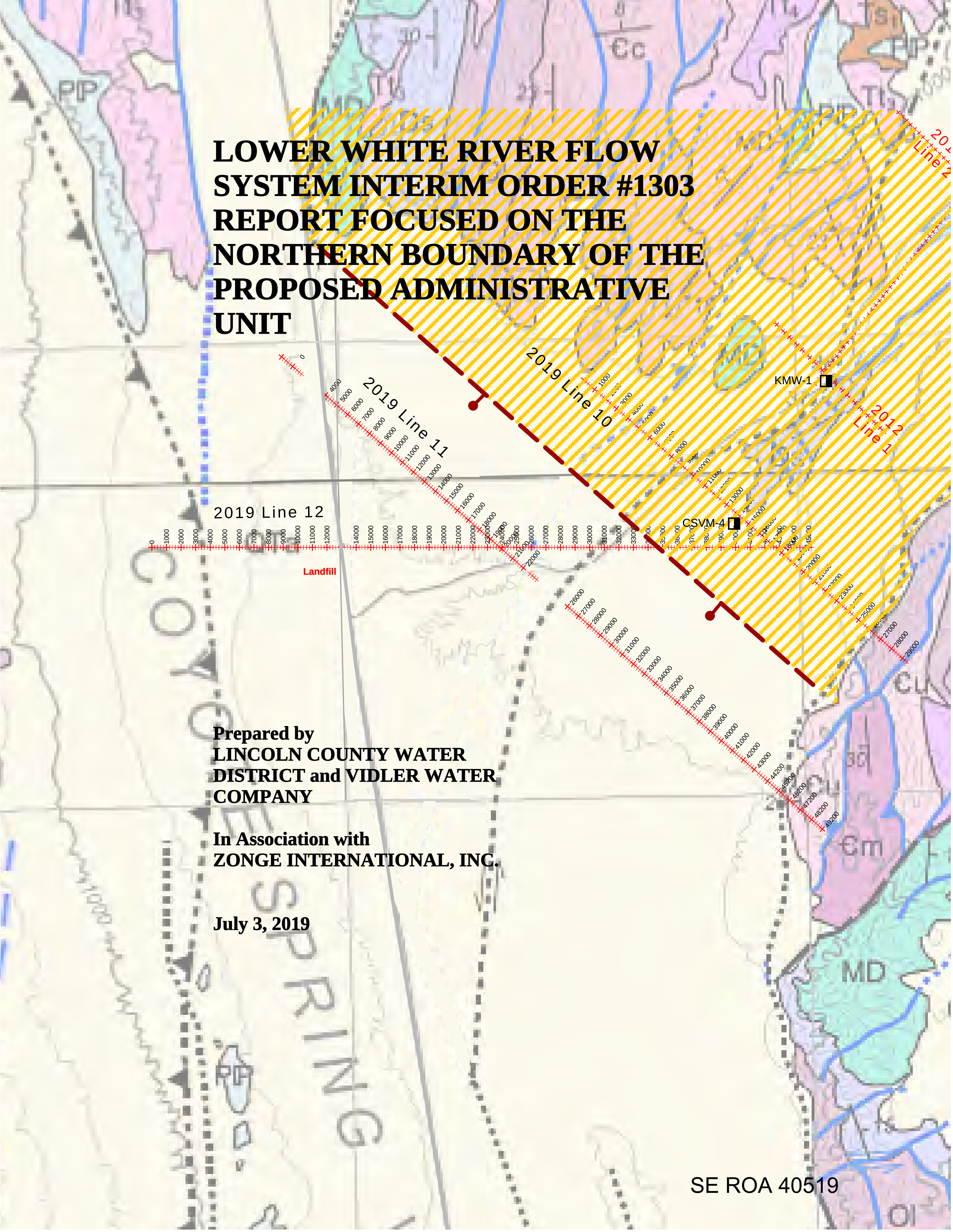
Thrust sheet—a rock mass or sequence of rock units that have been moved over another rock mass or sequence of rock units during the process of thrusting and resulting in a thickening of the crust.

Total porosity—a ratio representing the volume of voids (includes primary and secondary porosity—that is, interstitial porosity, fractures, and solution cavities) to the total volume of porous medium.

Unconformity—a surface of erosion that separates two rock sequences of different ages.

Water table—the ground-water surface in unconfined aquifers (under atmospheric pressure).

LOWER WHITE RIVER FLOW SYSTEM INTERIM ORDER #1303 REPORT FOCUSED ON THE NORTHERN BOUNDARY OF THE PROPOSED ADMINISTRATIVE UNIT



Prepared by
LINCOLN COUNTY WATER DISTRICT and VIDLER WATER COMPANY

In Association with
ZONGE INTERNATIONAL, INC.

July 3, 2019

LOWER WHITE RIVER FLOW SYSTEM INTERIM ORDER #1303 REPORT FOCUSED ON THE NORTHERN BOUNDARY OF THE PROPOSED ADMINISTRATIVE UNIT

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LOWER WHITE RIVER FLOW SYSTEM
INTERIM ORDER #1303 REPORT
FOCUSED ON THE NORTHERN BOUNDARY OF THE PROPOSED ADMINISTRATIVE UNIT

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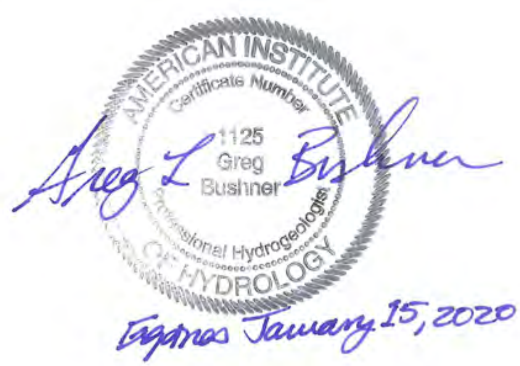

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LIST OF ACRONYMS

ac-ft	acre-feet
ac-ft/yr	acre-feet per year

amsl	above mean sea level
CEMP	Community Monitoring Environmental Program
COOP	Cooperative Observer Network
CSAMT	Controlled Source Audio Frequency Magneto Telluric
CSV	Coyote Spring Valley
°F	Degrees Fahrenheit
Ds	Devonian Simonson Dolomite
IO	Interim Order
KSV	Kane Springs Valley
KSW	Kane Springs Wash
LVVWD	Las Vegas Valley Water District
Lincoln/Vidler	Lincoln County Water District and Vidler Water Company
LMVW	Lower Meadow Valley Wash
LWRFS	Lower White River Flow System
Mg/L	milli-grams per liter
MRSA	Muddy River Springs Area
NSE	Nevada State Engineer
NW-SE	northwest—southeast
pmc	percent modern carbon
RDCA	Regional Deep Carbonate Aquifer
RAWS	Remote Automated Weather Station
SNWA	Southern Nevada Water Authority
TDSS	Total Dissolved Solids Sum
WRFS	White River Flow System
Zonge	Zonge International, Inc

1.0 EXECUTIVE SUMMARY

The Nevada State Engineer (NSE) through Rulings #5712 (NSE 2007) and #6254 (NSE 2014) has made several findings about Kane Springs Valley (KSV), the impacts from KSV and the effects of pumping from KSV on springs in the Lower White River Flow System (LWRFS) and further south of the LWRFS. The NSE has historically supported and affirmed the exclusion of KSV from the LWRFS since the Order No. 1169 requirements, including the Order No. 1169 aquifer test (NSE 2002) and since the hearing on by Lincoln County Water District and Vidler Water Company (Lincoln/Vidler) groundwater rights in 2006 (NSE 2007).

In this report, groundwater elevation data from wells in KSV and in the LWRFS groundwater basins[1], precipitation and recharge data, and groundwater chemistry and temperature data are used to illustrate the hydrologic differences between KSV and the basins of the LWRFS. Using the groundwater level data, which can be found on the NSE's website: *http://www.nv.gov/WaterLevelData.aspx*, Lincoln/Vidler identified a distinct "break" in water levels in the regional hydraulic gradient, including several distinct breaks in water levels from wells throughout the LWRFS. These "breaks" in gradient can mostly be attributed to geologic structures in the Regional Deep Carbonate Aquifer (RDCA). As a general statement, wells within the LWRFS exhibit very consistent groundwater levels that are indicative of high transmissivity values across this area. However, in KSV the gradient between well KPW-1 and down-basin wells is much steeper, which again implies some type of impediment to groundwater flow near the mouth of KSV.

There was an exceptional precipitation event that occurred in 2005 that overwhelmed the hydrologic system in KSV as identified in monitor wells KMW-1 and CSVM-4 groundwater levels. This event obscured the overall regional trend in groundwater levels in this region making identification of a response to the Order No. 1169 aquifer test not relevant neither appropriate. The

[1] The "joint administrative unit" includes the following hydrographic basins: Coyote Spring Valley (210), a portion of the Black Mountains Area (215), Garnet Valley (216), Hidden Valley (217), California Wash (218), and the Muddy River Springs Area (AKA Upper Moapa Valley) basin (219).

finding that water levels in KSV did not response to the Order No. 1169 aquifer test is supported by the lack of response or correlation of groundwater levels in well KMW-1 to groundwater pumping from Coyote Spring Valley (CSV).

Lincoln/Vidler have been collecting groundwater recharge data for over a decade in order to better understand and quantify the actual recharge that is occurring in the KSV hydrographic basin. These data have been submitted to the NSE and interested parties in the form of quarterly reports. A preliminary analysis of these data indicates in-basin groundwater recharge values that range from 4,700 acre-feet per year (ac-ft/yr) to 11,000 ac-ft/yr (T. Umstot, Daniel B. Stephens & Associates (DBS&A), unpublished data and analysis, 2019).

A comprehensive analysis of the regional geochemistry data including stable isotopes, temperature, and carbon-14 data was presented during the Lincoln/Vidler groundwater rights hearing in 2006. That analysis found that the groundwater pumped from KSV could not be identified in the source water for the Big Muddy Springs, nor other springs farther south and outside the geographic boundaries of the LWRFS. This means that groundwater pumped from production well KPW-1 is on a different groundwater flow path from the springs, which is again consistent with the differences in hydraulic gradients, groundwater levels, and the existing and recently collected geophysical data that documents the structural changes between KSV/northern CSV and the rest of the LWRFS groundwater basins.

The combined existing and new geophysical data collected in and around KSV allows the recognition of significant geologic structures in southern KSV and northern CSV that explain why groundwater level elevations in this area are different in KSV and northern CSV, than in the LWRFS groundwater basins to the south. The geophysical data identified significant changes in resistivities between the Delamar Mountains, southern KSV, and northern CSV. These changes are consistent and correlate well with the distribution of existing geochemistry and groundwater temperature data that can be used to identify different groundwater flow paths. The extensive faulting that occurs in southern KSV and northern CSV, explained by the interpretation of the geophysical data forms the basis for the exclusion of KSV from the LWRFS administrative basin.

As will be shown later in this report, virtually all of the reduction in flows of the Muddy River and its associated springs over the past several years can be explained by the amount of groundwater pumping within the documented declines in the Muddy River Springs Area (MRSA). This provides a road map for the NSE in administering rights in this area with the intent of mitigating impacts to these springs. Focus should first be placed on both the carbonate and alluvial pumping in the MRSA. Secondly, since there is approximately 8,000 acre-feet of groundwater inflow from Lower Meadow Valley Wash (LMVW) to the MRSA, more research should be done to identify and quantify this inflow into the MRSA as it lies adjacent to and directly down-gradient of LMVW.

Lincoln/Vidler are not a party to, nor have ever been a participant of the Order No. 1169 aquifer test proceedings. The NSE never requested that Lincoln/Vidler provide a report on the outcome of the Order No. 1169 aquifer test results; hence none was ever developed.

In conclusion, KSV should remain excluded from the LWRFS administrative unit. Any revisions to the current LWRFS administrative unit boundary should also exclude northern CSV.

2.0 INTRODUCTION

The purpose of this report is to provide additional data and documentation that demonstrates KSV is hydrologically and geologically-structurally separate from the area defined by the NSE as the "joint administrative unit" known as the LWRFS, see Figure 2-1. This report is submitted by Lincoln/Vidler as owner of water rights, in addition to pending applications Nos. 74147, 74148, 74149, and 74150 in KSV.

Consideration of water rights in KSV fits squarely in the administrative boundaries of Nevada Water Law for the appropriation of groundwater from a hydrographic basin. This is based on a basin-by-basin analysis of perennial yield and is very dis-similar from what the NSE proposes for the LWRFS, which is as a managed unit. The basis of this report is new data collected to support the NSE in their determination of the proposed boundary of the LWRFS. Review of the relevant administrative policy that affects groundwater appropriations in Nevada and specific to KSV is provided below (Section 2.1). This is followed by a review of the matters requested to be addressed by the NSE in Interim Order (IO) #1303 (NSE 2019; Section 2.2). The remainder of the report provides hydrologic, geochemical, and geophysical data that supports the conclusion that KSV is not and should not be, included as part of the LWRFS administrative unit.

2.1 RELEVANT ADMINISTRATIVE POLICY

The NSE defines the perennial yield of a groundwater reservoir or basin as the maximum amount of groundwater that can be salvaged each year over the long term without depleting the groundwater reservoir. Perennial yield is ultimately limited to the maximum amount of natural discharge that can be salvaged for beneficial use. The perennial yield cannot be more than the *natural recharge* to a groundwater basin and in some cases is less.

The NSE's application of the groundwater appropriation system is based on a basin-by-basin analysis. This would change if KSV were to be included in the LWRFS and result in setting the precedent to include many other groundwater basins as part of the LWRFS. For instance, Cave, Dry Lake, and Delamar Valley basins have groundwater flow components that connect them together, and to CSV, and to KSV. Tacking on Cave, Dry Lake, Delamar, and KSV to the LWRFS administrative unit due solely to shared groundwater flows between them would override the historic basin-by-basin perennial yield analysis used by the NSE to administratively manage basins required by law, and instead in essence would create what would look strikingly like a "pachinko game" wherein if you had priority groundwater rights in the last basin downgradient you would get to withdraw the collective flow. This means that no water would be available from upgradient groundwater basins and the counties where these basins occur would not have the ability to utilize water for economic development in their county.

2.1.1 Previous Determinations by the Nevada State Engineer Regarding Kane Springs Valley

The NSE has already ruled on the issue of whether the appropriation of groundwater from KSV would affect the MRSA, or for that matter other springs of interest. This was documented in Nevada State Engineer Ruling #5712 (2007), on page 20 where it is stated:

> "The State Engineer finds there is not substantial evidence that the appropriation of the limited quantity [of water] being granted under this ruling will likely impair the flow at Muddy River Springs, Rogers Springs or Blue Point Springs."[2]

New geophysical data provided in this report and collected in response to IO #1303 (NSE 2019), provides strong evidence of faulting and fracturing of the regional carbonate system in southern KSV and northern CSV. Specifically, these data explain why there are differences in water levels in wells located in southern KSV and northern CSV versus the rest of the proposed LWRFS. These geophysical and water level data show why groundwater withdrawn based on the perennial yield of KSV would not likely impair flow at Muddy River Springs, not to mention Rogers or Blue Point Springs. Therefore, these data support the exclusion of KSV, and for that matter, exclusion of northern CSV (north of the major fault structures) from the LWRFS.

The NSE's determination that there would be no impairment from pumping in KSV was affirmed seven years later in Ruling #6254 issued in 2014. In Ruling #6254 (NSE 2014), the NSE

[2] No party appealed the NSE's determinations in Ruling #5712.

concluded and found that where no significant impact would be felt for hundreds of years, the upgradient groundwater could be appropriated. KSV groundwater can be developed because there will be no significant impact, if any, from appropriation of the groundwater for hundreds of years. Specifically, NSE (2014) Ruling #6254 at page 23 states:

> "…the State Engineer found that where no significant effects would be felt for hundreds of years, the upgradient water could be appropriated."

The NSE speaks explicitly to the difference between KSV and the Order 1169 groundwater basins (see footnote 1) further in Ruling #5712 (NSE 2007) by stating at page 21:

> "…carbonate water levels near the boundary between Kane Springs Valley and Coyote Spring Valley are approximately 1,875 feet in elevation, and in southern Coyote Spring Valley and throughout most of the other basins covered under Order No. 1169, carbonate-rock aquifer water levels are mostly between 1,800 feet and 1,825 feet. This marked difference in head supports the probability of a low-permeability structure or change in lithology between Kane Springs Valley and the southern part of Coyote Spring Valley."

The veracity and reliability of this statement by the NSE is confirmed by the extensive, new geophysical data Lincoln/Vidler has collected. As will be shown from these new data, there is a significant change in the continuity of lithology that occurs near the mouth of KSV and the end of the Delamar Mountains in northern CSV.

The NSE in Ruling #5712 (2007) further concluded on page 21:

> "The State Engineer finds there is not substantial evidence that the appropriation of a limited quantity of water in Kane Springs Valley Hydrographic Basin will have any measurable impact on Muddy River Springs that warrants the inclusion of Kane Springs Valley in Order No. 1169."

That finding was not challenged by any of the Order No. 1169 (NSE 2002) participants, including Southern Nevada Water Authority (SNWA) or Las Vegas Valley Water District (LVVWD).

Subsequently, neither SNWA or LVVWD provided any information or data in their October 5, 2018 (SNWA and LVVWD 2018) letter that indicate that appropriation of water in KSV will impact any of the springs in the MRSA.

2.2 REQUIREMENTS BY THE NEVADA STATE ENGINEER FOR THE INTERIM REPORT

In IO #1303 (NSE 2019), the NSE requested that the reports submitted address the following matters.

> "a. The geographic boundary of the hydrologically connected groundwater and surface water systems comprising the Lower White River Flow System;
>
> b. The information obtained from the Order 1169 aquifer test and subsequent to the aquifer test and Muddy River headwater spring flow as it relates to aquifer recovery since the completion of the aquifer test;
>
> c. The long-term annual quantity of groundwater that may be pumped from the Lower White River Flow System, including the relationships between the location of pumping on discharge to the Muddy River Springs, and the capture of Muddy River flow;
>
> d. The effects of movement of water rights between alluvial wells and carbonate wells on deliveries of senior decreed rights to the Muddy River; and,
>
> e. Any other matter believed to be relevant to the State Engineer's analysis."

The direct response to each of these items is specifically addressed in Section 6.0 under Key Findings and Conclusions. Lincoln/Vidler's response is focused on the northern boundary of the administrative unit. However, Lincoln/Vidler do provide information, data, and/or opinion on other issues that would be beneficial and helpful to the NSE in his decision-making process related to IO #1303 (NSE 2019). Indeed, clear evidence of the primary factors that have historically reduced Muddy River flows and headwater springs flows is presented and offers a road map for the NSE's technical deliberations supporting a LWRFS administrative unit.

3.0 REVIEW OF EXISTING DATA

This report includes a discussion and submission of existing data that includes: (a) groundwater elevation data from existing wells, including wells from KSV and CSV, (b) data collection activities that include analysis of water recharged in the KSV groundwater basin, (c) geochemistry, including whole water chemistry and stable isotopic age dating data, and (d) groundwater temperature data.

3.1 GROUNDWATER LEVEL DATA FROM WELLS IN KANE SPRINGS VALLEY AND NORTHERN COYOTE SPRING VALLEY

Groundwater elevation data have been collected throughout the LWRFS for over two decades. Figure 3-1 shows the location of the wells throughout the area of interest including KSV, CSV, and the MRSA. Hydrographs of these wells are provided in Appendix A, and the supporting data can be found at: *http://water.nv.gov/WaterLevelData.aspx*.

Lincoln/Vidler have been measuring water levels in monitor well KMW-1 quarterly since April 2007 (Figure 3-2). This well, located at the mouth of KSV and near northern CSV, encountered the Willow Springs Fault, which is a western bounding fault of the KSW Fault Zone (Figure 3-3). KMW-1 and associated production well KPW-1 are both completed in carbonate rocks that are considered part of the RDCA system of eastern Nevada. Wells KMW-1 and KPW-1 were constructed within 100 yards of each other and have the same well completion.

3.1.1 Regional Water Level Data in the Lower White River Flow System

During the administrative hearing for groundwater rights in KSV in 2006, Lincoln/Vidler identified the differences in hydraulic heads between wells drilled in the LWRFS versus wells drilled in KSV and northern CSV. A "break," or local increase, in the regional hydraulic gradient was shown between KSV/northern CSV and the LWRFS administrative unit (see footnote 1) groundwater basins. Groundwater elevation data from wells completed in the RDCA in southern CSV are remarkably flat across the LWRFS groundwater basins, whereas water levels in KSV/northern CSV have a steeper gradient, as shown in Figure 3-4. In summary, a key finding is that groundwater levels in RDCA wells are very similar in elevation (pre-pumping or minimal pumping of Order 1169 [NSE 2002] groundwater basins) everywhere downgradient of the KSW Fault Zone (CH2M Hill 2006a). Figure 3-5 is an update to a subset of the data provided in Figure 3-4 using the most current water level measurements.

To further illustrate the differences in groundwater elevations, an excerpt from Figure 3-5, identified in the red box, is presented as Figure 3-6, illustrates the differences in heads between the northern CSV (monitor wells CSVM-4 and CE-VF-2) and the rest of the wells, further south in the LWRFS (CSVM-6, MX-5, CSVM-1, UMVM-1, CSVM-5, and MX-6). Since northern CSV is downgradient of KSV, the difference in water levels indicates that KSV is not directly connected to the LWRFS. Just as in the 2006 testimony before the NSE and after several thousands of acre-feet pumped from wells in the LWRFS, the same groundwater elevation pattern persists.

Another way to view the data is to plot all the groundwater elevations at the same scale for elevation and over time (Figure 3-7). The graph in Figure 3-7 shows the distribution of heads across the northern and central part of the LWRFS, and also KSV. What is striking about this presentation of the data is the consistency in water level elevations for the wells in groundwater basins in the central LWRFS at below elevation 1,825 feet. What's also notable is that when plotted at this scale groundwater pumping from groundwater basins in the LWRFS has very little impact on water levels across these groundwater basins illustrating how exceptionally stable water levels in this aquifer system are.

Bushner (2018) noted another significant difference in the response in groundwater levels from wells in southern CSV compared to the response of water levels in wells in northern CSV and KSV by stating:

> "…monitor wells in the southern portion of CSV responded immediately to the start and end of the [Order No. 1169] aquifer test. However, this is not what occurred in CSVM-4 … which reflects a downward trend even after the end of the test. This is not reflective of recovery after an aquifer test especially given the significantly high hydraulic conductivities that exist south of the Kane Springs Wash Fault."

Given all these data and information, the NSE does have reason to view many of the basins in the LWRFS as a unit based on the remarkably consistent groundwater levels among wells completed in the RDCA (Figure 3-7). The NSE clearly noted this in Ruling #6254 (NSE 2014) at Page 12:

> "Changes in the potentiometric surface in any one of these basins [referring to the Order No. 1169 (NSE 2002) groundwater basins] occur in lockstep directly affecting the other basins, further demonstrating the regional nature of the aquifer across these basins."

Although Lincoln/Vidler concur with the effective administration of these basins collectively based on the hydrogeology, we disagree that the effects are all the same across the entire LWRFS administrative unit. In particular, northern CSV should be excluded from the LWRFS administrative unit as was done for most of the Black Mountains Area Hydrographic Basin. KSV should remain excluded from the proposed LWRFS administrative unit.

3.1.2 KMW-1 and CSVM-4 Groundwater Level Data

Detailed hydrographs of groundwater elevation data from monitor well KMW-1, located at the mouth of KSV, and CVSM-4, located in the north central portion of CSV (Figure 3-1) are provided in Figures 3-2 and 3-8, respectfully.

Groundwater elevations in monitor well KMW-1 declined approximately 2 feet from the time it was installed in early 2007 to early 2014 and then fluctuated over a range of approximately 1 foot. The actual groundwater elevations were at approximately 1,880 feet above mean sea level (amsl) in April 2007 (Figure 3-2) and approximately 1,878.4 feet amsl in April 2019.

The hydrograph from Well CSVM-4 is provided in Figure 3-8. Groundwater level elevations during the same time period, described in the previous paragraph concerning well KMW-1, in June 2007 was approximately 1,874.5 feet amsl, or approximately 5½ feet lower than at KMW-1. This difference of 5 ½ feet is larger than the gradient across much of the LWRFS and indicates a distinctly different situation in the RDCA. The period of record for well CSVM-4 started more than 3 years earlier than that of KMW-1 (July 2003) and measurement continues to the present.

The hydrographs for both KMW-1 and CSVM-4 are plotted with the same time and water-level elevation scale for their combined period of record in Figure 3-9. The difference in head between these wells is explained due to the presence of a fault that occurs between them based on the newly collected geophysical data (Section 4.0). What is also striking regarding the hydrographs from both these wells is the consistency in their trends, suggesting that they are related and again how KSV and northern CSV are isolated from the rest of the LWRFS. Without the groundwater elevation data from well CSVM-4, prior to the installation of well KMW-1, what would have been missed is the huge recharge precipitation event that occurred in 2005 that created a strong response of water levels in the hydrologic system in this area. This event took years to dissipate in the aquifer as manifested by the change in groundwater elevations. The precipitation event and data that supports it are discussed below in Section 3.2. If this recharge event is removed from the data set, then a long-term decline in groundwater levels over time is revealed as approximately 1-foot per decade (0.1 foot per year; Figure 3-9).

3.2 IN-BASIN RECHARGE AND PRECIPITATION

The basis for a groundwater appropriation under the Law of the State of Nevada within a hydrographic basin is to document the availability of water in that basin that can be withdrawn over the long term without (1) affecting existing water rights, and (2) causing excessive groundwater mining in the hydrographic basin. Lincoln/Vidler have been actively collecting and using recharge data to estimate recharge throughout KSV. These data provide a solid technical basis for determining the perennial yield within KSV, which in turn identifies the volume of water that can be withdrawn from this hydrographic basin. These data quantify additional precipitation and recharge in KSV and the available water that can be appropriated.

3.2.1 In-Basin Recharge Data Collection

In order to develop a solid technical foundation for determining the perennial yield value for KSV, Lincoln/Vidler, beginning over a decade ago in October 2007, have been collecting basin-specific data through the use of totalizing rain gages, tipping bucket rain gages, runoff event data loggers, and chloride collectors. We continue to collect and submit these data, to the NSE and interested parties, in an effort to better understand and quantify recharge occurring in KSV and to share that technical foundation transparently with others. Based on analysis of the ongoing basin-specific data collection effort, there is unappropriated water available in KSV. This is due to the fact that recharge values clearly show that there is more water available under Nevada State Law than has been appropriated. Much like Cave Valley, Dry Lake Valley, and Delamar Valley, groundwater appropriated in KSV is also recharged within the basin (NSE 2014). A copy of the second quarter 2019 quarterly recharge report that presents the runoff, precipitation, and chloride data collected to date, is provided in Appendix B. Based on a preliminary analysis of these data, estimates of in-basin recharge are approximately between 4,700 to 7,500 ac-ft/yr from the chloride mass balance analysis method and approximately 7,100 to 11,000 ac-ft/yr from the watershed model (T. Umstot (DBS&A), unpublished data and analysis, 2019).

Independently of the data Lincoln/Vidler have been collecting to support the recharge value in KSV, SNWA conducted an analysis of recharge for hydrographic basins in the White River Flow System (WRFS). SNWA derived an annual recharge value of 4,329 acre-feet for KSV (SNWA 2009, pages 9-13 and 9-14). This too, indicates that there is water available under Nevada State Law for appropriation within KSV.

In summary, groundwater recharge is documented to occur in KSV and does not contribute to the proposed local recharge of the LWRFS administrative unit, i.e., the recharge occurs within KSV and not in the LWRFS basins. This recharged water is available for appropriation in KSV, according to Nevada State Law, as the perennial yield based on a solid recharge data collection and analysis research program in KSV. Our research demonstrates that significant in-basin groundwater recharge occurs within the KSV, primarily in Delamar Mountains (Appendix B). However, local recharge in the Upper WRFS, which includes Cave, Dry Lake, and Delamar Valleys is not counted in the discharge of groundwater to the LWRFS, neither should local groundwater recharge that occurs within KSV be included in the LWRFS administrative unit.

3.2.2 Precipitation During Winter Water Year 2005

An extreme precipitation event occurred during water year 2005 (Figure 3-10 and Table 3-1) that resulted in clear groundwater responses across the hydrologic system in southeastern Nevada. Table 3-1 shows precipitation data from the Remote Automated Weather Station (RAWS) in KSV as well as five other stations in the surrounding area. Precipitation for that water year in KSV was approximately 26 inches. To put that in perspective, the average yearly precipitation for the RAWS in KSV is approximately 7½ inches per year (Figure 3-10). This event was 3.5 times larger than the average precipitation of other years in the area. The Elgin COOP Station, located at the north end of KSV, also had an extreme amount of precipitation during water year 2005 and in the amount of 30.69 inches (Table 3-1).

Table 3-1. Precipitation Date in Kane Springs Valley and Surrounding Areas for the 2005 Water Year

	Kane Springs RAWS	Alamo CEMP	Pahranagat Widlife Refuge	Hiko COOP	Elgin COOP	Caliente CEMP
Oct-04	4.93	2.30	1.76	3.38	5.18	4.73
Nov-04	1.04	1.14	1.27	1.25	2.48	1.74
Dec-04	2.91	1.02	0.84	0.23	2.66	1.50
Jan-05	5.54	2.44	3.13	2.94	6.49	2.26
Feb-05	3.15	2.07	1.93	2.72	3.31	1.60
Mar-05	1.56	0.99	1.03	0.84	2.38	2.05
Apr-05	1.85	1.06	0.88	0.85	1.75	1.83
May-05	0.31	0.36	0.57	0.45	0.24	0.28
Jun-05	0.32	0.25	0.13	0.80	0.58	1.08
Jul-05	0.43	0.43	0.50	0.11	0.65	0.23
Aug-05	3.79	1.93	2.03	2.52	4.95	2.54
Sep-05	0.09	0.57	0.68	0.64	0.02	0.28
	25.92	14.56	14.75	16.73	30.69	20.12

3.3 GEOCHEMISTRY AND GROUNDWATER TEMPERATURE DATA

There are some significant differences in the general groundwater chemistry data exhibited in monitor wells from southern KSV and northern CSV compared with the general chemistry of groundwater and surface water of the LWRFS. An extensive geochemistry investigation and analysis was made of KSV and surrounding groundwater basins from Pahranagat and Delamar Valleys through and including the LWRFS by Lincoln/Vidler during the 2006 hearing on their pending groundwater rights applications. The data and analysis still hold true as presented in CH2M Hill's 2006 report: *Hydrologic Assessment of Kane Springs Hydrographic Area (2006): Geochemical Framework*, which is provided in its entirety in Appendix C. The salient point of this report, based on the regional geochemistry, including stable isotopes**,** temperature, and carbon-14 data is that:

> "A comparison of these chemical and isotopic relationships with Big Muddy Springs and particularly Rogers Spring and Blue Point Spring indicates that the groundwater from KPW-1, assumed representative of the KSV groundwater, is too strongly attenuated with CSV to be identifiable in these springs." (Appendix C: CH2M Hill 2006b, Pages 12 and 13).

To further support this statement, Lincoln /Vidler provides the following a discussion of general chemistry data, groundwater and spring temperature data, and carbon-14 data.

3.3.1 General Chemistry Data

These data are used to illustrate the groundwater chemistry at samples analyzed from production well KPW-1 and monitor well CSVM-4, the closest monitor well to and down gradient of the KSV groundwater basin, and other wells and springs in the LWRFS and surrounding areas. An extensive database of water quality data is included in CH2M Hill (2006b) reproduced from Thomas, Calhoun, and Apambire (2001) and supplemented by other sources as noted in Appendix C. A discussion of Total Dissolved Solids Sums (TDSS) is presented first followed by a discussion of Carbon-14 data, and groundwater temperature data.

3.3.1.1 Total Dissolved Solids Sums

The TDSS is the summation of the concentrations of silica, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, and chloride (CH2M Hill 2006b). The analysis from well KPW-1 is provided in Table 3-2. The TDSS from the groundwater produced from well KPW-1 is calculated to be 774 milli-grams per Liter (mg/L) and the TDSS for well CSVM-4 is calculated to be 682 mg/L (Table 3-2). Groundwater from well KPW-1 is either on a different groundwater flow path exiting the KSV hydrographic basin, or it comingles with groundwater in northern CSV that has a fresher source of water. This fresher source of water would need to be such that mixing with Kane Springs groundwater would be enough to reduce the Total Dissolved Solids by approximately 100 mg/L. One such source of groundwater mixing is from monitor well CSVM-7, installed in volcanic rocks to the northeast of CSVM-4 (Figure 3-1). In fact, the water chemistry, stable isotope data, and temperature at CSVM-4 can be simulated quite precisely by assuming approximately 74% KPW-1 groundwater and approximately 26% groundwater similar to that measured at CSVM-7. These data provide evidence that groundwater in southern KSV and northern CSV may commingle or have similar recharge sources. Furthermore, CH2H Hill (2006b) found that groundwater in KSV is chemically and isotopically "unique for the regional carbonate groundwater in this area," and greatly attenuated in CSV, and not likely present at Big Muddy Springs, nor Rogers Spring, and Blue Point Spring. The recently collected geophysical data provides the structural basis for why groundwater movement through southern KSV and northern CSV to the LWRFS is restricted and why it is unlikely related to spring flow at Big Muddy Springs, Rogers Spring, and Blue Point Spring.

Table 3-2. Total Dissolved Solids Sum for Selected Wells and Springs

	Parameter						
Water Source	Na + K	Ca	Mg	Cl	HCO3	SO4	TDSS
Big Muddy Spring	108	64	27	61	276	177	713
Pederson's Warm Spring	111	71	26	60	270	190	728
KPW-1	168	48	14	63	341	140	774
MX-5	96.3	48.7	21	35.7	294	93.1	588.8
CSVM-4	145	40	13	53	311	120	682

3.3.1.2 Carbon-14 Data

Carbon 14 data can be used to obtain the age of groundwater or in this case the apparent age of the groundwater. CH2MHill (2006b) provided a comprehensive analysis of carbon-14 data in their report which is reproduced here in its entirety below. In addition to the quote below, CH2M Hill (2006b) also provided a table of percent modern carbon analyzed from various wells and springs in and surrounding KSV. This table is reproduced for this report as Table 3-3 (which is labelled as Table 3 in the CH2M Hill (2006b) report). The following quote is from the CH2M Hill (2006b) report.

> "Table 3 lists a summary of carbon-14 data and the simple apparent age for hydrographic areas, KSV well KPW-1 as well as Big Muddy, Rogers and Blue Point Springs. Most of the apparent ages are in the 14,000 to 35,000 years before present range. The KSV well, KPW-1, has one of the oldest apparent ages at 29,900 years. Assuming that the apparent ages are somewhat true, and in this case may be, it is not probable that KSV groundwater represented by KPW-1 with this age could represent a significant contribution to the flow at Big Muddy Springs."

Table 3-3. Carbon - 14 percent modern carbon (pmc) values and apparent ages for hydrographic areas KSV well KPW-1, major springs in Pahranagat Valley as well as Big Muddy, Rogers, and Blue Point Springs

Hydrographic Area/Well/Spring	Carbon -14 (pmc)	Apparent Age (Years Before Present)
Pahranagat Valley, Major Springs	6.3-8.4	20,300-21,700
KPW-1	2.7	29,900
Coyote Springs Wells	4.2-17.9	14,200-26,200
Garnet Valley Wells	3	29,000
MRSA	8.4	20,500
Big Muddy Springs	7	22,000
Rogers Spring	1.6,2.4	30,900-34,200
Blue Point Spring	7.2,5.4	21,800-24,100

Note that the older age of KPW-1 can also be an indicator of deeper circulation of water compared to other sources in the area, which is supported by its higher water temperature as discussed below.

3.3.1.3 Temperature Data

Representative temperature data for groundwater and springs in the LWRFS and in KSV are provided in Figure 3-11. The data used to create Figure 3-11 are provided in Table 3-4. The local geothermal gradient can be used to estimate that expected temperature distribution due to a relatively uniform heating and allows identification of unusual values of groundwater temperature that indicate distinctive local groundwater flow processes. A typical geothermal gradient in this area is about 3.6 degrees Fahrenheit (ºF) per 328 feet of depth beginning at approximately 96 feet (Nicholson 2007). Using the data from Table 3-4, the groundwater temperature data from wells completed in the RDCA center around two values of approximately 78ºF and 99ºF. The warm springs that occur in the MRSA are consistently centered around 89ºF to 90ºF, which is in the middle of this expected range. The production well drilled and tested in KSV (KPW-1) yielded a groundwater temperature of 136ºF at the end of the seven-day aquifer test (URS 2006a), which is well above this expected range and suggests deep circulation of groundwater arriving at this location and/or a geothermal source. Using the typical geothermal gradient as noted above and applying it to the production well in KSV (Figure 3-3), the change in groundwater temperature based solely on the geothermal gradient would be approximately 19ºF. Applying this value to either set of carbonate wells yields groundwater temperatures of 97ºF to 118ºF. None of these values are close to the 136ºF of the groundwater found at KPW-1, which indicates local groundwater flow, distinct from any other groundwater data point in the LWRFS.

The differences in groundwater temperatures suggest distinctive groundwater flow paths through the RDCA in this area. Most importantly the difference in the temperature data from well KPW-1 versus that of the rest of the wells in the RDCA indicates a very different source for the groundwater flowing through KSV as compared to the rest of LWRFS. Figure 3-12 is the graphical representation of the data from Table 3-4 and from the map shown in Figure 3-11. It’s evident from Figure 3-12 that there are several wells that can be connected based on temperature, as well as, wells that do not connect with any other data. The same colors on Figure 3-12 represent the same flow paths on Figure 3-11, and are typically north to south. These groundwater temperatures are consistent with the geophysics and the mapped geologic structures in the LWRFS. In summary, the groundwater temperature data from KPW-1 doesn’t fit the groundwater temperature data from the other wells, with the exception of some mixing with well CSVM-4, and therefore indicate a flow path distinctive from that of wells in the LWRFS.

Table 3-4. Temperature Data from Selected Carbonate Sourced Groundwater Wells and Springs

Well/Spring Description	Temperature Range	Source
CSVM-2	99.87º - 99.82º	1
CSVM-3	78.02º - 77.04º	1
CSVM-4	106.56º - 107.89º	1
CSVM-5	75.69º - 76.11º	1
KPW-1	129.91º - 135.77º	2
Big Muddy Spring	89.78º	3
Pederson Warm Springs	89.96º	3
CSI-1	89º	3

References - Source of Data:

1. URS – 2006b CSV Monitor Well Sampling Report
2. URS – 2006a KSV Final Well Completion Report
3. CH2MHILL – 2006b Geochemistry Report

4.0 GEOPHYSICAL DATA

Lincoln/Vidler have collected extensive lines of geophysical data in both KSV and CSV. The Controlled Source Audio Frequency Magneto Telluric (CSAMT) method has been used for this work, an explanation of which is provided below. Lincoln/Vidler has applied CSAMT for characterization of the RDCA to thousands of feet below land surface over several decades and in several hydrographic basins with great success. For this discussion, existing geophysical data is considered to be that collected in KSV in 2012 by Zonge International, Inc. (Zonge). These existing data are discussed in the following section. New geophysical data were collected in February and March of 2019 for this report to the NSE to augment the existing geophysical data from KSV. The new geophysical data were collected in northern CSV and both sets of data are considered together for the purposes of this report.

A CSAMT geophysical survey is a high-resolution electromagnetic sounding technique that uses a fixed grounded dipole as a signal source (a dipole is a pair of equal and oppositely charged or magnetized poles separated by a distance). A complete, published, and peer-reviewed discussion of the CSAMT method can be found in Zonge and Hughes (1991) and Zonge (1992).

As applied here, the CSAMT geophysical survey method used a CSAMT transmitter signal source that usually consists of a grounded electric dipole 3,500 and 6,500 feet in length located three to six miles from the area where the measurements are to be made (Figure 4-1). At the receiver site, grounded dipoles detect the electric field and a magnetic field coil antenna detects the magnetic field (Figure 4-2). The electrical resistivity of the geologic formations can be determined from the combination of these electric and magnetic field measurements. Varying the frequencies of the observations controls the depth of investigation using the CSAMT method. Depth sections can be generated using the CSAMT method by measuring the electric and magnetic fields over a range of frequencies and using computer modeling to produce a cross-section of resistivity at different depths.

CSAMT data are usually shown as resistivity values in ohm-meters. Resistivity is essentially a measure of the ground’s ability to conduct electrical current. Though the resistivity contour lines often at first glance appear to be indications of contacts between lithologic layers they are lines of equal resistivity and not necessarily boundaries between different lithologies. While different rock types do indeed often exhibit different resistivities, most rock types exhibit a range of resistivities, and the resistivity ranges for different rock types may overlap. The ranges in resistivity result from the fact that there are several factors that affect resistivity, including the amount of pore fluids, the type of pore fluids, mineralization, clay content, and the size and interconnectedness of the pore spaces, as examples. As a result of all these variables, in some cases two different lithologies may exhibit similar resistivity, and in other cases, a single lithologic unit may exhibit different resistivities in different areas.

This survey technique is a well-established method, commonly used primarily by the minerals, geothermal, and groundwater exploration industries, and has been in use since the early 1980's when CSAMT equipment was first commercialized. It is not a proprietary method so it can be, and has been, replicated or repeated by independent exploration geophysicists. Zonge is one of several manufacturers of CSAMT equipment whose systems have been purchased by and are in use by numerous government agencies including the US Geological Survey, universities, national laboratories, and private entities.

4.1 DISCUSSION ABOUT USE OF THE CSAMT GEOPHYSICAL METHOD

It is not unusual for faults or other geologic structures to not be apparent to non-geophysicists reviewing a CSAMT resistivity cross section. The following is provided to help explain how various structures are identified in these CSAMT cross sections. In resistivity plots, faults can be manifested in several different ways, since the data are showing an electrical property of the subsurface that may or may not be indicative of changes in lithology. Figure 4-3 provides two examples of the CSAMT geophysics plots that can be used to identify different fault structures. The fault on the left in Figure 4-3 looks like a vertical, narrow, low resistivity feature centered at station 350 (where the client drilled and accessed water). On the right-hand side of Figure 4-3 is a more traditional looking plot of faulting, with the left side of the section offset higher relative to the right part of the section, with the fault between stations -300 and -150. Both of these examples show how geologic structures can be identified in transects conducted through southern KSV and northern CSV using the CSAMT geophysical method.

4.2 GEOPHYSICAL DATA COLLECTED IN KANE SPRINGS VALLEY

An extensive geophysical survey using the CSAMT method was conducted by Zonge in 2012 to further refine potential well locations in KSV. Several geophysical transects were conducted perpendicular to the axis of the KSV basin (Figure 4-4). A transect was also conducted along the axis of the southern part of the basin. For the transects conducted in CSV, the same northwest-southeast (NW-SE) orientation as the KSV transects was used to assist in evaluating the geologic structures in this area.

To best understand the geologic structures in northern CSV, a review of the first geophysical transects, Lines 1 and 2, through the southern end of KSV is warranted. These transects in both southern KSV and northern CSV are plotted on an excerpt (Figure 4-4) of the most recent geologic map of this area by Rowley and others (2017).

4.2.1 CSAMT Transect Line 2 through Southern Kane Springs Valley

In order to track the geologic structures that occur in southern KSV into northern CSV, the northern-most transect used in this report is discussed below and provided as Figure 4-5. The view of the transect is looking to the northeast into the KSV basin.

Beginning on the right side (or east side) of Line 2 illustrated in Figure 4-5, the data exhibits a very highly resistive block essentially from land surface to final investigation depth. This demonstrates "ground-truthing" of the CSAMT method as this is an exposed block of RDCA. From station number (the station numbers are across the top of the transect) 15100 the high resistivity values occur adjacent to low resistivity values and are representative of faulting in this area as also interpreted at this location on the geologic base map. These values represent the eastern boundary of the Kane Springs Wash (KSW) Fault Zone (Figure 4-4).

Numerous other faults are represented on the Line 2 transect through southern KSV. This area ranges from approximately station number 8500 through station 15100. This area represents the KSW Fault Zone and is very consistent with the surficial geologic map by Rowley and others (2017).

The next significant feature shown on Figure 4-5 is the block of high resistivity that occurs between stations 7500 and 8500 with a top at an elevation of approximately 1,500 feet. This feature ties directly to the large carbonate rock outcrop mapped at the mouth of KSV (Figure 4-4, between Lines 1 and 10, labelled “Ds”). The northwest side of the transect of Line 2 (Figure 4-5) confirms the presence of the mapped Willow Springs Fault on the geologic map (Figure 4-4). This occurs between stations 500 to 700 (Figure 4-5).

4.2.2 CSAMT Line 1 through Southern Kane Springs Valley

Line 1 of the KSV CSAMT transect (closest to southwest end of KSV) is provided in Figure 4-6. This transect includes and is ground-truthed using both the down-hole geophysics and geologic log of wells KPW-1 and KMW-1. These wells were drilled adjacent to the exposed outcrops of Devonian Simonson Dolomite (Ds) illustrated in Figure 4-4. This well also intersects the Willow Springs Fault as shown on Figure 3-3. The geophysical transect confirmed the exposure of dolomite, the attitude (dip) of both geologic units, and the occurrence of the KSW Fault Zone. The ground-truthing of CSAMT across the exposed dolomite outcrop in the center of Line 1 is convincing.

Unlike Line 2 (Figure 4-5), the Line 1 (Figure 4-6) CSAMT transect does not extend to the exposed hard rock outcrops of either the Delamar Mountains or the Meadow Valley Mountains. Other important features shown on Line 1 include:

- Faulting within KSW Fault Zone at stations 8100 through the end of this transect (Figure 4-6).
- Faulting on west side of KPW-1 near boundary of outcrops at Station 2100.

4.3 GEOPHYSICAL DATA COLLECTED IN NORTHERN COYOTE SPRING VALLEY

New geophysical data were collected in February and March 2019 in northern CSV just south of the KSV basin boundary (Figure 4-4). These data were collected in direct response to the request from the NSE in IO #1303 (NSE 2019) calling for new data to be provided in order to assist him in addressing the issues identified in the Interim Order (see Section 1.2).

Two new CSAMT geophysical transects, in CSV, were conducted parallel to the previously collected Lines 1 and 2, in southern KSV. The southwestern-most transect in KSV, Line 1, includes wells KPW-1 and KMW-1. The new transects in CSV are labelled Lines 10 and 11 (Figure 4-7), with Line 10 being the most northerly transect closest to the mouth of KSV. Both of these transects are located in a NW-SE orientation, perpendicular to the known geologic structures identified on the geologic map of the area (Rowley and others 2017). A third transect, Line 12, was conducted in an east-west alignment in northern CSV and intersected both Lines 10 and 11 (Figure 4-4).

The following sections specifically discuss the new CSAMT data, and then discuss what this information means relative to the geology and associated controls on groundwater flow in southern KSV and northern CSV.

4.3.1 CSAMT Line 10 Northern Coyote Spring Valley

The northern most transect in CSV (Figure 4-7) is located just southwest of the exposed outcrop of dolomite (Ds) at the mouth of KSV (Figure 4-4). Monitor well CSVM-4 is also located to the southwest of station 13900 on Line 10.

There are several significant features that can be identified on CSAMT Line 10.

- The transect is dominated by high resistivity blocks.
- From the ground-truthing discussed previously for Lines 1 and 2, and on this line at its far southeast end, these high resistivity blocks are most likely RDCA.
- This transect also shows the down thrown nature of the boundary fault on the far southeastern end – stations 23900 to 24300. This fault occurs to the western side of the Meadow Valley Mountains and forms the eastern boundary of the Kane Springs West Fault Zone (Figures 4-4 and 4-7) which is consistent with the geologic map (Rowley and others 2017). This fault can be traced through these transects (Figures 4-4 and 4-7) from KSV into CSV (Rowley and others 2017).
- Well CSVM-4 was drilled near the highly resistive block of exposed dolomite in KSV. This block of dolomite is not exposed at the surface in CSV but can be traced from KSV through to the geophysical transect of Line 10 in northern CSV.

- The concealed Delamar Thrust Fault drawn on Rowley and others (2017) cannot be identified—or is not present—on CSAMT transect of Line 10. If present, it would be located at approximate station 4100.
- Faulting does occur from stations 8300 to 10500. This would agree with the concealed strike slip fault identified on Rowley and others (2017) along the northwest edge of the outcrop Ds at the mouth of KSV (Figure 4-4).
- The highly resistive block that outcrops as Ds at the mouth of KSV continues to occur beneath the surface as shown in Line 10. This occurs from stations 13500 to 16300.
- There are numerous faults that occur from station 16300 though station 24300, which is representative of the KSW Fault Zone.

4.3.2 CSAMT Line 11 in Northern Coyote Spring Valley

CSAMT Line 11 is located approximately 12,500 feet to the southwest of Line 10 (Figure 4-4). Monitor well CSVM-4 is located approximately 11,700 feet to the northeast of station 31100 of Line 11.

There are several significant features that can be identified on CSAMT Line 11.

- The most striking difference of Line 11 from Line 10 is the virtual lack of the highly resistive blocks that dominated the transect of Line 10. This constitutes over 2,800 feet or a half mile of thickness of highly resistive block not present just 12,500 feet or approximately two miles south of Line 10.
- This transect also shows the down-thrown nature of the southeastern boundary fault. This fault occurs to the western side of the Meadow Valley Mountains and forms the eastern boundary of the Kane Springs West Fault Zone (Figures 4-4 and 4-7, stations 45300 - 45700).
- Again, the southeastern boundary fault (or northwest exposed side of the Meadow Valley Mountains [Figures 4-4 and 4-7]) is identified by the geophysics and can be traced through this transect from KSV into CSV (Rowley and others 2017).

- Similar to Line 10, there are numerous faults throughout this transect and especially so on the southern half of this transect.
- There is no evidence of the Delamar Thrust Fault (that would be at station 21500) as extrapolated from the Delamar Mountains on the geologic map (Rowley and others 2017) from the geophysical transect of Line 11.
- The concealed strike-slip fault that forms the western boundary of the KSW Fault Zone, i.e., the strike slip fault identified on Rowley and other (2017) along the northeast edge of the outcrop Ds at the mouth of KSV may be located at approximately station 26700 on Line 11 (Figure 4-7).
- The low resistivity zones may be the result of thicker volcanics versus higher resistivity carbonates, or it may just be different materials in the alluvial cover (i.e., more or less clays in some alluvial sediment layers than others, obviously much more in an overall sense than in the RDCA). Also, along some parts of the line, there are multiple low resistivity layers (stations 30000 to 38000, for example).
- Comparison of Line 10 to Line 11 suggests that the structural boundary between southern KSV/northern CSV and the rest of CSV to the south occurs between these two lines.

4.3.3 CSAMT Lines 12 East – West Line through Northern Coyote Spring Valley

CSAMT Line 12 (Figure 4-8) is an east-west transect that intersects both CSAMT Lines 10 and 11 at stations 42700 and 23800, respectively, at a 45-degree angle. There are several significant features that can be identified on this transect.

- The Gass Peak Thrust Fault (a very large, regional structural feature) appears to be present at station 1300 (Figure 4-8; Rowley and others 2017).
- Low resistivity values occur at the land surface on the western side of this transect. This is significant because it correlates with an area of surface vegetation which is an indication of a source of water supported by the low resistive materials.
- There is no real evidence of the regional normal fault mapped on the geologic map around station 13000 (Rowley and others 2017).
- Remnants of KSW Fault Zone, i.e., the strike slip fault identified on Rowley and others (2017) along the northwest edge of the outcrop Ds at the mouth of KSV, occur from

approximately station 30300 through 44100. Specifically, there is an obvious change between the layering of resistivities east and west of approximately station 30000.

- Well logs from monitor wells CSV3009 and CSV3011 confirm the presence of unconsolidated or alluvial materials, i.e., silts, clays, sands, and gravels to at least a depth of approximately 1,580 feet below land surface (Figures 3-1 and 4-4). There are no highly resistive (carbonate) rocks that occur on the western portion of Line 12 (Figure 4-8).

4.4 MAJOR POINTS IDENTIFIED AND DERIVED FROM THE GEOPHYSICAL DATA

The following major points can be made about the geophysical data from lower KSV and northern CSV.

- Geophysics validate many but not all of the concealed faulting extrapolated on the geologic map.
- It is reasonable to connect the highly resistive feature that extends from southern KSV (Line 2) through northern CSV (Line 10) and in exposed Devonian rock in southern KSV.
- The KSW Fault Zone is a massive geologic feature that extends from northern KSV where it transects the KSV Caldera Complex into northern CSV.
- Well KPW-1 was drilled near the confluence or intersection of the Willow Springs Fault and the western boundary fault of the KSW Fault Zone. In fact, the Willow Springs Fault Zone joins with, if it doesn't replace the western bounding fault of the KSW Fault Zone (Figures 4-4 through 4-7).
- The KSW Fault Zone expands from the southern part of KSV into northern CSV where it extends to approximately 18,500 feet across (Figure 4-7).
- The KSW Fault Zone in northern CSV is dissected by dozens of faults as shown in the geophysical transect of Line 11 (Figure 4-7). This area exhibits an "accommodation zone" pattern of faulting where numerous normal faults occur "en-echelon," or parallel to each other, throughout the area (Figure 4-7).
- Because of the potential for incorporating less permeable materials in the process at a regional scale, groundwater will flow easier along fault zones than across fault zones. Small sections of faults may certainly have enhanced permeability and focus groundwater flow

along their extents, but this is rarely maintained over miles of extent, which is the scale being considered here of hydrographic basins and their relation to the LWRFS.

- CSAMT geophysics run perpendicular to the axis of KSV and known faulting in northern CSV was captured by the geophysics and shows the structure quite clearly to depths of approximately 3,000 feet bls.
- The faulting that occurs in northern CSV (especially the difference between Lines 10 and 11 presented here) explains why the water levels in KMW-1 and CSVM-4 are distinctly higher than those found in the rest of the basin (Figures 3-4 through 3-9).
- These faults significantly impede the flow of groundwater from KSV and northern CSV (where monitor well CSVM-4 is located) into the southern portion of CSV, south of the transect of Line 11 (Figure 4-7).
- Comparison of Line 10 to Line 11 suggests that the structural boundary between southern KSV/northern CSV and the rest of CSV to the south occurs between these two transects (Figure 4-7).
- This extensive faulting provides a basis (along with other, associated hydrogeologic data) for excluding KSV from being included in the LWRFS. This extensive faulting provides an explanation as to why the water levels are different in the KMW-1 and CSVM-4 wells and at CSVM-3 and CSVM-7.

4.5 DISCUSSION OF GEOHPHYSICAL DATA AND HOW IT RELATES TO THE HYDROGEOLOGY AND BASIN WATER LEVEL DATA

The geophysical data combined with the known water level data provide an explanation of groundwater flow from KSV through northern CSV. Figure 4-9 illustrates the interpretation of what we're calling the Northern LWRFS Boundary Fault that has been identified by the new CSAMT geophysical data. The Northern LWRFS Boundary Fault is a very large structure at the end of the Delamar Mountains that provides an explanation of the abrupt end of the Delamar Mountains in this area. Groundwater flowing southwest out of KSV, and southwest out of the Delamar Mountains in the RDCA, would run directly into this large fault system. Since the highly resistive blocks occur in Line 10, interpreted to be the RDCA, and not in Line 11 (Figure 4-7), the Northern LWRFS Boundary Fault is interpreted to be down thrown to the southwest as shown on

Figure 4-9. This means that groundwater flowing out of the Delamar Mountains and KSV would run into lower permeability Tertiary basin fill materials, perhaps interbedded with Tertiary volcanics (as identified in Section 4.3.2). This would cause the water levels to build up on the upthrown side of the fault (to the northeast – Figure 4-9) until there is enough head built up (a few tens of feet) for groundwater to push through into northern CSV.

The geophysical data collected in northern CSV shows that there is approximately 3,000 plus or minus feet of remarkably flat Tertiary Basin fill, that is perhaps interbedded with volcanics, that are lithologically different or much more highly fractured and faulted en-echelon in a band against the Meadow Valley Mountains (see Section 4.4, above). The RDCA from the southern Delamar Mountains and KSV runs directly and unavoidably into these Tertiary basin fill sediments, which directly affects the flow of groundwater in this area as shown by the geophysical data and corroborating water level, groundwater chemistry, and temperature data.

A long-term aquifer test, approximately 25 ½ months, was conducted (Order No. 1169) to look at the effects of groundwater pumping on the MRSA, but there were no effects ascribable to the start and subsequent stop of a major pumping stress in monitor wells KMW-1 or CSVM-4. There are several reasons for this including the significant distance the cone-of-depression would have to extend out from the pumping well for the pumping and recovery effects to be identifiable in the monitor well in southern KSV. This is a distance of over 15 miles from the MX-5 well. It should be noted that the distance from the KPW-1 well to the springs in the MRSA is over 23 miles if measured by line-of-sight. Secondly, there is a very large sequence of carbonate rocks between the location of the Order No. 1169 pumping and KSV and northern CSV and that thick sequence likely has a very large transmissivity, which is indicated by the nearly flat-water level elevation in much of the LWRFS. For hydraulic head changes (drawdown and build-up/recovery) to travel through these thick sequences of carbonate rocks, they would also have to travel through much more restrictive structures such as the en-echelon faulting that was found farther north in the KSW Fault Zone. Finally, groundwater from KSV has to flow through the Northern LWRFS Boundary Fault where the geologic structure changes as demonstrated by the new geophysical data (Figure 4-9).

5.0 OTHER ISSUES OF THE NEVADA STATE ENGINEER'S REQUEST

There are four other matters the NSE requested be addressed in IO #1303 (NSE 2019) in addition to the request for information regarding the geographic boundary. The other four issues are:

- The information obtained from the Order No. 1169 aquifer test and subsequent to the aquifer test and Muddy River headwater spring flow as it related to aquifer recovery since the completion of the aquifer test;
- The long-term annual quantity of groundwater that may be pumped from the Lower White River Flow System, including the relationships between the location of pumping on discharge to the Muddy River Springs, and the capture of Muddy River flow;
- The effects of movement of water rights between alluvial wells and carbonate wells on deliveries of senior decreed rights to the Muddy River; and,
- Any other matter believed to be relevant to the State Engineer's analysis.

Lincoln/Vidler are responding to each issue below although it may not be germane to whether KSV is included in the LWRFS administrative unit.

5.1 ORDER 1169 AQUIFER TEST

As stated in Lincoln/Vidler's correspondence to Jason King, NSE, dated October 10, 2018 (Lincoln/Vidler 2018):

> "Lincoln/Vidler have not been involved in any of the Order 1169 studies to date."

There was no indication at the time the Order No. 1169 aquifer test was completed and the NSE called for an analysis of the pumping test data, that KSV would be part of the LWRFS administrative unit. In fact, the NSE made this clear in his Ruling #5712 (NSE 2007) by stating at page 21:

> "The State Engineer finds there is not substantial evidence that the appropriation of a limited quantity of water in Kane Springs Valley Hydrographic Basin will have

> any measurable impact on Muddy River Springs that warrants the inclusion of Kane Springs Valley in Order No. 1169. Therefore, the State Engineer denies the request to hold these applications in abeyance and include Kane Spring Valley within the provisions of Order No. 1169."

Because KSV was not included in Order No. 1169, Lincoln/Vidler were not noticed via Order 1169A (NSE 2012) requesting reports on the outcome of the Order No. 1169 aquifer test results (NSE 2002) to participate and provide their input in the Order No. 1169 proceedings. As stated in Lincoln/Vidler's correspondence dated October 10, 2018 (Lincoln/Vidler 2018), and we reiterate in this report:

> "Putting us [Lincoln/Vidler] into this Order now puts us at a great disadvantage as we have not been privy to or participated in any of the meetings, data collection activities, nor have we had the ability to analyze any of the collected data or, as would likely be the case, collect our own data and information relevant to the issue of Order 1169."

5.2 LONG-TERM ANNUAL QUANTITY OF GROUNDWATER PUMPING FROM THE LWRFS

Lincoln/Vidler provides no statement or analysis here as to the long-term annual quantity of groundwater that could be pumped from the LWRFS administrative unit. Lincoln/Vidler do however state that KSV can be part of the solution to the water issues affecting the LWRFS groundwater basins. There is unappropriated water within KSV that can be used as a source of supply for down-gradient groundwater basins with little reasonable likelihood of impacting or affecting the MSRA because of the large distances and complex geologic structures in between.

5.3 IMPACTS AND EFFECTS OF PUMPING FROM ALLUVIAL AND CARBONATE WELLS NEAR THE MRSA

Lincoln/Vidler have previously stated in a letter to the NSE (Bushner 2018) that all of the groundwater pumped from the Order No. 1169 aquifer test can be explained by data provided by SNWA. Figure 5-1 (reproduced from SNWA 2018) is very illustrative of what was stated at the beginning of Lincoln/Vidler's 2018 comment letter. This analysis benefits from considering the reliable data spanning over two decades, not just the duration of the Order No. 1169 Test.

First, SNWA normalized the flows of the Muddy River, where flood flows have been removed from the hydrograph and diversions from the Muddy River have been added back into the hydrograph. The red line on Figure 5-1 shows the calculated Muddy River flow deficit. Groundwater pumping over time is plotted from wells in the alluvium (tan colors) in the MRSA and groundwater pumping from wells in the carbonate rock aquifer (dark blue color) in the MRSA. The light blue bars represent groundwater pumping from carbonate wells in the CSV. What can be concluded from this chart and graphical representation of the Muddy River flow and groundwater pumpage is that the red line plots in between the dark blue (MRSA carbonate rock aquifer pumpage) and the light blue (CSV carbonate rock aquifer pumpage). This indicates that pumpage from the MRSA completely explains the reductions in flows of the Muddy River and associated springs. Groundwater pumpage from CSV (light blue bars) is not needed at all to explain the declines since the 1990s in the flows in the Muddy River.

5.4 ANY OTHER MATTER BELIEVED TO BE RELEVANT TO THE STATE ENGINEER'S ANALYSIS

With a clear understanding of the cause of reduced flows on the Muddy River and its headwater springs, the NSE can proceed directly to define how the LWRFS administrative unit will work and where the focus should be when trying to protect springs that are at issue in the MRSA. First and foremost, the impacts from groundwater pumping on the MRSA are within the MRSA itself, and therefore, the focus should be within the MRSA first. Secondly, CSV should be monitored, however, impacts from pumping in the CSV do not cause the biggest impacts to the springs. Finally, inflows to the MRSA from the Lower Meadow Valley Wash hydrographic area should be monitored and protected. Lincoln/Vidler also addressed this issue in the correspondence to the NSE (Bushner 2018) stating:

> "…as identified by SNWA through the Cave, Dry Lake, and Delamar Valleys hearing and associated reports, identifies 8,000 acre-feet of groundwater inflow from upgradient hydrographic basin Lower Meadow Valley Wash … If one of the

goals to the LWRFS administrative unit determined by the NSE is to protect the springs in the MRSA then the Lower Meadow Valley Wash hydrographic basin and its groundwater inflow should not only be included as part of the LWRFS administrative unit but should also be the focus and the priority of the NSE."

6.0 KEY FINDINGS AND CONCLUSIONS

The following are the key findings and conclusions from this existing data and geophysical data documentation report.

6.1 KEY FINDINGS

- KSV is a perennial yield groundwater basin under the Laws of the State of Nevada.
- KSV is too distant and isolated due to geologic structures for pumping the perennial yield there to likely cause impairment of Muddy River Springs, Blue Point, or Rogers Springs.
- The effects of pumping from KSV would not be felt for over 100 years outside of KSV.
- The NSE did not include KSV in the Order No. 1169 aquifer test.
- Groundwater elevation data show distinctive differences in heads between KSV/northern CSV and the southern portion of CSV, which are confirmed by the geologic structures that occur in KSV and northern CSV.
- There is no discernable trend/pattern in water levels overtime between production well KPW-1 and pumping trends.
- There is no correspondence between the water level trends in wells in KSV/northern CSV, and wells located in southern CSV.
- Lincoln/Vidler have been collecting data for nearly over a decade to better quantify the volume of precipitation that occurs in KSV and that becomes local in-basin recharge.
- There was an over-arching precipitation event that occurred in southern Nevada in 2005 that had a major effect on water levels in wells throughout the area.
- The trend in water levels in both KMW-1 and CSVM-4 indicate water levels are still being affected by the 2005 precipitation event.
- The key finding of the geochemistry data is that "A comparison of these chemical and isotopic relationships with Big Muddy Springs and particularly Rogers Spring and Blue Point Spring indicates that the groundwater from KPW-1, assumed representative of the KSV groundwater, is too strongly attenuated with CSV to be identifiable in these springs." (Appendix C: CH2M Hill 2006b, Pages 12 and 13).

- Groundwater from KPW-1 and CSVM-4 are related and on similar groundwater flow paths based on the TDSS values and other geochemical data. This supports the existence of a significant fault in northern CSV corroborating the geophysical data.
- KPW-1 groundwater has one of the oldest apparent ages of 29,000 years. Assuming that the apparent ages are somewhat true, and in this case may be, it is not likely that KSV groundwater represented by KPW-1 with this age could contribute to the flow at Big Muddy Springs.
- Based on the groundwater temperature data, none of the other groundwater temperature data are close to the 136°F of the groundwater found at KPW-1, suggesting deep circulation of groundwater in KSV.
- Groundwater temperature data are consistent with the geophysical data and represent differing groundwater flow paths occurring in southern KSV and the northern most portion of CSV compared to groundwater flow paths elsewhere in CSV.

6.2 CONCLUSIONS

It is clear that a Management Order and presumably a conjunctive use element for that Management Order and the Order No. 1169 basins is appropriate. However, there is no evidence-based reason to impose that plan on basins outside of the Order No. 1169 geographic area. In fact, and on the contrary, there are science-based reasons to exclude KSV/northern CSV from the LWRFS as identified in this report.

While we appreciate the gravity of the issues before the NSE in managing the water resources of the State, frankly the record and science is clear relative to KSV: there is no likely impact to the Order No. 1169 basins.

7.0 RECOMMENDATIONS

Lincoln/Vidler submit the following recommendations as requested by IO #1303.

1. Continue to exclude KSV from the LWRFS administrative unit.

The scientific data supports excluding KSV from the LWRFS administrative unit. The most salient point is that the carbonate wells KPW-1 in southern KSV and CSVM-4 in northern CSV have different hydraulic heads than other heads further south in the LWRFS. This was explained by the new geophysical data that was collected from northern CSV which shows that there are several structural controls, including faults, that occur in the northern CSV and would represent impediments for groundwater flowing from KSV/northern CSV into the LWRFS groundwater basins.

There is no indication from the water level data of either KMW-1 or CSVM-4 that there were any noticeable effects from the Order No. 1169 aquifer test. What was observed and was significant was the dissipating effects of an over-arching precipitation event in 2005 that affected water levels in these wells for years.

2. Recommended boundary revisions.

Lincoln/Vidler recommend that in addition to KSV remaining excluded from the LWRFS administrative unit, the northern portion of CSV should also be excluded from the LWRFS administrative unit based upon the geophysical data and corroborated by groundwater level data, geochemistry data, and groundwater temperature data.

3. Additional recommendations:

Lincoln/Vidler recommend the NSE reduce or eliminate pumping adjacent to or near the springs in the MRSA, and also define and protect the up-gradient watershed of LMVW. The data provided by SNWA (2018) demonstrates that the depletions on the spring flows in the MRSA are completely explained by groundwater pumping from wells in the alluvial and carbonate rock aquifers within the MRSA hydrographic basin. Secondly, but much less impactful, is groundwater pumping from CSV. Thirdly, there is approximately 8,000 acre-feet of groundwater inflow from the LMVW. If one of the goals of the LWRFS administrative unit determined by the NSE is to protect the springs in the MRSA, then the LMVW hydrographic basin, where there is a dearth of data, and its groundwater inflow should not only be included as part of the LWRFS administrative unit but should also become a focus and the priority of the NSE.

Lincoln/Vidler concur the NSE has reason to view many of the basins in the LWRFS as hydraulically connected based on the remarkably consistent water levels among wells completed in the RDCA. Lincoln/Vidler identified this effect in 2006 during the initial KSV hearing before the NSE for applications for new groundwater appropriations in this basin. Although we concur with the effective administration of these basins collectively based on the hydrogeology, Lincoln/Vidler disagree that the effects are all the same across the entire LWRFS administrative unit.

We must reiterate what we stated previously in Lincoln/Vidler's letter to the NSE dated October 10, 2018:

> "While we appreciate the gravity to the issues before the State Engineer in managing the water resources of the State, frankly the record and the science is pretty clear relative to Kane Springs Valley and its lack of impact to the 1169 basins. While there are no easy tasks ahead for water solutions in much of Nevada, perhaps the focus should rest on viewing many of the existing water resources upgradient as pieces of the puzzle for solutions by willing participants not as "taking away" flow that some would improperly characterize as gratuitously "*belonging*" to the downgradient basin even if it is within the perennial yield of the upgradient basin. Our basin and range geography still allows for the appropriation of perennial yield within those upgradient basins."

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FIGURES

APPENDICES

Comments Pertaining to a Draft Order for the LWRFS

(As Distributed During Working Group Meeting in Overton, NV on Sept. 19, 2018)

Prepared by Jay Dixon, P.E. and Hugh Ricci, P.E. (on behalf of NCA-1 and 2)

October 5, 2018

Overview

Nevada Cogeneration Associates Nos. 1 and 2 (NCA 1 and 2, or NCA) operate combined cycle gas-fired cogeneration facilities located at the southern end of the Lower White River Flow System (LWRFS). NCA 1 and NCA 2 began commercial operations in June 1992 and February 1993, respectively. Collectively, the two plants account for 170 MW in baseload generation capacity. NCA sells 100% of its electric output to NV Energy under the terms of a long-term Power Purchase Agreement and both facilities supply hot exhaust gas and chilled water (via a closed loop system) to Georgia Pacific and Pacific Coast Building Products' gypsum facilities under the terms of an Energy Purchase Agreement.

The NCA facilities have played an integral role in economic output in the region for more than 25 years. NCA's water rights have been placed to continuous use since construction of facilities in 1992 and 1993. The continued access of their certificated water rights is critical for NCA's sustained operations.

Comments

1. Over the past three years, total pumping in the amount of 9,318 AF was provided as the average between the years 2015 to 2017 within the area defined by the Lower White River Flow System (LWRFS).

2. As indicated on the draft order, the cumulative pumping in 2017 was 9,028.3 AF.

3. A check on available Pumpage Inventory reports indicates that 9,027.51 AF may have been pumped (on average) between 2015-17. Note that an inventory report is not published for Hidden Valley (Basin 217) but the only active underground right in that basin is permit 54074 (SNWA), which has not been pumped. The source of this apparent (290.49 AF) discrepancy is unknown.

4. Between 2015-17, the average pumping for NCA 1 and 2, was 1,463.03 AF. Based on NDWR's Pumping Inventory for Basin 215 and NCA records, NCA's average pumping from 1993 to 2017 was 1,557 AF.

5. NCA's documented pumping is relevant as to its use of water being limited by permits issued under Nos. 55269, 58031 and 58032 and subsequent certificate Nos. 17123, 17124 and 17125, respectively. These s were issued in 1989 (No. 55269) and 1990 (Nos. 58031 and 58032), with respective priority dates of October 30, 1989 and September 13,1990. The duty under these permits and subsequent certificates was limited to 1,665 AF. The NCA-1 facility came online in June 1992 and the NCA-2 facility was active by February 1993. The 25-year average pumping of 1,557 AF is 93.5% of the certificated water to NCA and 17% of the proposed limit provided in the draft order (9,318 AF).

6. This use of water over a substantial period shows that NCA has made a reasonable effort to place the granted water to use for which the permits were issued. NRS 533.070 is very explicit in this regard as it states that "*The quantity of water from either a surface or underground source which may here after be appropriated shall be limited to such water as may reasonably be required for the beneficial use to be served*."

7. The approval of a permit under NRS 533.070 also requires that an applicant must have an intention of construction of the works of diversion and reasonable expectation to apply the water to the intended beneficial use with reasonable diligence. NCA has shown in both instances that it completed the works and showed beneficial use with reasonable diligence.

8. NCA also complied with NRS 533.380 regarding requirements for filing proofs of completion and beneficial use in that the measure of reasonable diligence is the steady application of effort to perfect the application.

9. The cumulative 2017 pumping value at the priority date of March 31, 1983 is 3,089.61 AF, with "senior rights" pumping approximately one-third of the 9,318 AF mentioned in the draft order. Thus, "junior rights" pumped two-thirds of the proposed limit, which includes NCA who pumped approximately 25% of those "junior rights".

10. The draft order suggests under Section VII (4) that junior rights will not be curtailed until the unused senior water right use reaches the limit of 9,318 AF. Again, a review of the LWRFS groundwater rights by priority, indicates that the cumulative duty as of the March 31, 1983 date is somewhere between approximately 8,000 to 12,400 AF. This means that only 3,089.61 AF of this duty was used in 2017.

11. This places NCA in a very tenuous position in that it did everything required under the statutes, yet those senior water right holders who did not put their water to use may be allowed to start a project and use a portion of that unused water and put NCA's rights at risk.

12. To allow for additional time to evaluate anticipated changes in withdrawals as a result of the proposed LWRFS draft order and potential changes in impacts, the order should be issued such that it shall be re-evaluated after a period of 3-years. During this time, the pumping should be limited to not more than what was pumped in 2017 or the 2015-2017 average.

13. The LWRFS order should consider providing flexibility for entities to maintain their water rights in good standing without risk of cancellation for not developing those rights during a temporary period of time subject to adoption of a management plan.

Report

Hydrologic Assessment of Kane Springs Valley Hydrographic Area (206): Hydrologic Framework, Hydrologic Conceptual Model, and Impact Analysis

Presentation to the Office of the Nevada State Engineer

Prepared for
Lincoln County Water District and Vidler Water Company

Prepared by

CH2MHILL

April 2006

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Contents

Introduction/Objectives

A hydrologic assessment of the local and regional conditions that affect the movement and storage of groundwater in the Kane Springs Hydrographic Area (206) was conducted to address the following objectives:

- Develop an understanding of the existing conditions of local groundwater resources within Kane Springs Valley (KSV).
- Assess the availability of these resources.
- Assess potential impacts to local and downgradient water users and water resources including local and regional springs, and water courses.
- Develop a conceptual framework to support potential monitoring and/or mitigation measures, as appropriate.

The principal components of the assessment included the following:

- Development of a hydrologic framework to provide physical context for the assessment.
- Installation of test well and companion monitoring well, and conduct aquifer testing. This component of the assessment was performed by URS Corporation and the specific results and analyses that arose from this work is presented under separate cover in URS (2006).
- Conducting groundwater sampling from both KSV and adjacent Coyote Spring Valley.
- Evaluation of the local and regional geochemical conditions of the groundwater based on the analyses of water chemistry and stable isotopes.
- Development of hydrologic conceptual model of KSV both locally and in the context of regional groundwater flow.

Based on the resulting conceptual model:

- Assess the availability of groundwater in the KSV
- Assess potential impacts resulting from groundwater withdrawals from the KSV.

Hydrologic Framework

KSV – Physical Features and Conditions

Kane Springs Valley is an elongated north-northeast/south-southwest trending valley in southern Nevada that is flanked by the Delamar Mountains to the west and north, and the Meadow Valley Mountains to the south. Covering an area of approximately 232 square miles, KSV is approximately 28 miles long and an average of approximately 8 miles wide. The floor of the valley slopes south-southwest from a high of approximately 4000 feet near the base of the Clover Mountains toward the mouth of the valley where the elevation is approximately 2900 feet. Within the KSV hydrographic area, the Delamar Mountains reach 7720 feet and receive most of the local precipitation. The Meadow Valley Mountains are considerably lower with a maximum elevation of 5676 feet. The Clover Mountains, while technically east of the KSV basin, affect precipitation patterns within the northeastern portion of KSV.

The ephemeral Kane Springs Wash, which drains the entire valley, is the dominant surface water feature in the basin. Springs discharging from the surrounding mountains are generally low-flowing (i.e., less than 10 gallons per minute [gpm]) and are considered to be locally recharged based on their water chemistry (Thomas et al., 1996). With the exception of small areas below these springs, phreatophytic vegetation is generally absent; therefore, groundwater discharge through transpiration is a negligible component of the water budget for the KSV basin.

Figure 1 shows the location of the study area focused on KSV. Figure 2 shows the location of KSV Hydrographic Area with respect to the Colorado River Basin and other hydrographic areas within the Colorado River Basin. Figure 3 shows detail of KSV highlighting the various local geographic features: Kane Springs Wash, the Meadow Valley Mountains, the Clover Mountains, the Delamar Mountains, and the locations of various local springs.

Geologic Framework

The general lithology of much of the mountains surrounding KSV is Tertiary volcanic rocks, although outcrops of underlying Paleozoic carbonate rocks can be found in the western portion of both the Delamar and Meadow Valley Mountains. The valley bottom is composed of Quaternary basin-fill deposits, which form soils that are fairly uniform throughout the valley.

KSV is located is located in the middle of the vast Carbonate-Rock Province, which underlies as much as 50,000 square miles in Nevada alone, but also stretches into Idaho, Utah, and California (Dettinger et al., 1995). The location of KSV in relation to the Carbonate Rock Province is shown in Figure 4.

The specific geology of the study area is shown in Figure 5, and geologic cross sections (indexed and shown in Figures 6 through 17) reveal the subsurface structure and lithology with important implications with respect to the occurrence and movement of groundwater through the carbonate rocks, which underlie the study area.

Based on examination of these cross-sections, the following conclusions can be drawn:

- Carbonate aquifer truncated by Clover Mountain calderas in upper portion of KSV.
- Considerable thickness of carbonate rock units (over 1 Km) in lower portion of KSV.
- Considerable faulting has occurred both within and along the margins of KSV.
- Faulting is mapped as occurring deep in the carbonate rocks implying the potential for deep groundwater occurrence and flow.
- Kane Springs Wash fault zone truncates carbonate rocks along the northern flank of the Meadow Valley Mountains.
- Basin-fill deposits in KSV are relatively thin.
- Thick sequences of carbonate rocks are present down Coyote Spring Valley and into the Muddy Springs Area, Hidden Valley, Garnet Valley, California Wash and Black Mountains Area.
- Considerable vertical faulting occurs in all these areas.

Hydrologic Conceptual Model

The groundwater environment in KSV includes both basin-fill deposits and fractured rock, which includes primarily volcanic and carbonate rocks.

Basin-Fill Deposits

In the absence of much direct information on the composition and extent of the basin fill, these deposits are assumed in this study to be composed principally of fine-textured sediments (silt and clay) across much of the basin, except immediately adjacent to the basin margins where alluvial fan deposits contain more coarse-textured sediments. The lithologic logs from the boreholes drilled near the mouth of the basin support the hypothesis of a primarily fine-textured basin fill (URS, 2006). The basin-fill deposits are the product of the erosion of the surrounding mountains, which are mainly volcanic in origin. These volcanic rocks readily weather to clay-size particles. In addition, both the Delamar and Meadow Valley Mountains are generally low in relief, and do not engender high-energy erosion environments capable of transporting large quantities of relatively coarser material (i.e., gravel, cobbles) onto the basin floor.

As a result, the basin-fill deposits in KSV are generally not favorable for the development of laterally continuous aquifer units, although these deposits are undoubtedly locally saturated over some depth interval at least seasonally.

Fracture-Rock

The fractured-rock groundwater medium in KSV is composed of both local volcanic and regionally occurring carbonate rocks. Volcanic rocks of the Clover and Delamar Mountains, which are composed of various ash-flow tuffs, rhyolite and basalt, typically do not support development of significant aquifer system because of heterogeneous intrinsic permeability and the general lack of continuous faulting and folding structures. Volcanic rocks, however, do provide local conduits for groundwater to recharge into deeper (carbonate) aquifer system. Carbonate rocks, which are highly fractured and laterally/vertically continuous, are the primary groundwater medium in KSV, and provide the principal means of inter-basin groundwater flow from KSV.

Groundwater Recharge to KSV

Walker (2006) performed an analysis of recharge to KSV that involved multiple means of estimating precipitation, and used two separate means to estimate recharge based on the precipitation estimates. Precipitation was estimated using vegetation mapping in two ways: (1) vegetation/precipitation/elevation correlations were developed resulting in precipitation estimates representative of sequential bands of elevation, and (2) vegetation communities were mapped to develop a map of the spatial distribution of precipitation irrespective of elevation. In addition, precipitation data from PRISM was used to develop a spatial distribution of precipitation across KSV as a third means of comparison.

Recharge was approximated both using a slightly modified version of the Maxey-Eakin approach (Maxey and Eakin, 1949), and through a water budget approach. For the water-budget approach, the areas of the basin where evapotranspiration was at least 12 inches, based on literature values (see Walker, 2006), were subtracted from a given precipitation distribution resulting in the amount of water available for infiltration or surface runoff. Subtracting estimates of surface runoff and discharge from local springs, resulted in estimates of groundwater recharge that are summarized in the following table.

Precipitation Estimation Method/Source	Total Precipitation (AF/yr)	Recharge Estimation Method	Recharge Estimate (AF/yr)	Recharge/Total Precipitation (percentage)
Vegetation Indicators as function of elevation	128,270	Maxey-Eakin	5,700	4
		Water-Budget	6,350	4
Vegetation Communities	118,668	Maxey-Eakin	5,300	4
		Water-Budget	6,600	5
PRISM-based	133,920	Maxey-Eakin	9,600	7
		Water-Budget	14,155	10
LVVWD (2001)[a]	140,218	Maxey-Eakin	6,757	4
		Water Budget	5,950	4
State Water Plan–1971[b]	80,000	–	500	0.6

a LVVWD (2001).

b Nevada Department of Natural Resources, Division of Water Resources. 1971. State of Nevada Planning Report

From these results, Walker (2006) estimated that the average annual recharge to groundwater in the KSV is on the order of 5,000 acre-feet/year (AF/yr).

It is concluded here that a value of 5,000 AF/yr is a reasonable estimate for average annual recharge based on:

- General consistency among different estimating approaches.
- Size of basin (232 square miles), which is considerable area over which to receive precipitation.
- Significant area within KSV that is of higher elevation (69 square miles > 5,000 ft, or 30% of basin)
- The various methods for estimating average annual precipitation results in a reasonable value of roughly 120,000 AF/yr, which translates to an average precipitation across the basin of approximately 9 inches/year, which is considered a reasonable estimate.
- An overall percentage of precipitation that becomes recharge (approximately 5 percent) is considered reasonable.

Groundwater Conditions

Figure 18 shows the locations of selected wells in the study area. A subset of these wells through which a vertical profile has been developed is shown in Figure 19. The vertical profile, in turn, is shown in Figure 20.

Key conclusions from the vertical profile in Figure 20 are as follows:

- Only the upper-most 1,000 to 2,000 feet of the aquifer is penetrated by existing wells. Accordingly, only a fraction of the carbonate rock is penetrated by existing wells based on published geologic cross sections that indicate that the carbonate units are typically 2-4 kilometers (6,500 – 13,000 feet) thick.
- Differences in lithology within screen interval influences water level.

Figure 21 shows the location of the test well and monitoring well installed in KSV relative to local geologic features; principally the Kane Spring Wash fault zone and the Willow Spring fault. Figure 21 also shows the location of a geologic cross section through the well site. The cross section is shown in Figure 22. The significance of the cross section is that it shows the vertical proximity of the Willow Spring fault relative to the test well KPW-1. During aquifer testing on KPW-1, a recharge boundary was encountered within the first hour of the test reflecting a higher transmissivity zone associated with the Willow Spring fault. Figure 23 shows the drawdown in monitoring well KMW-1. One of the Hantush-Jacob type curves used to calculate aquifer transmissivity and storage coefficient is also shown on the figure. The level portion of the curve clearly demonstrates a source of water to the well that truncates further drawdown.

Another important implication of the aquifer testing results based on Figure 23 is that the shape of the drawdown curve is indicative of a porous medium (i.e., there is no evidence of conduit or discrete fracture flow).

A summary of the aquifer test results are shown in the following:

Summary of Results From 7-Day Sustained Aquifer Test Pumping KPW-1 at 1,800 gpm

Data	Method*	Transmissivity (gal/day/ft)	Storage Coefficient	Source
KMW-1 drawdown	Hantush-Jacob (leaky-confined)	30,000	10^{-4}	URS (2006a)
	Jacob-Cooper (mid-time)	30,000	10^{-4}	Feast Geosciences**
	Jacob-Cooper (late-time)	240,000		Feast Geosciences
KMW-1 Recovery	Theis (mid-t/t')	95,000	--	URS (2006a)
	Theis (late-t/t')	240,000	--	URS (2006a)
	Jacob-Cooper (mid-t/t')	85,000	--	Feast Geosciences
	Jacob-Cooper (late-t/t')	236,000	--	Feast Geosciences
KWPW-1	Theis Recovery (late-t/t')	380,000	--	URS (2006a)

* Methods based on Lohman (1979)

** Feast Geosciences unpublished aquifer test analysis, 2006

Based on the aquifer test results, two values of transmissivity determined:

1. Representative of the "regional" aquifer between approximately 30,000 and 80,000 gallons per day per foot (gpd/ft).

2. Representative of higher transmissivity zone associated with the Willow Springs Fault of approximately 300,000 gpd/ft.

Figure 24 shows the location of local geologic structure affecting groundwater conditions in KSV. The hydraulic affect of these structures are apparent from the aquifer test and groundwater level data. Of note is evidence for the extension of the Kane Springs Wash fault zone southwestward into Coyote Spring Valley.

Figure 25 is a schematic diagram of Kane Springs Wash fault influence on groundwater levels in Coyote Spring Valley. Based on geologic logs of the wells obtained from Berger et al. (1988) and the most current water levels from December 2005 obtained from Southern Nevada Water Authority Central Data Repository, it is clear that there is a steep hydraulic gradient between these wells CE-VF-2 and CSVM-6. The Kane Spring Wash fault zone likely:

- Acts to impede but not inhibit groundwater flow across the fault zone.
- Has the potential to limit the northward advance of the cones of depression from pumping wells downgradient of the fault (as a function of distance – the closer the pumping to the fault, the less the limiting influence.)
- Has the potential to limit the southward advance of the cones of depression from pumping wells upgradient of the fault (as a function of distance from the fault).

Evidence of the influence of the fault zone is also shown on Figure 26, which depicts the spatial distribution of the most recent water levels on record for selected carbonate wells in the study area. Based on this map of water levels (Figure 26):

- Kane Springs Wash fault zone causes break in regional (carbonate rock) hydraulic gradient in Coyote Spring Valley.
- Upgradient of fault: Gradient "steeper"
- Downgradient of fault: Gradient "flatter"
- With a few exceptions (e.g., CSVM-5, CSV-2), carbonate groundwater levels are very similar generally everywhere downgradient of Kane Springs Wash fault zone.
- Implication of "flat" gradient is relatively high transmissivity across the southern half of the study area.
- Implication of relatively high transmissivity is high potential for regional groundwater flow

Figure 27 shows the spatial distribution of transmissivity values across the study area. The results on the figure are consistent with the water level data, which indicate that high transmissivity values are present across the study area.

Estimation of Groundwater Flow Through Kane Springs Valley

Groundwater flow through Kane Springs Valley was roughly approximated based on the following 1-D application of Darcy's Law:

$$Q = Tw\Delta h$$

where,

> Q = groundwater discharge across a given cross sectional area
>
> T = aquifer transmissivity
>
> w = aquifer width over which T is assumed representative
>
> Δh = horizontal component of hydraulic gradient perpendicular to the aquifer width

The rationale for determining representative thickness of the carbonate aquifer underlying KSV is based on the following:

- Published geologic cross sections which indicate:
  - Considerable thickness of carbonate rock in vicinity of KSV (> 3,000 feet).
  - Considerable faulting has occurred both within and along the margins of KSV.
  - Vertical faulting is mapped across (deep) all carbonate rock in KSV implying the potential for deep groundwater flow through this basin.
- Groundwater temperature from KPW-1 is very hot (~ 130 °F) and deuterium concentrations light (-104) indicating circulation of deep groundwater under KSV.
- Published data on carbonate wells elsewhere in Nevada indicate the potential for carbonate wells to exceed depths of 5,000 feet (Dettinger et al., 2005, Table 6).

It is therefore concluded that 3,000 feet is a reasonable, and likely conservative, estimate for the thickness of the carbonate aquifer in KSV.

Based on an assumed representative value of aquifer thickness of 3000 feet, a representative value for aquifer transmissivity was determined using the aquifer test results as a starting point. Specifically, using the relationship,

Transmissivity = aquifer thickness x hydraulic conductivity

the following table runs through the procedure followed to develop values of aquifer transmissivity that reflect the total aquifer thickness.

Portion of Aquifer	Calculated Range of T (gpd/ft)	Aquifer Thickness Tested (Based on KPW-1 Construction, ft)	Calculated Hydraulic Conductivity (ft/day)	Assumed Total Aquifer Thickness (ft)	Revised Transmissivity (Based on total aquifer thickness, gpd/ft)	Assumed Representative Value of Transmissivity (gpd/ft)
Bulk Aquifer	30,000 – 80,000	1,000	4 – 9	3,000	90,000 – 200,000	150,000
Local Fault Zone	300,000	1,000	40	3,000	900,000	900,000
* From 8-day aquifer test at KPW-1						

The next step is to determine the regional horizontal component of hydraulic gradient that would be representative of the gradient driving groundwater flow into the KSV.

The bases for estimating regional horizontal component of hydraulic gradient are presented in the following table.

Location	Representative Water Level Elevation (ft amsl)*	Distance Between Locations (ft)				
		Pahranagat Springs	CSVM-3	KPW-1	CSVM-4	CE-VF-2
Pahranagat Springs**	3190	0	68,500	96,500	96,500	132,000
CSVM-3	2206	68,500	0	37,190	36,060	66,130
KPW-1	1879	96,500	37,190	0	10,760	56,450
CSVM-4	1874	96,500	36,060	10,760	0	45,950
CE-VF-2	1857	132,000	66,130	56,450	45,950	0
* Well data from December 2005						
** Approximated by elevation of Lower Pahranagat Lake						

In the absence of readily available data for groundwater level in the carbonate rock in the Pahranagat Springs area, the elevation of Lowe Pahranagat Lake was used as a general approximation as it represents a lower area collecting discharge from regional carbonate springs.

The regional horizontal component of hydraulic gradient was subsequently estimated by considering the change in water level elevation between Pahranagat Springs, CSVM-3, and CE-VF-2:

$$\text{Pahranagat Springs/CSVM-3} = (3190 - 2206)/68{,}500 = 0.014$$

$$\text{CSVM-3/CE-VF-2} = (2206 - 1857)/66{,}130 = 0.0053$$

The gradient between Pahranagat Springs and CSVM-3 is considered to be too steep to be representative of flow into KSV. It is therefore concluded that a representative value for the regional hydraulic gradient is on the order of 0.005

In estimating the hydraulic gradient for groundwater flow from KSV it was assumed the gradient along Willow Spring fault would be most representative and roughly approximated by the change in water level elevation between

$$\text{KPW-1/CSVM-4} = (1879 - 1875)/10{,}760 \approx 0.0005$$

The final step in the determination of groundwater flow through KSV is the approximation of representative values of aquifer width through which groundwater flows into and out of the KSV. Assuming flow through carbonate rocks, the inflow width of aquifer is defined as being perpendicular to assumed regional hydraulic gradient where carbonate rocks mapped within KSV (approximately 3 miles). Figure 28 shows the location and length of the width of aquifer identified as being representative of groundwater flow into KSV.

The width of the aquifer though which groundwater flows out of the aquifer is defined as being perpendicular to the assumed direction of local flow from KSV, and parallel and controlled by the Kane Springs Wash fault zone.

Due to the influence of the Willow Spring fault on the aquifer test results, two components to the local aquifer width are considered:

- Width representative of fault zone transmissivity (approximately 0.5 miles);
- Width of aquifer representative of transmissivity unaffected by fault zone (approximately 3.5 miles).

The location and length of the representative width of the aquifer through which groundwater flows out of KSV is shown on Figure 29.

With values for all of the parameters required to apply the Darcy's Law approach, the approximation of the volumetric flux of groundwater through KSV is summarized in the following table.

Groundwater Flow Component	Transmissivity (gpd/ft)	Aquifer Width (ft)	Hydraulic Gradient	Calculated Volumetric Groundwater Flow (AF/yr)	Volumetric Groundwater Flow (rounded down to nearest 1,000 AF/yr)
Regional Groundwater flow into Kane Springs Valley	150,000	15,840	0.005	13,300	13,000
Groundwater outflow from Kane Springs Valley into Coyote Springs Valley	150,000	18,480	0.005	15,500	15,000
	900,000	2,640	0.0005	1,300	1,000
Combined Groundwater Outflow from Kane Springs Valley	--	--	--	16,800	16,000

Based on the resulting values of volumetric groundwater flow, the following summary of groundwater inflow and outflow from KSV was developed:

Inflow to Kane Springs Valley:

Regional groundwater flow.. 13,000 AF/yr

Recharge within Kane Springs Valley*... 5,000 AF/yr

Total groundwater inflow to Kane Springs Valley .... 18,000 AF/yr

Outflow from Kane Springs Valley:

Local groundwater discharge into Coyote Spring Valley .... 16,000 AF/yr

* based on analysis by Walker (2006)

Clearly the inflow estimate does not balance with the estimate of outflow, but the difference is within about 10 percent, and reflects the uncertainty in parameter values and the applicability of the approach. In particular, the aquifer thickness is likely significant, but unknown.

However, it is concluded that:

- At least approximately 15,000 AF/yr flows through the aquifer system of KSV.
- KSV perennial yield, however, is on the order of 5,000 AF/yr based on recharge analysis.

This conclusion is shown conceptually on Figure 30.

Impact Analysis

The impacts analysis focused on the assessment of potential effects of lowering groundwater levels on local permitted points of diversion and local and regional springs

Permitted Groundwater Points of Diversion

Complex aquifer conditions in KSV (local presence of fault structures that both enhance and impede groundwater flow), multidimensional groundwater flow, together with limited spatial distribution of data on water levels and aquifer parameters, make meaningful predictions of groundwater level decline problematic. Accordingly, a simple analytical approach, which most likely over estimates resulting groundwater declines, is applied here.

Specifically, the analytical solution for transient groundwater flow to well developed by Theis (1935) is applied to approximate "worst case" water level declines within reasonable distance (~ 10 miles) from pumping well in KSV. Theis (1935) provides the transient solution to the partial differential equation for the radial flow to pumping well, arranged to solve for drawdown (s), as follows:

$$s = \frac{Q}{4\pi T} \int_{u}^{\infty} \frac{e^{-u} du}{u}$$

where, Q = pumping rate

T = aquifer transmissivity

and,

$$u = \frac{r^2 S}{4Tt}$$

where, r = the radial distance from the pumping well

S = storage coefficient

t = time since pumping began

In applying the Theis solution to determine the lateral extent of the cone of depression from a point of hypothetical pumping in KSV, the following general approach was followed. First, the Theis-predicted water level declines at distances from the pumping well were compared to locations of the nearest existing permitted groundwater points of diversion. Second, the resulting groundwater declines were assessed as to whether they would impair the permit (e.g., assess if predicted water level decline would dewater an existing well at a permitted point of diversion).

The Theis solution assumes an ideal porous medium consisting of an aquifer of homogenous properties, including isotropic permeability, over infinite extent. In addition the application for the impact analysis assumed the following:

- Pumping from a single well at 3,000 gpm (5,000 AF/yr) for 100 years.
- Location of pumping well at KPW-1
- Values of input parameters based on KSV aquifer test results.

Using the Theis solution to predict long-term drawdowns as a result of pumping from KSV will overestimate the predicted water level declines for the following reasons:

- The approach assumes that there is no local or regional hydraulic gradient, which would restrict propagation of the cone of depression both lateral to the horizontal orientation of the gradient and downgradient of the pumping well (i.e., the resulting circular cone of depression extends further downgradient and in directions perpendicular to the local natural direction of groundwater flow).

- The resulting circular cone of depression is also in contradiction with the probable effects of both the Willow Spring fault (positive boundary) and the Kane Springs Wash fault zone (negative boundary), which would ultimately impede the propagation of the cone of depression.
- Single pumping well concentrates drawdown at a point. Less drawdown would occur at same distance from the pumping well if pumping divided among multiple wells spaced at least 1 mile or more apart.

Based on the following values for the input parameters:

Q = 3,000 gpm

$S = 10^{-4}$

t = 100 years

the predicted drawdowns for two different values of transmissivity are as follows:

Transmissivity (gpd/ft)	Predicted drawdown at distance = r (ft)	
	r = 5000	r = 50,000
150,000	30	20
300,000	16	11

A transmissivity value of 300,000 gpd/ft is representative of the local aquifer conditions affected by the Willow Spring fault. However, over 100 years, a lower value of transmissivity may be more applicable. Accordingly, results for 150,000 gpd/ft are presented. Using a value of 50,000 gpd/ft was not considered representative of long-term pumping at the KPW-1 location.

The permitted points of diversion within 10 miles are identified on Figure 31.

Based on the results, wells 10 miles away from KPW-1 location would experience a maximum additional water level decline of between 10 and 20 feet. Wells greater than 10 miles away from KPW-1 would experience less decline.

This level of additional drawdown is not considered to be deleterious. Because of the inherent assumptions in the Theis solution (i.e., homogenous aquifer of infinite extent), the use of these results to predict potential reductions in downgradient regional spring flow is inappropriate because it the method overestimates water level declines at greater distances.

Local Springs

Based on field observations, permitted local springs in KSV represent groundwater flowing through the surrounding upland areas that are not connected to the regional carbonate aquifer. Accordingly, pumping from the carbonate aquifer locally within KSV would not affect the discharge from these springs.

Regional Springs

The approach to assessing potential impacts to regional springs generally consisted of conducting a review of water chemistry and hydraulic data, and published geologic interpretations to assess the potential linkage between groundwater withdrawals in KSV and the discharge of Muddy River Springs and Rodgers/Blue Point Springs.

Figure 32 repeats the spatial distribution of the most recent groundwater level elevations in selected carbonate wells within study area and Figure 33 presents hydrographs for selected carbonate wells in the study area.

Based on Figures 32 and 33, the following conclusions can be drawn:

- Groundwater levels progressively lower from north to south across the study area, supporting concept of generally southerly groundwater flow in regional carbonate aquifer.
- Kane Springs Wash fault zone causes a break in the regional hydraulic gradient ("steeper" to the north, "flatter" to the south).
- Regardless of fault, there is a general trend of rising groundwater levels since spring of 2005 in most wells (less so in wells near Arrow Canyon Well).
- Similar water level trend implies regional influence on carbonate aquifer.

- Flat hydraulic gradient south of KSW fault indicative of fairly homogeneous distribution of high aquifer transmissivity.

- High aquifer transmissivity supports high potential for substantial groundwater flow through the carbonate aquifer within the study area.

Figure 34 repeats the vertical profile through selected carbonate wells in study area and shows the conceptual location of the Kane Springs Wash fault zone.

Based on Figure 33 the following conclusions can be drawn:

- Wells down downgradient of KSW fault have similar groundwater levels despite variable screen intervals.

- Implication is that the aquifer is highly transmissive and fairly homogeneous in this regard with depth (suggesting isotropic permeability).

- Water levels in wells at elevations above top of rock indicative of groundwater under pressure, and therefore driven by deep regional gradients.

This hydrologic assessment also included a geochemistry component that is presented under separate cover in CH2M HILL (2006). The key points developed in that report with respect to regional groundwater flow are summarized as follows:

- Deep carbonate aquifer groundwater flows from north to south across the study area; specifically, from Pahranagat Valley and Kane Spring Valley into Coyote Spring Valley, and from there to both the Muddy River Springs Area and into Hidden Valley and Garnet Valley.

- Discharge to Muddy River Springs is comprised of approximately 60 percent regional carbonate groundwater.

- The remaining 40% of the discharge is comprised of water of non-carbonate aquifer origin. This 60/40 split of carbonate to non-carbonate origin groundwater is prevalent in wells throughout the downgradient portion of the carbonate aquifer within the study area (i.e., Garnet Valley and California Wash, in addition to the Muddy River Springs). The implication of this prevalence is that groundwater flowing through the regional carbonate aquifer in Coyote Spring Valley does not necessarily have a preferred flow path toward the Muddy River Springs, but also flows into Garnet Valley via Hidden Valley. This conclusion regarding the origin of carbonate aquifer groundwater in Garnet Valley is supported by C-14 data from GV wells. Specifically, the C-14 data imply that the groundwater in Garnet Valley is very old (29,000 years). Therefore, a more local source of this water in GV (e.g., from the Sheep Range) at least in any significant proportion, is unlikely.

- Discharge at Rogers and Blue Point Spring is comprised of roughly 40% regional carbonate groundwater.
- The remaining 60 percent of the discharge is comprised of water of non-carbonate aquifer origin.
- Rogers and Blue Point Springs are not the terminus of all carbonate groundwater that by-passes the Muddy River Springs.
- Groundwater movement between basins is on the order of thousands of years, consistent with the low hydraulic gradients observed.

The generalized regional groundwater flow in the study area is summarized in Figure 35.

Based on the combination of water chemistry (CH2M HILL, 2006) and hydraulic data, and published geologic interpretations the following fundamental conclusions and other considerations are presented:

- It is understood that the carbonate aquifer within the study area underlies hundreds of square miles and likely extends to depths of several thousand feet. The implication is that there is a considerable volume of groundwater flowing through this aquifer system within the study area.
- The carbonate rock aquifer appears to be highly transmissive across much of the study area enabling movement of significant amounts of groundwater.
- Areas of high transmissivity are not limited to the Arrow Canyon area that leads to the Muddy River Springs. Accordingly, a preferred groundwater flow path specifically from Coyote Spring Valley toward these springs can only currently be assumed.

- The "flat" hydraulic gradients over large areas caused by high transmissivity result in poorly defined groundwater flow paths in the southern portion of the study area.
- Flat hydraulic gradient does not necessarily imply that there is little groundwater movement through the aquifer as evidenced by large discharge from Muddy River Springs downgradient of area of high transmissivity.
- Within the KSV, the Kane Springs Wash fault zone will have the effect of concentrating the resulting drawdown from local pumping to within KSV.
- In Coyote Spring Valley, the Kane Spring fault zone will likely have the effect of impeding the propagation of a cone of depression originating within KSV from migrating south.
- Approximately 40 percent of the discharge of the Muddy River Springs is comprised of water that is not from the regional carbonate aquifer (i.e., the discharge represents both carbonate and non-carbonate groundwater that have mixed along the flow path leading to the springs. The implication is that if it is assumed that the regional carbonate aquifer only contains a finite amount of ancient water that has entered the system many miles to the north of the study area, then 40 percent of the water in the carbonate rock flow system is missed because it is derived from non-carbonate sources (e.g., recharge through the alluvium). This conclusion is supported both by deuterium ratios and by major ion chemistry that indicates non-carbonate signatures are observed in wells completed in carbonate rock (indicating that the groundwater from those wells has flowed through media other than carbonate rock).

Lastly, pumping 5,000 AF/yr from KSV should not affect downgradient regional springs because local recharge in KSV is on the order of 5,000 AF/yr. However, roughly 10,000 AF/yr over the local amount recharged is estimated to flow into Coyote Spring Valley from KSV.

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FIGURE 1
Kane Springs Valley Study Area

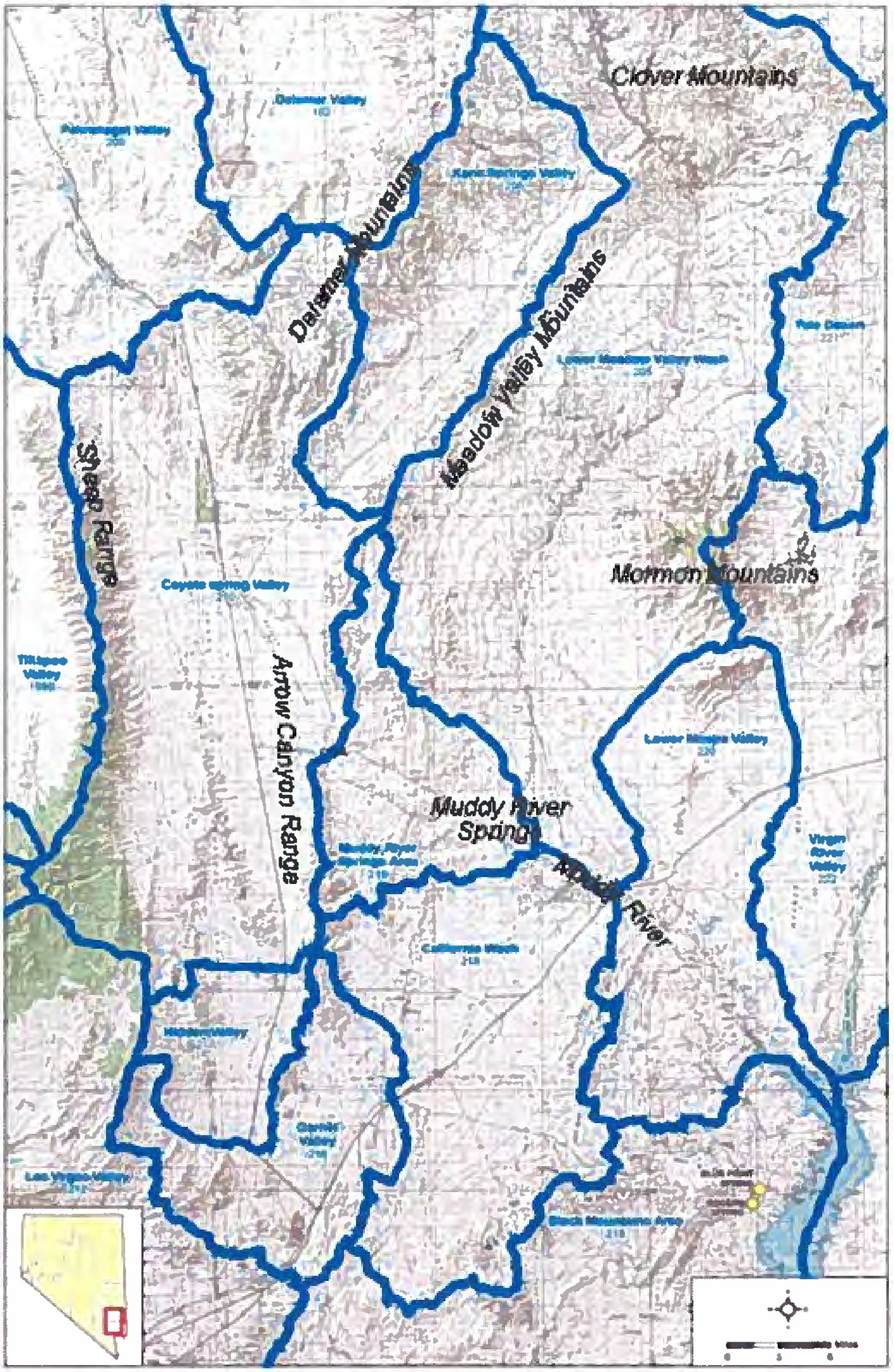


FIGURE 2
Location of Kane Springs Valley (206) With Respect to Colorado River Basin

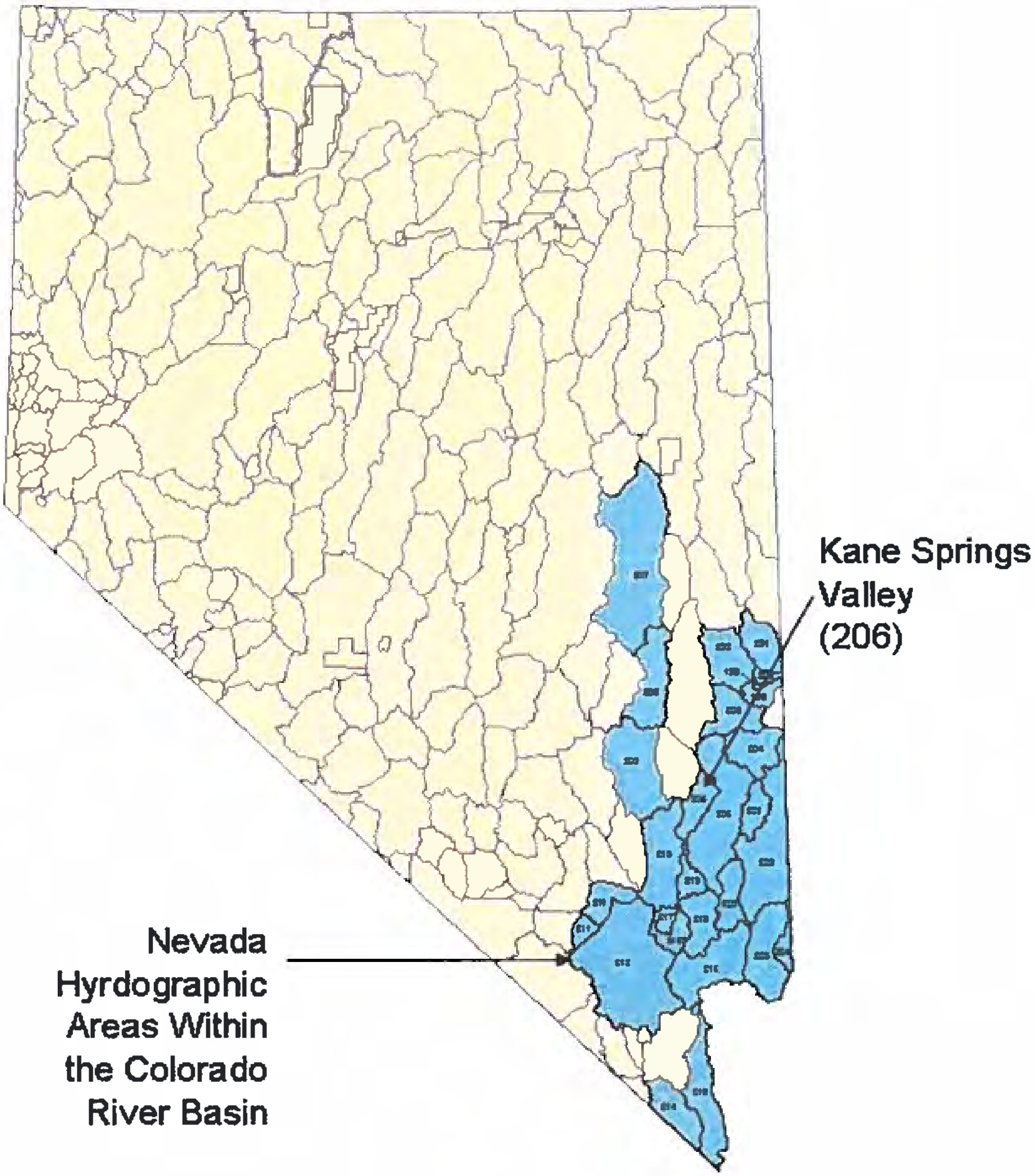
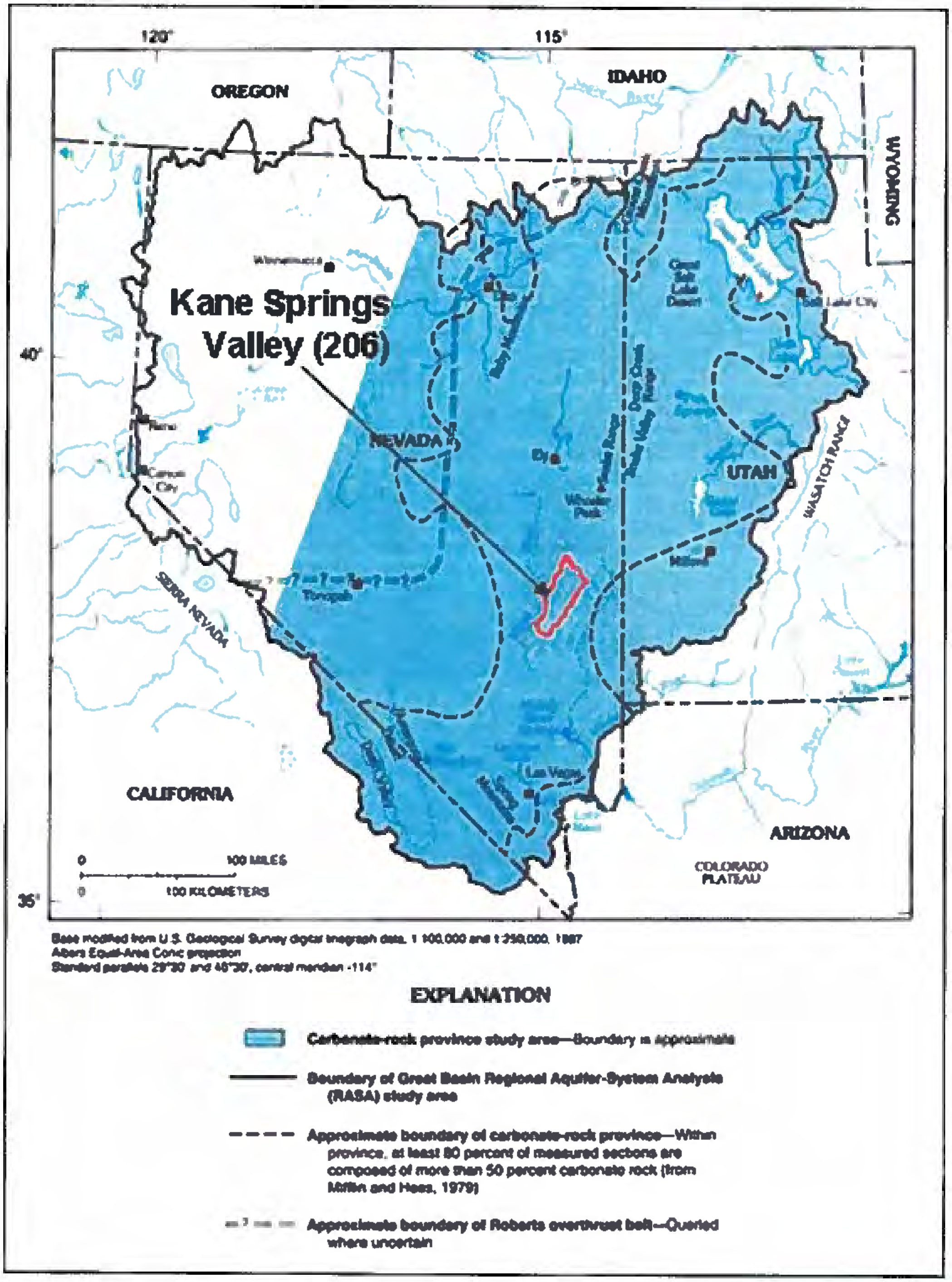


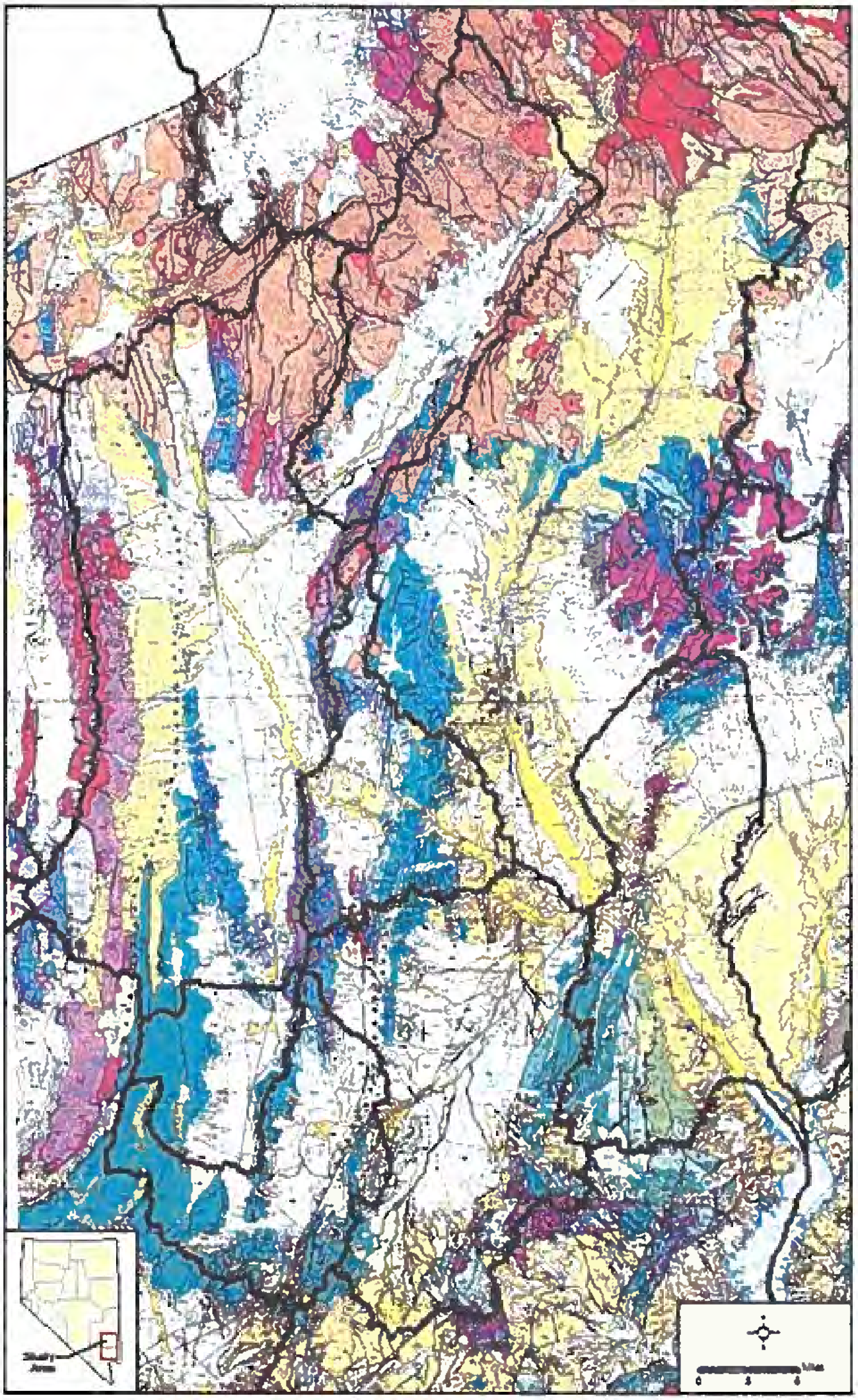
FIGURE 3
Kane Springs Valley (206) Hydrographic Area

FIGURE 4
Kane Springs Valley In Relation to Carbonate-Rock Province



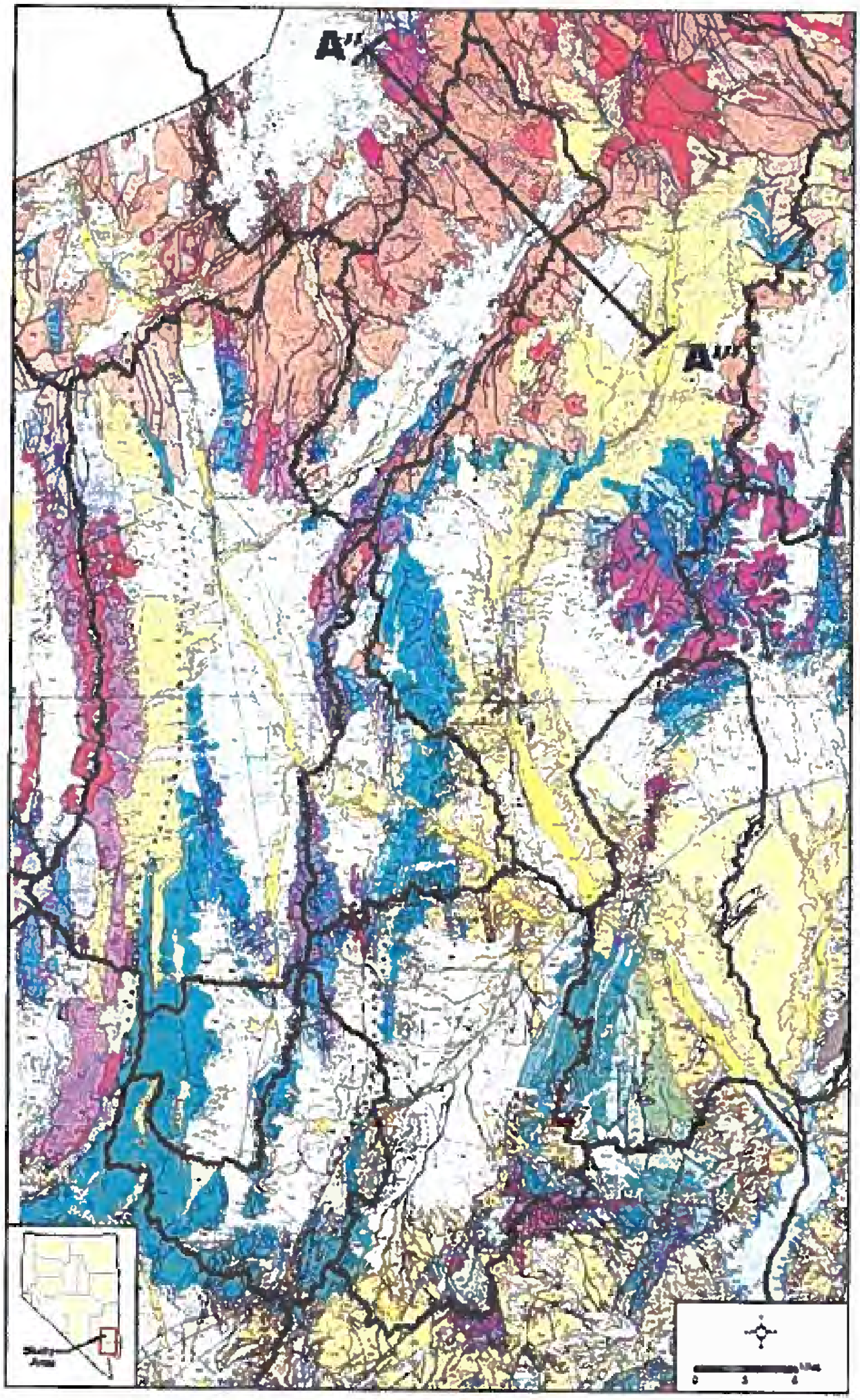
Modified from: Prudic, David E., James Harrill and Thomas Burbey. 1995. Conceptual Evaluation of Regional Ground-Water Flow in the Carbonate-Rock Province of the Great Basin, Nevada, Utah, and Adjacent States. US Geological Survey Professional Paper 1409-D.

FIGURE 5
Geologic Map of Parts of the Colorado River Basin



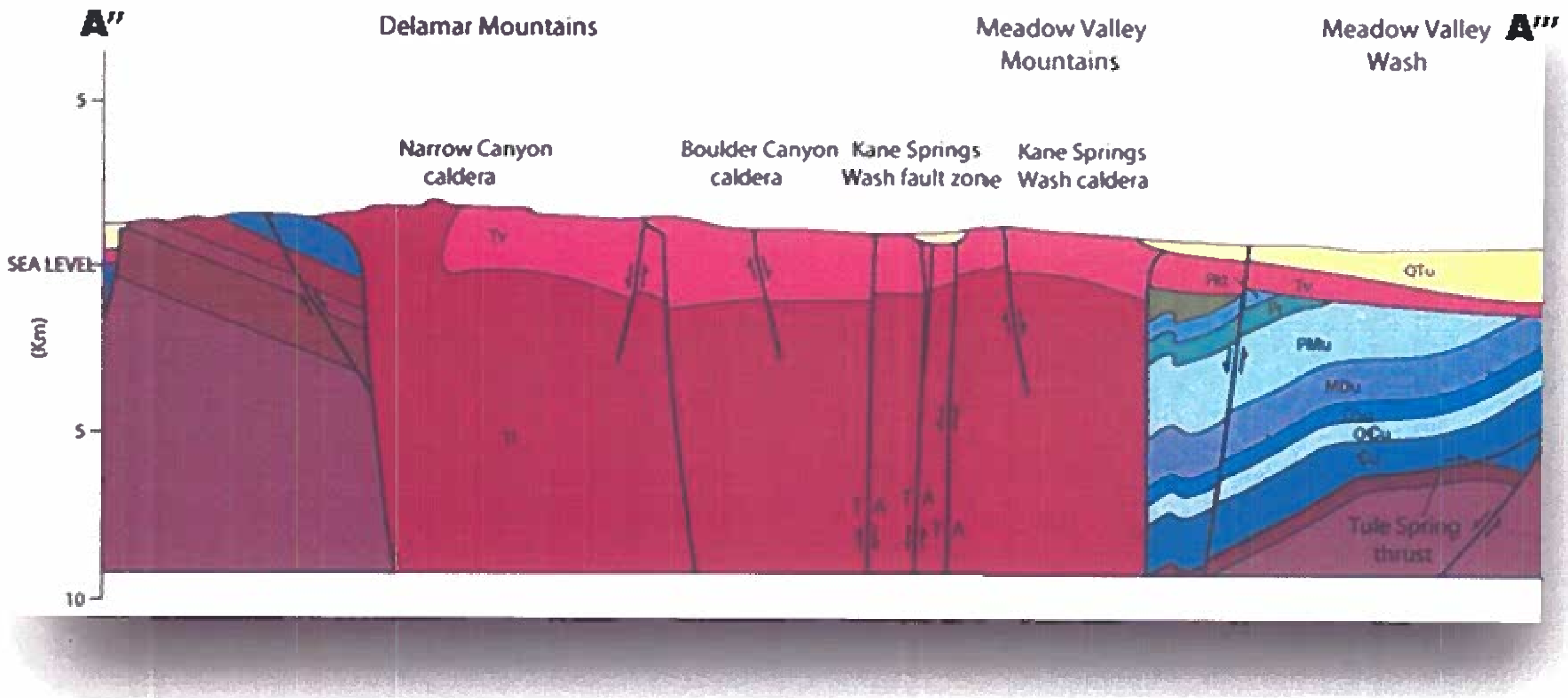
Source: Page, W. R., G. Dixon, P. Rowley, and D. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

FIGURE 6
Location of Geologic Cross Section A"-A'"



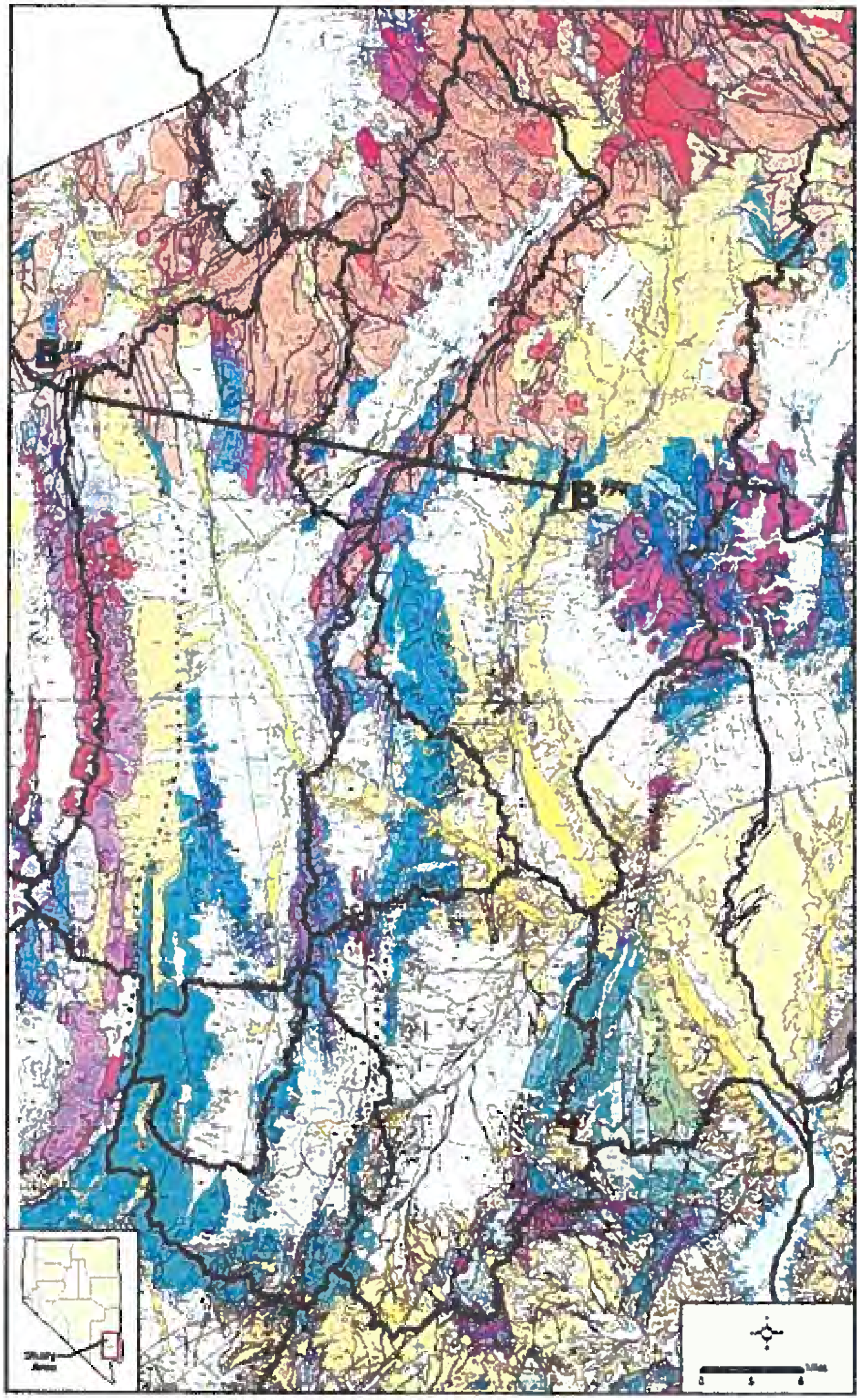
Source: Page, W.R., G. Dixon, P. Rowley, and R. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

FIGURE 7
Geologic Cross Section A"-A'"



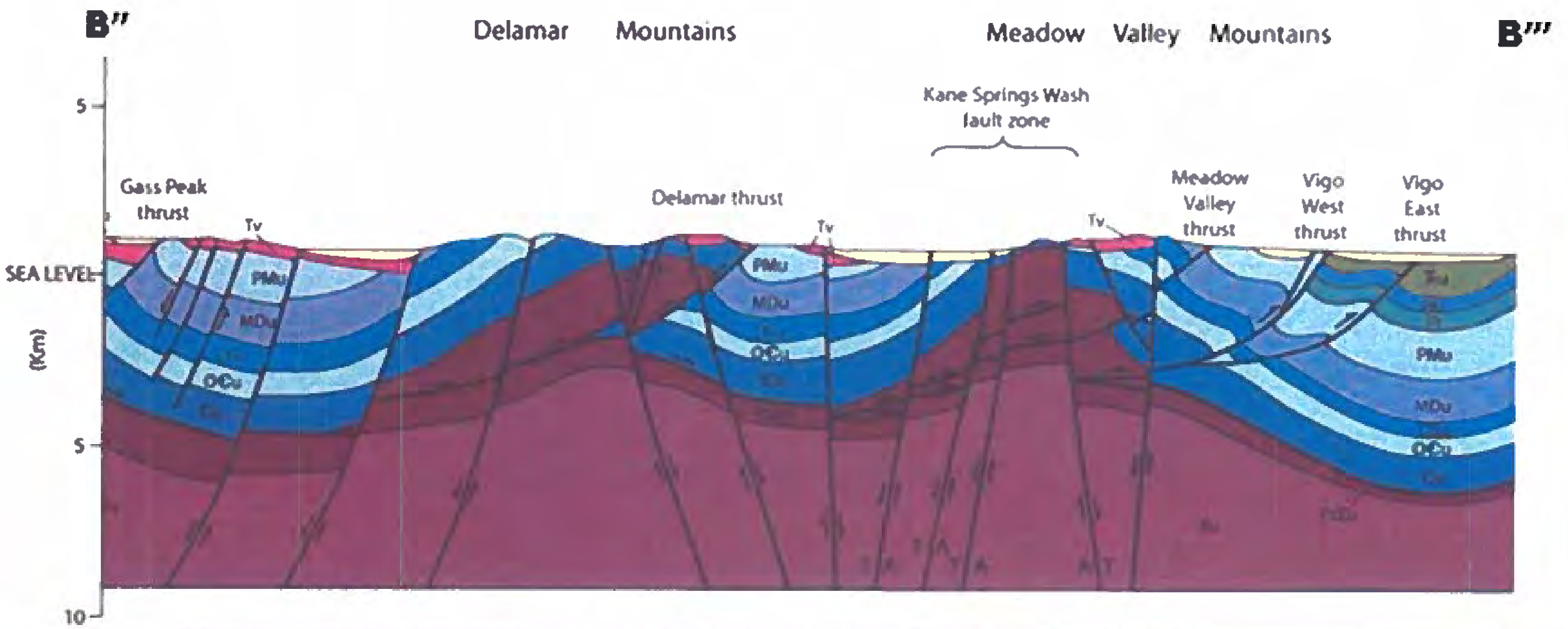
Source: Page, W.R., D.S. Schreirer, and V.E. Langenheim. 2006. Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems. Nevada, Utah, and Arizona. U.S. Geological Survey Open-File Report 2006 – 1040.

FIGURE 8
Location of Geologic Cross Section B''-B'''



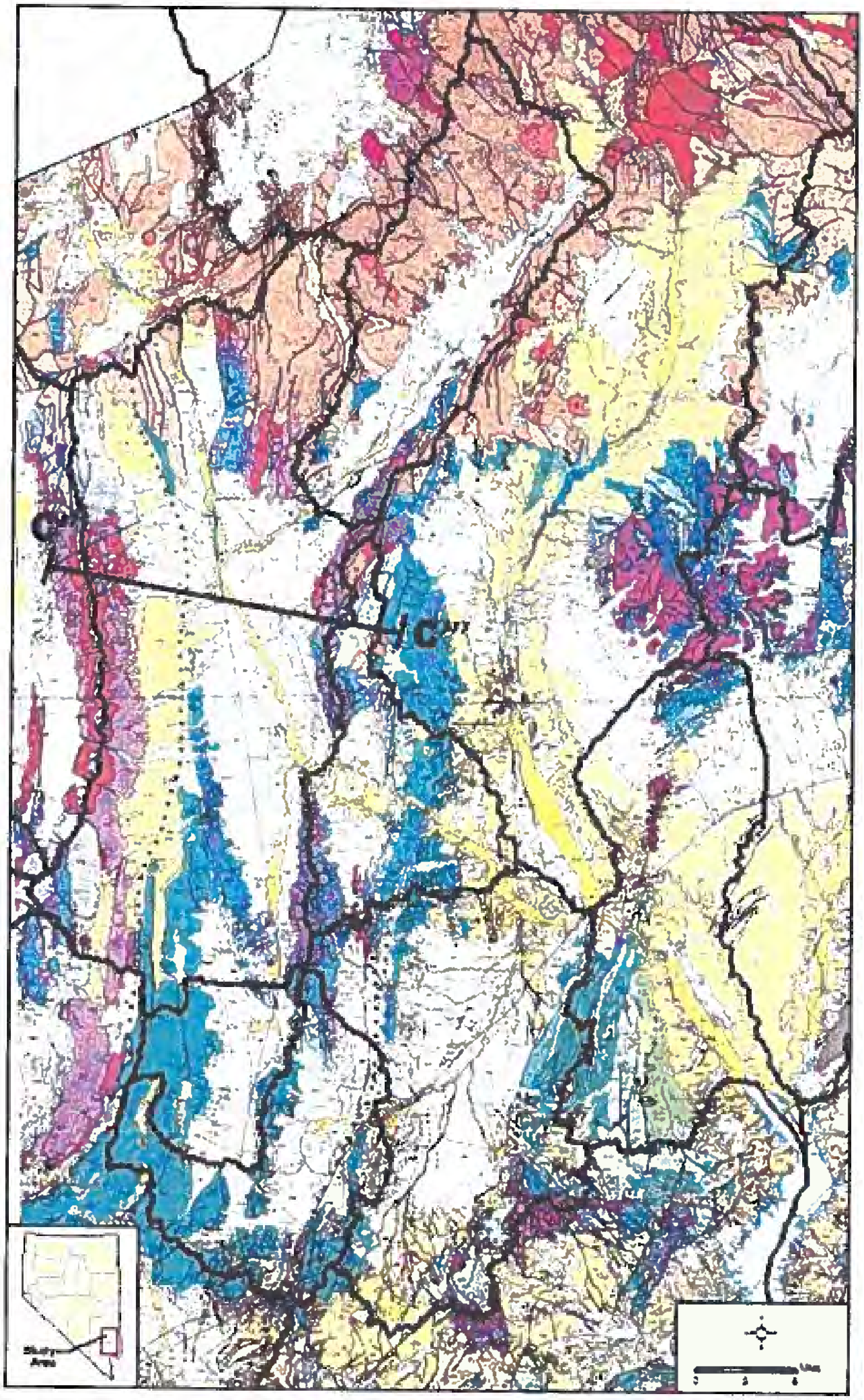
Source: Page, W.R., G. Dixon, P. Rowley, and R. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

FIGURE 9
Geologic Cross Section B''-B'''



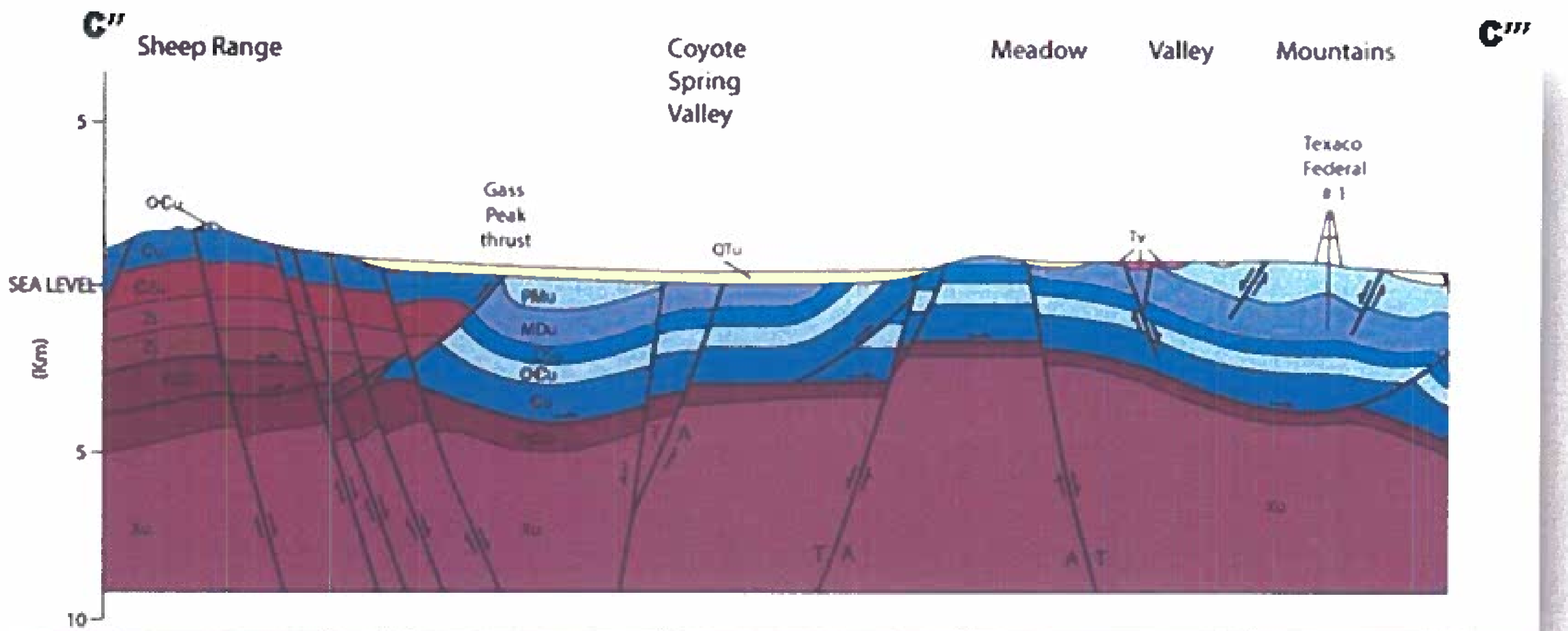
Source: Page, W.R., D.S. Schreirer, and V.E. Langenheim. 2006. Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems. Nevada, Utah, and Arizona. U.S. Geological Survey Open-File Report 2006 – 1040.

FIGURE 10
Location of Geologic Cross Section C"-C'"



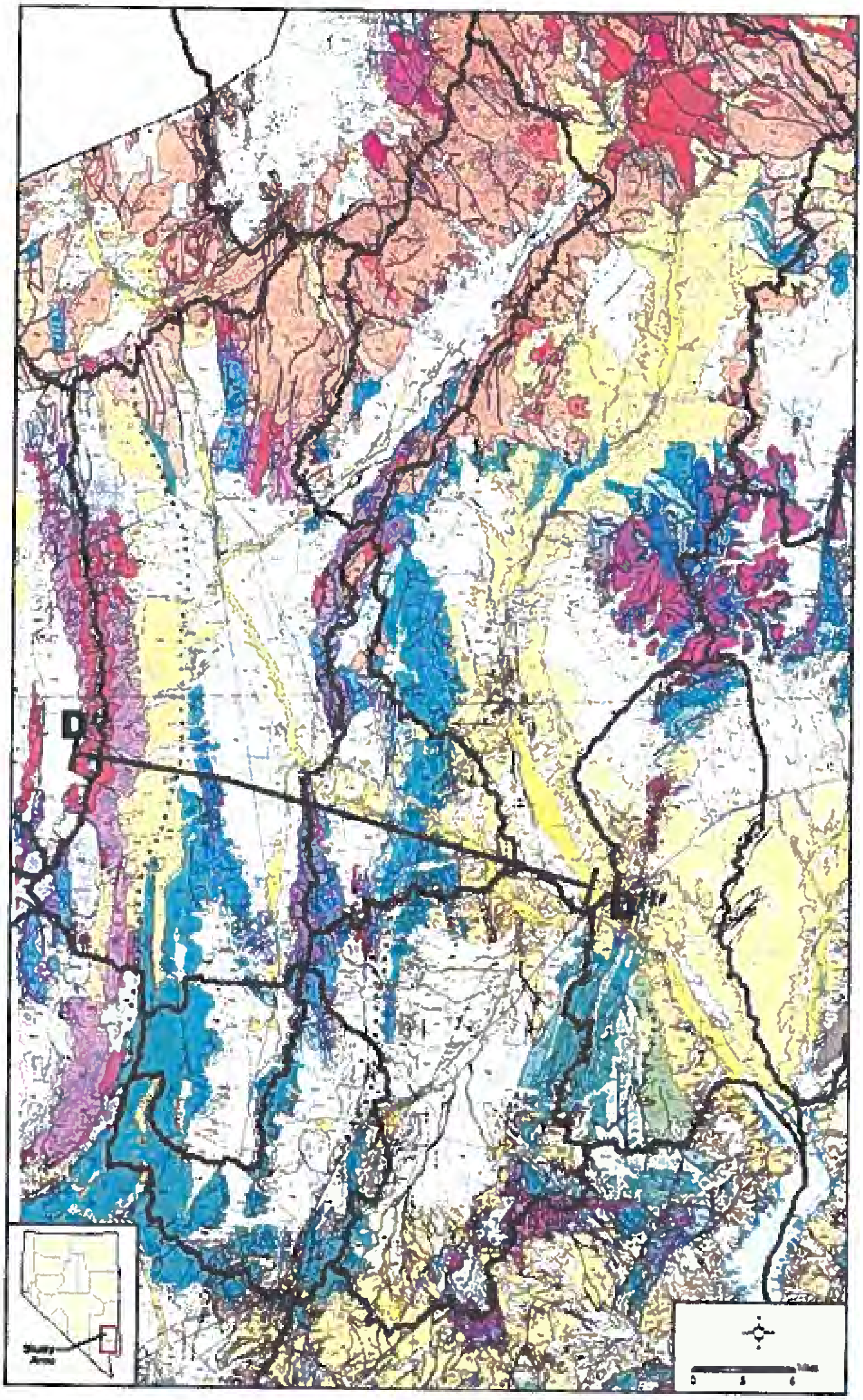
Source: Page, W.R., G. Dixon, P. Rowley, and R. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

FIGURE 11
Geologic Cross Section C"-C'"



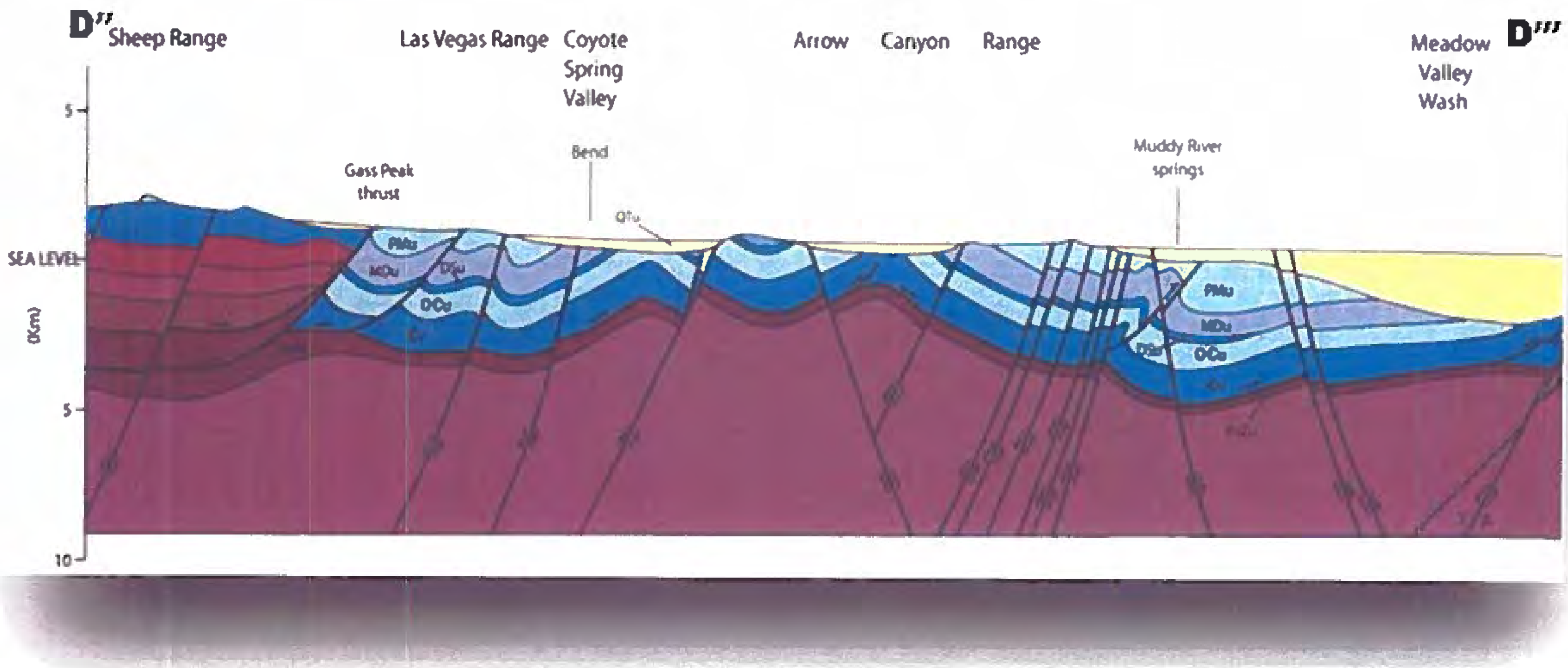
Source: Page, W.R., D.S. Schreirer, and V.E. Langenheim. 2006. Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems. Nevada, Utah, and Arizona. U.S. Geological Survey Open-File Report 2006 – 1040.

FIGURE 12
Location of Geologic Cross Section D"-D'"



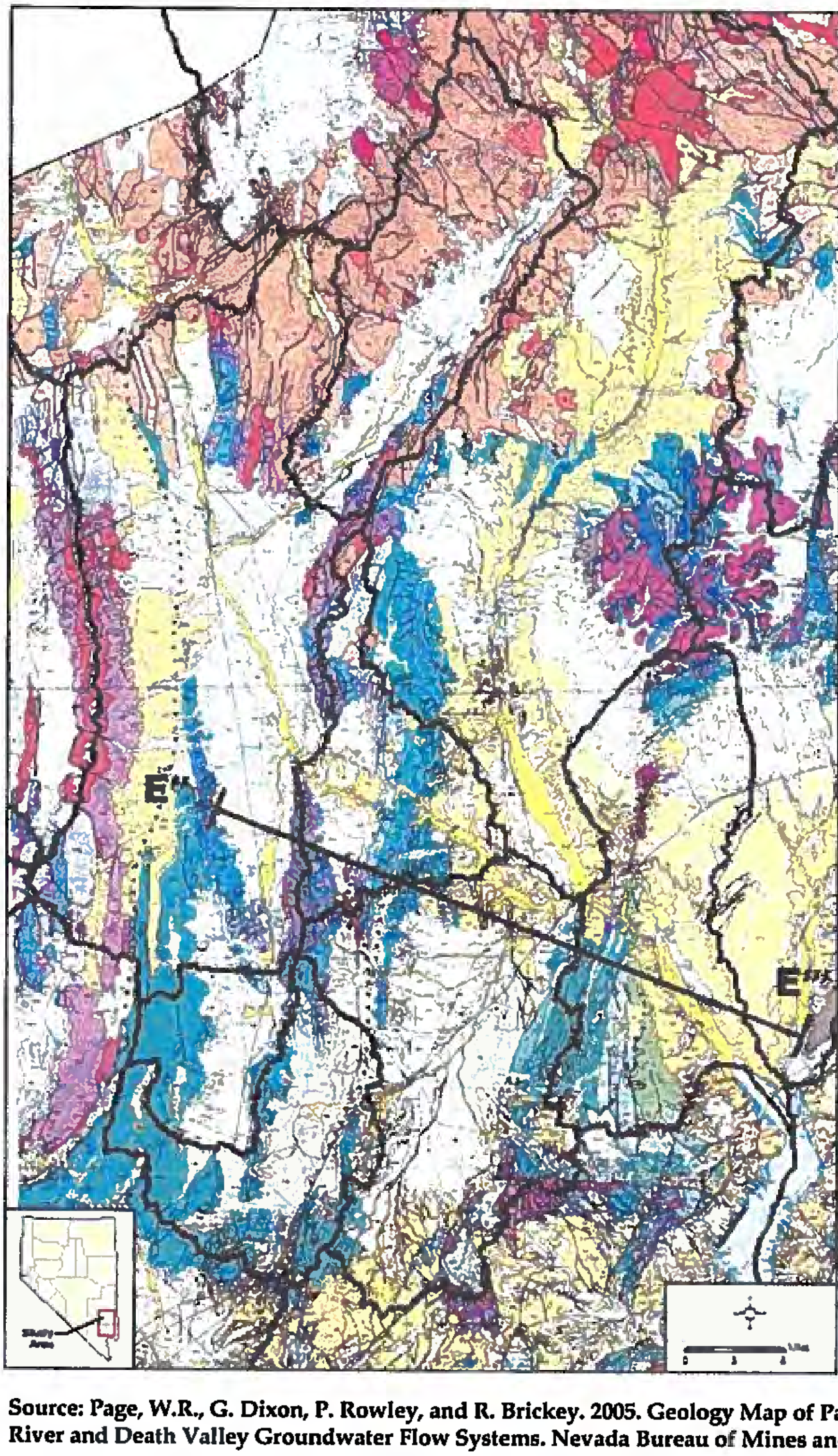
Source: Page, W.R., G. Dixon, P. Rowley, and R. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

FIGURE 13
Geologic Cross Section D"-D"'



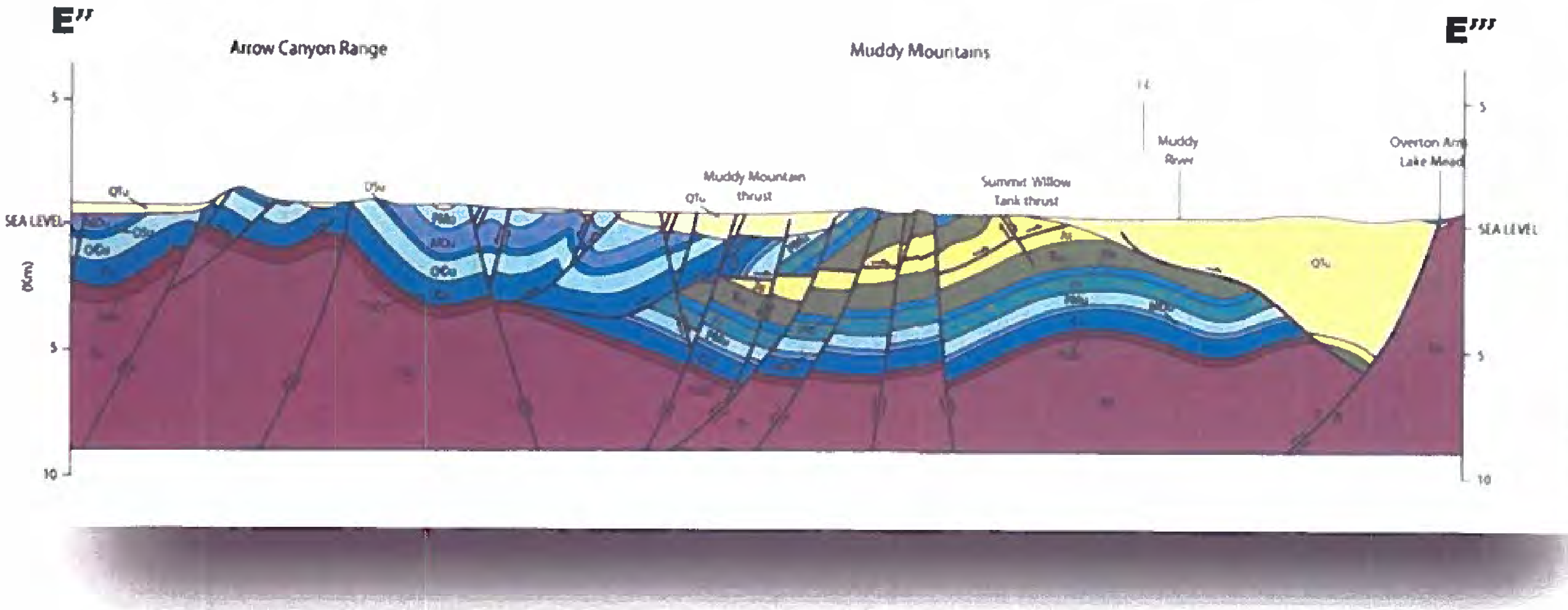
Source: Page, W.R., D.S. Schreirer, and V.E. Langenheim. 2006. Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems. Nevada, Utah, and Arizona. U.S. Geological Survey Open-File Report 2006 – 1040.

FIGURE 14
Location of Geologic Cross Section E"-E'"



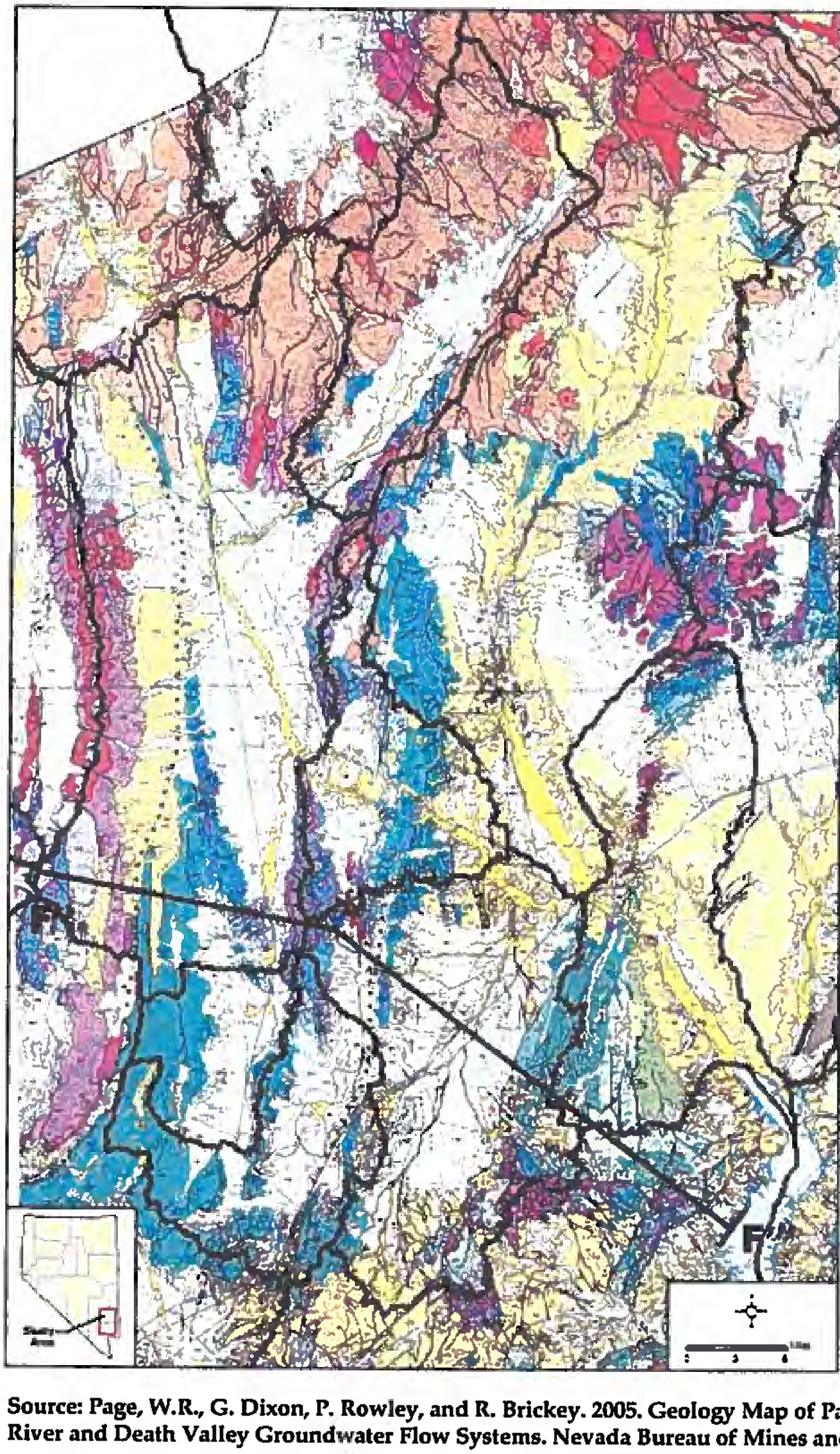
Source: Page, W.R., G. Dixon, P. Rowley, and R. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

FIGURE 15
Geologic Cross Section E''-E'''



Source: Page, W.R., D.S. Schreirer, and V.E. Langenheim. 2006. Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems. Nevada, Utah, and Arizona. U.S. Geological Survey Open-File Report 2006 – 1040.

FIGURE 16
Location of Geologic Cross Section F"-F'"

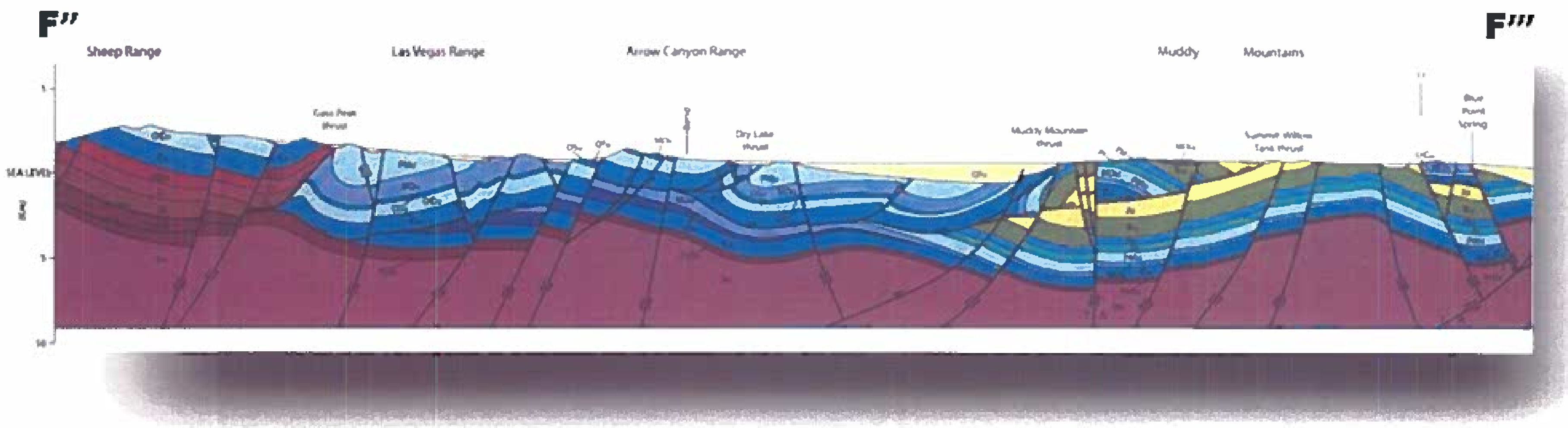


Source: Page, W.R., G. Dixon, P. Rowley, and R. Brickey. 2005. Geology Map of Parts of the Colorado, White River and Death Valley Groundwater Flow Systems. Nevada Bureau of Mines and Geology Map 150.

SE ROA 41304

JA_11601

FIGURE 17
Geologic Cross Section F"-F'"



Source: Page, W.R., D.S. Schreirer, and V.E. Langenheim. 2006. Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems. Nevada, Utah, and Arizona. U.S. Geological Survey Open-File Report 2006 – 1040.

FIGURE 18
Location of Selected Wells in Study Area

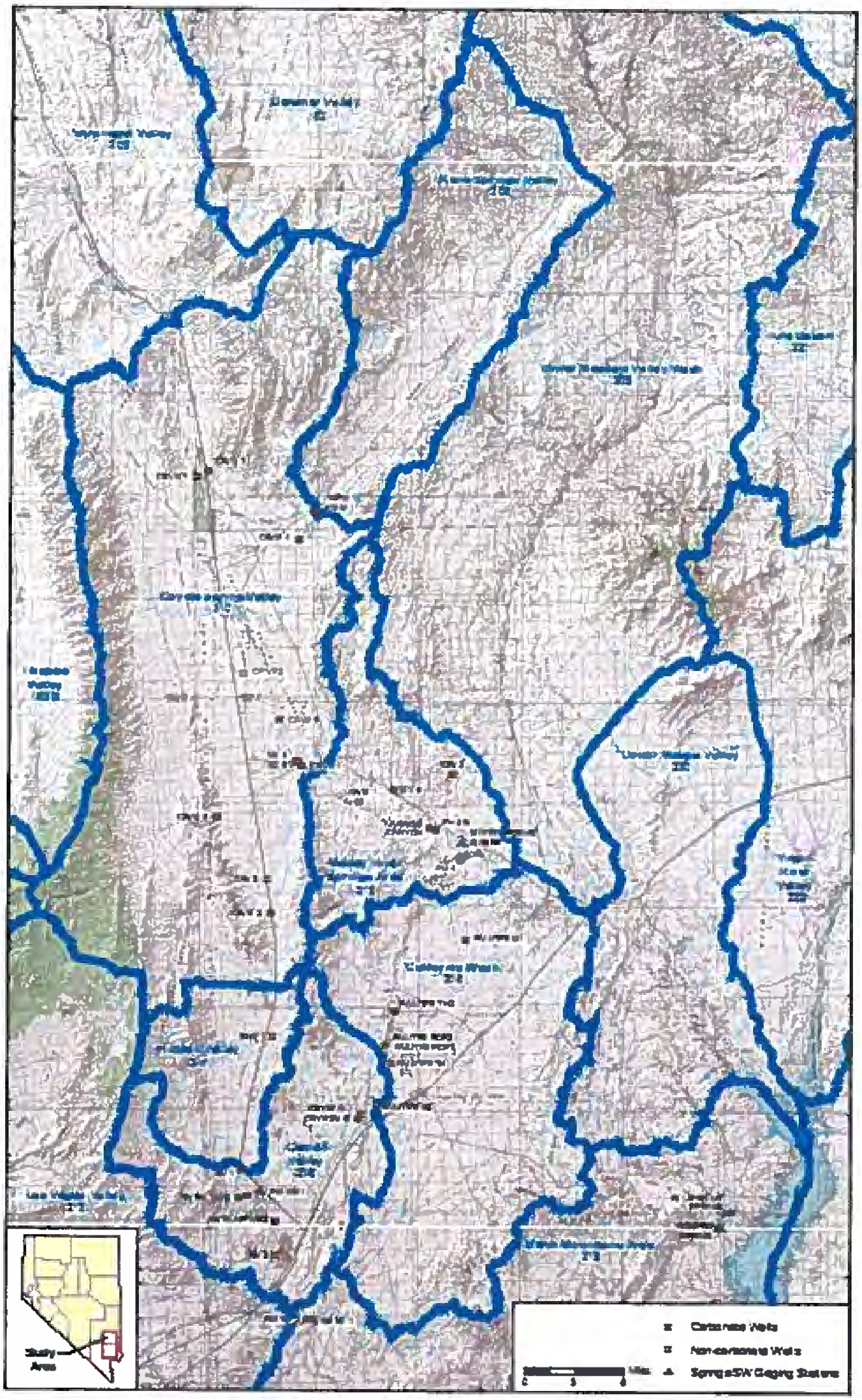


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FIGURE 19
Location of Selected Carbonate Wells Used in Schematic Cross Section

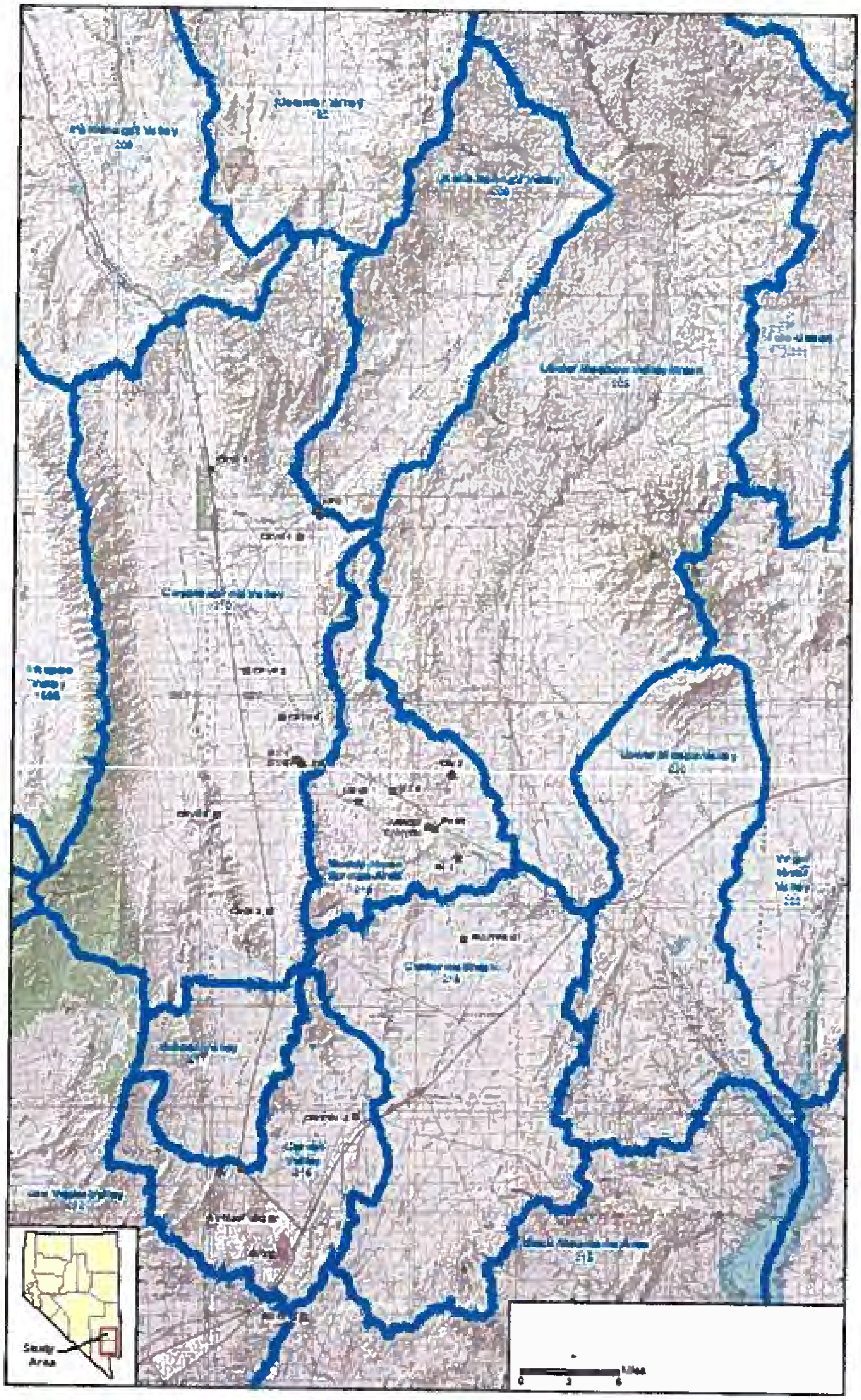


FIGURE 20
Vertical Profile Through Selected Carbonate Wells in Study Area

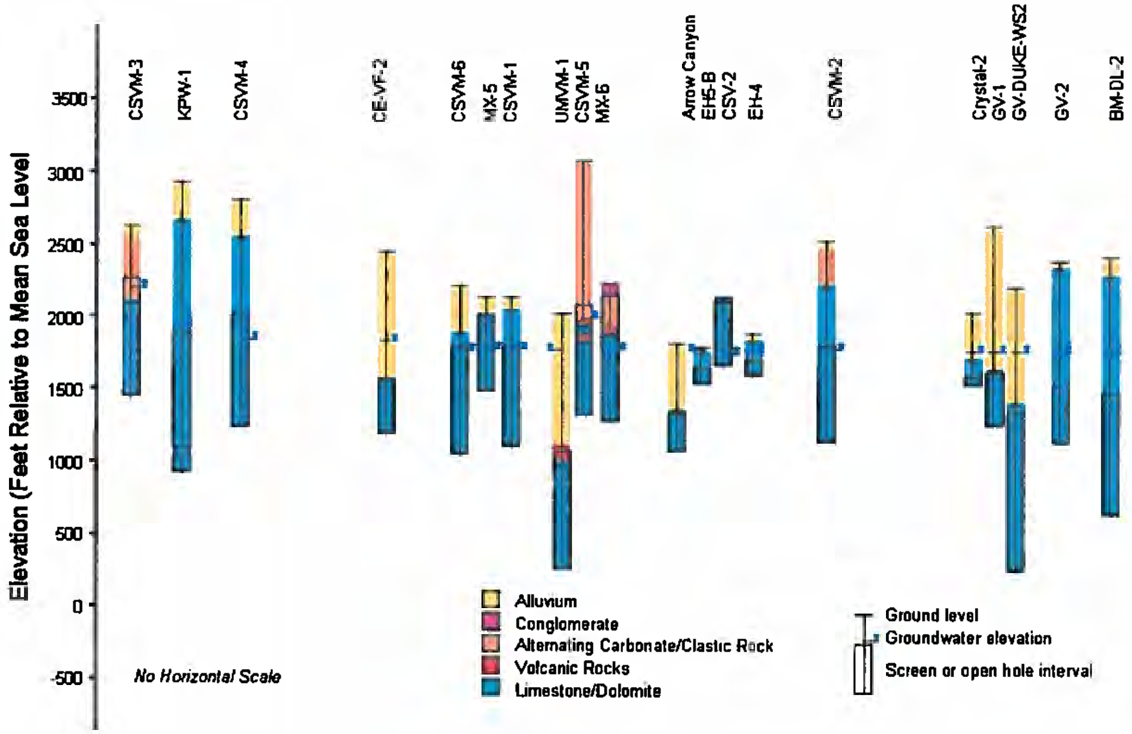
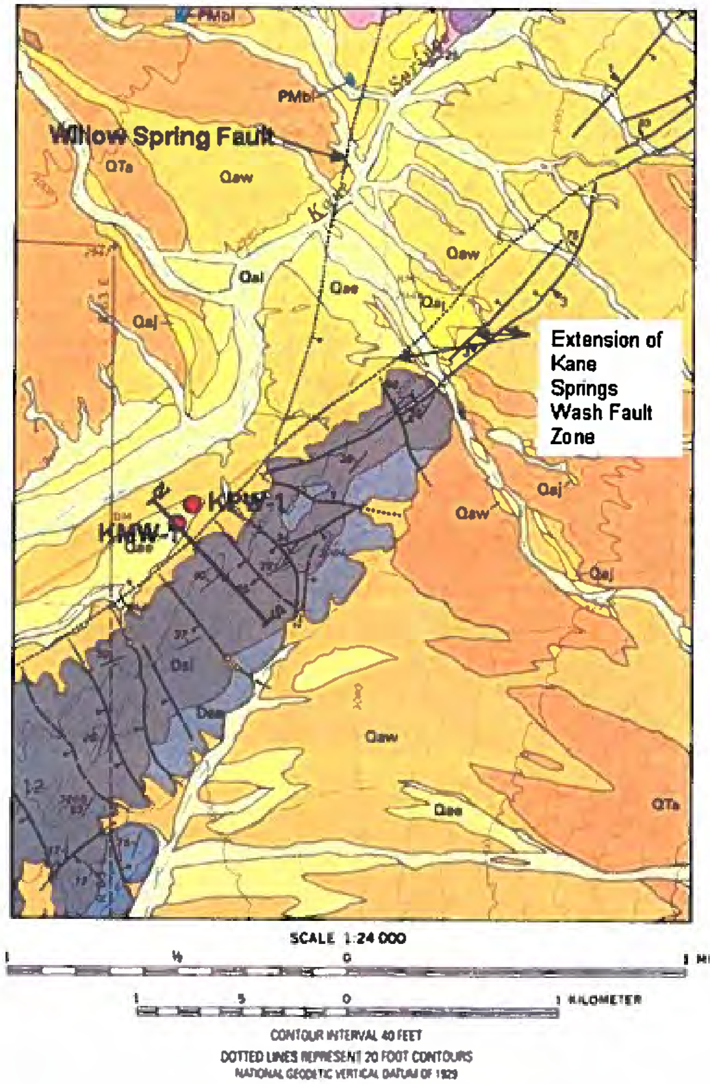


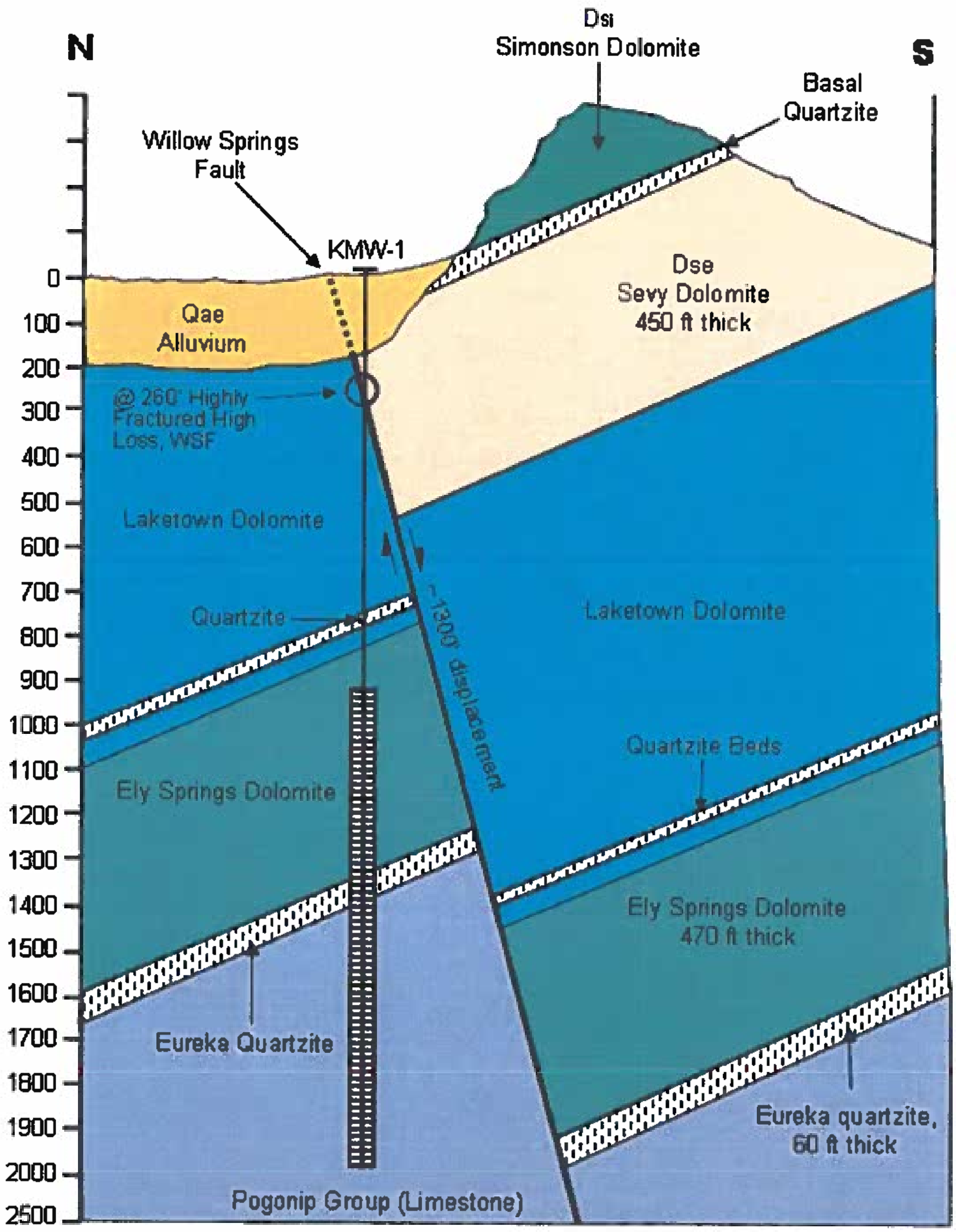
FIGURE 21
Location of Kane Spring Valley Wells Relative to Local Geologic Features



Dsi = Simonson Dolomite
Dse = Sevy Dolomite
Q = Quaternary Alluvial Deposits (Various Ages)

Source: Swadley, W. C., W. R. Page, R. B. Scott, and E. H. Pampeyan. 1994. Geologic Map of the Delamar 3SE Quadrangle Lincoln Co., Nevada. USGS Geologic Quadrangle Map, GQ-1754.

FIGURE 22
Localized Cross Section Through KMW-1, Kane Springs Valley



Source: Unpublished field notes taken during Drilling KMW-1 by Feast Geosciences

FIGURE 23
Drawdown Curve in Monitoring Well KMW-1 at a Distance of 143 Feet; KPW-1 Pumping @ 1800 gpm

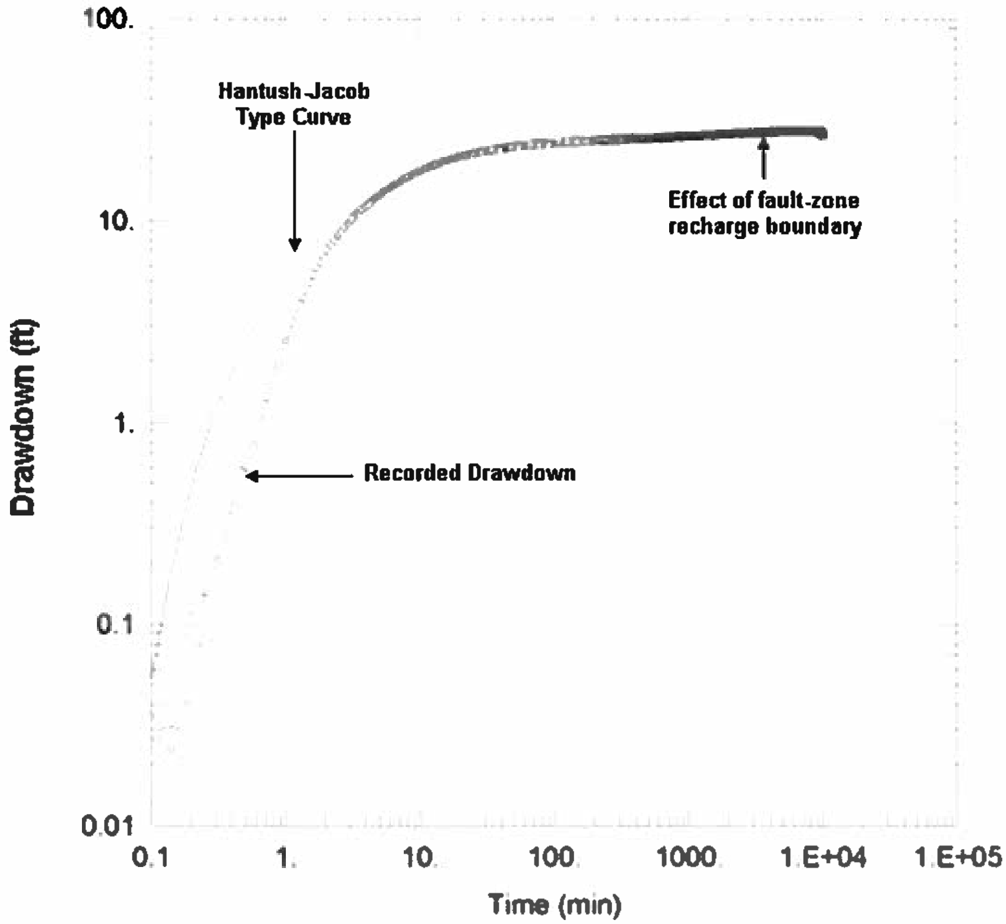
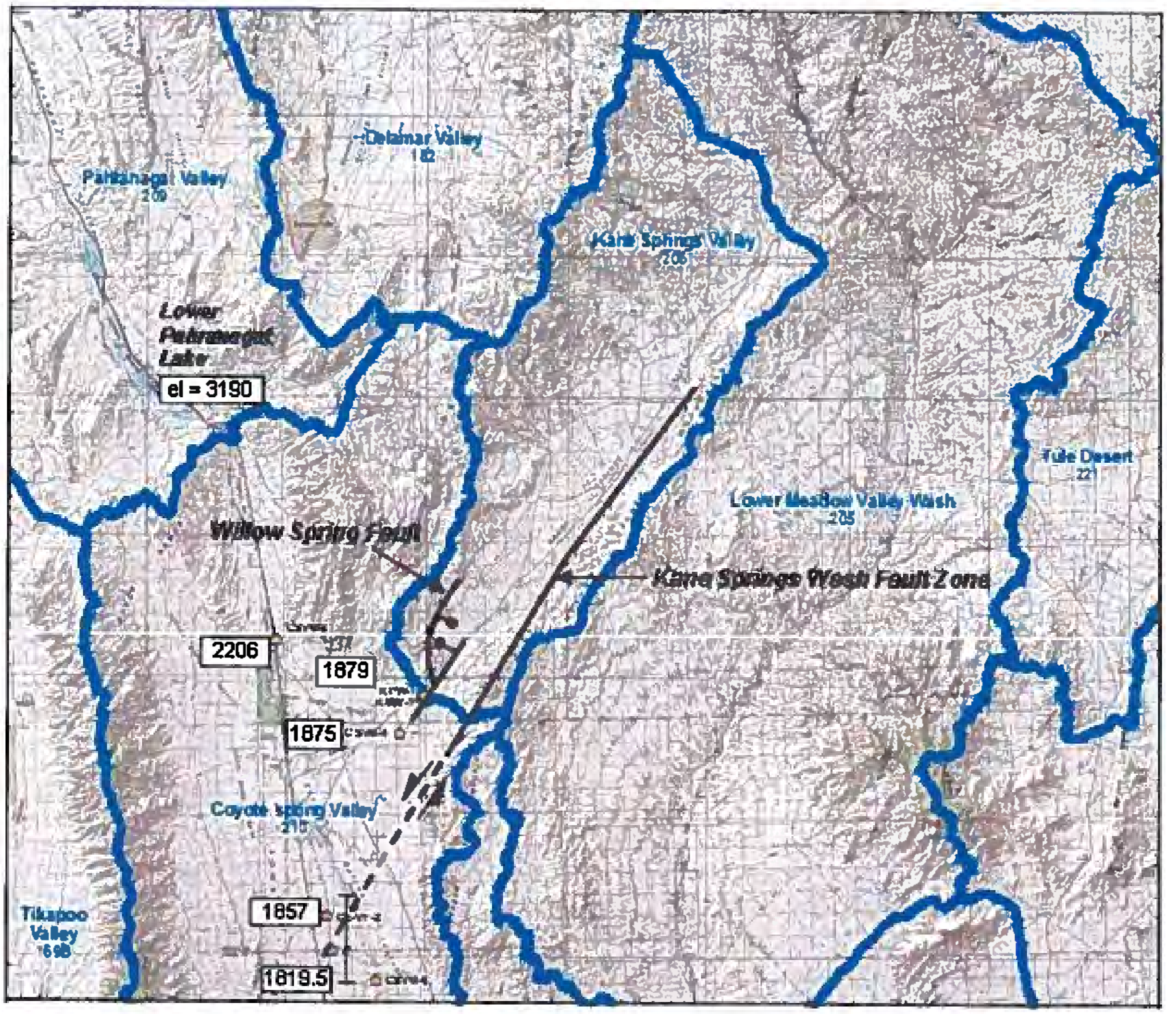


FIGURE 24
Local Geologic Structure Affecting Groundwater Conditions



[2206] Dec. 2005 Water Levels (ft amsl)
Source: Southern Nevada Authority Central Data Repository

FIGURE 25
Schematic Diagram of Kane Springs Wash Fault Influence on Groundwater Levels in Coyote Spring Valley

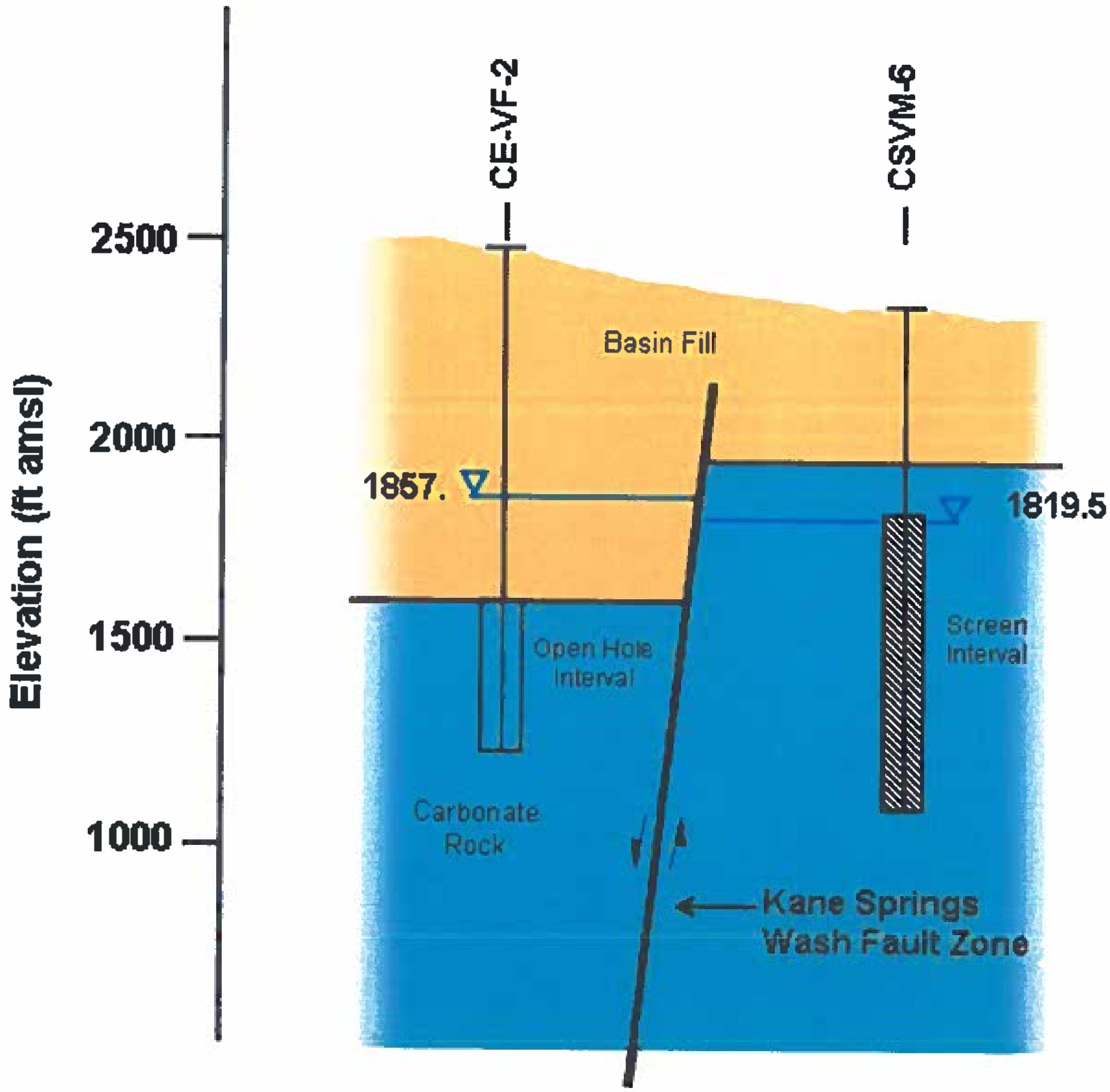
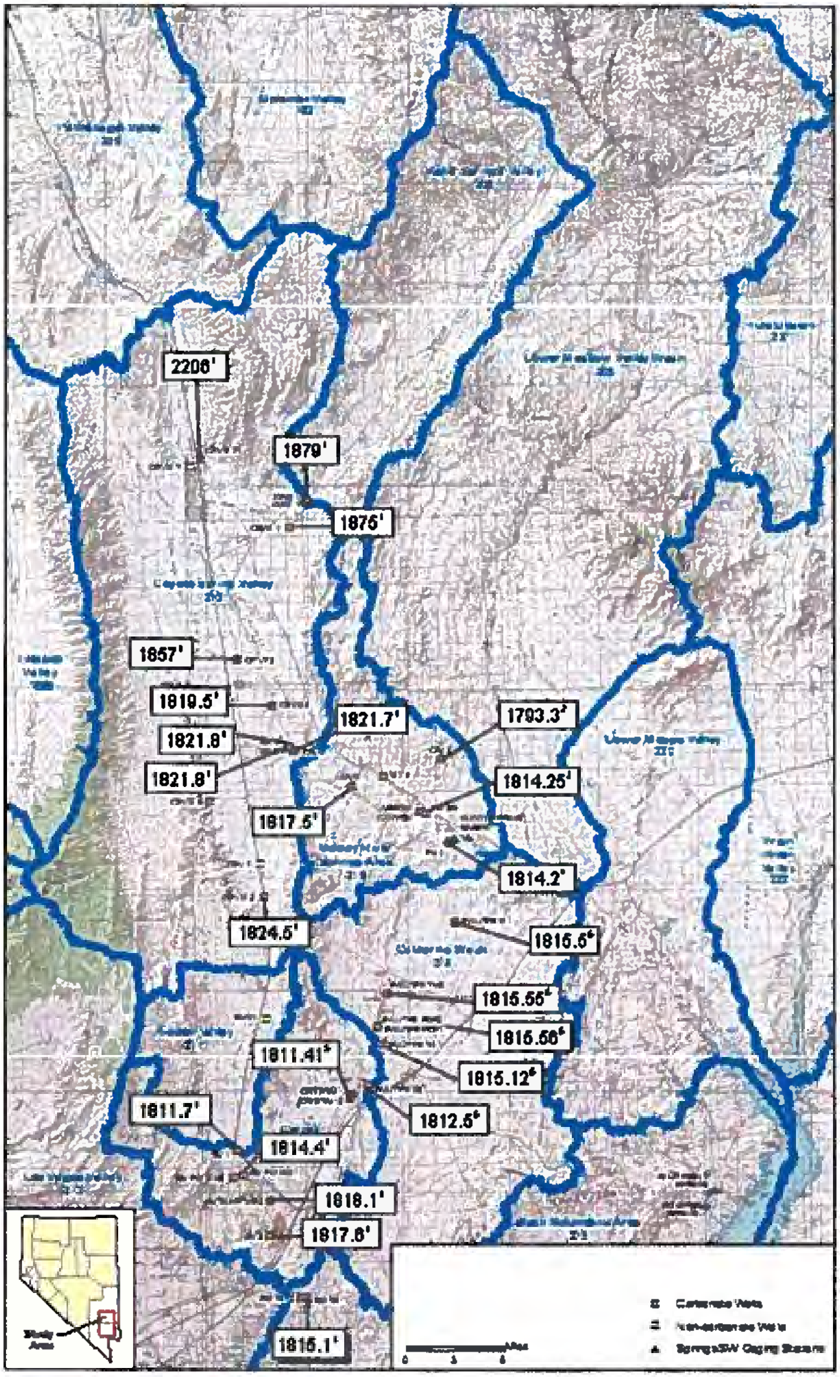


FIGURE 26
Most Recent Groundwater Level Elevations (ft amsl) in Selected Carbonate Wells Within Study Area

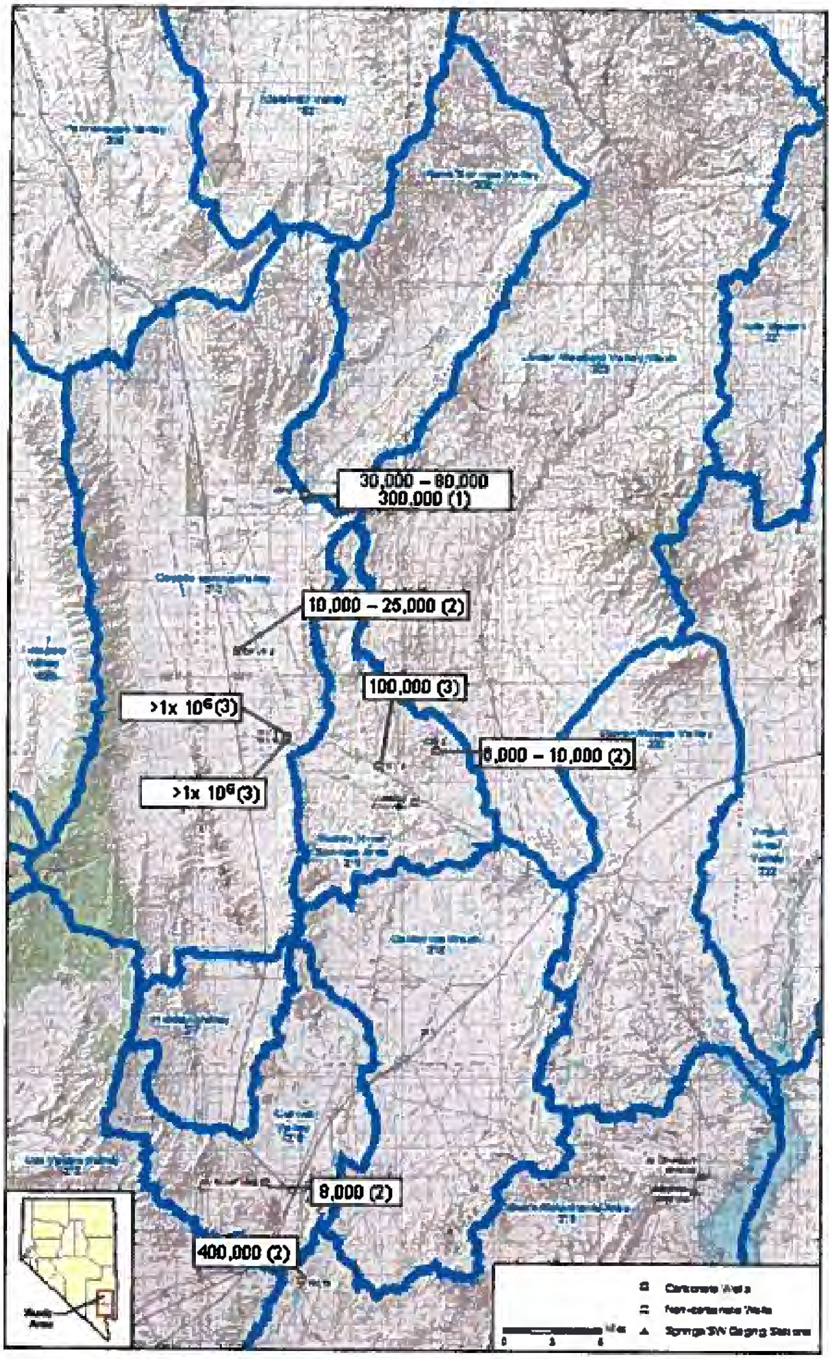


[1]Dec 05
[2]June 04
[3]Dec 04
[4]Nov 04
[5]Mar 04
[6]Feb 01

Water Level Source:

Southern Nevada Water Authority
Central Data Repository

FIGURE 27
Aquifer Transmissivity (gpd/ft) at Selected Carbonate Wells in the Study Area



Sources:
(1) URS (2006)

(2) CH2M HILL Unpublished Analysis

(3) Dettinger et al. (1995)

FIGURE 28
Width of Carbonate Aquifer Through Which Groundwater Flows into Kane Springs Valley

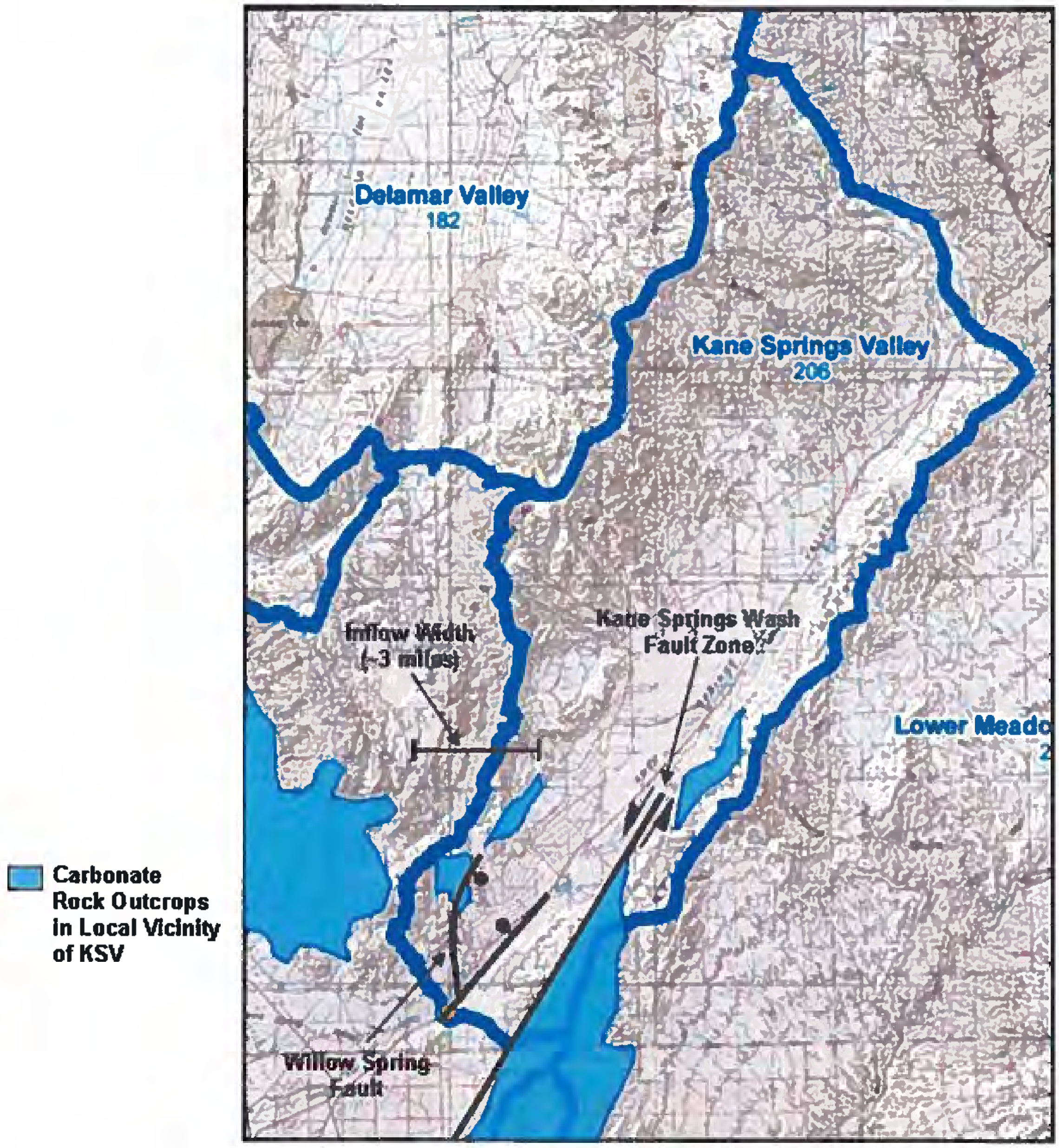


FIGURE 29
Width of Carbonate Aquifer Through Which Groundwater Flows out of Kane Springs Valley

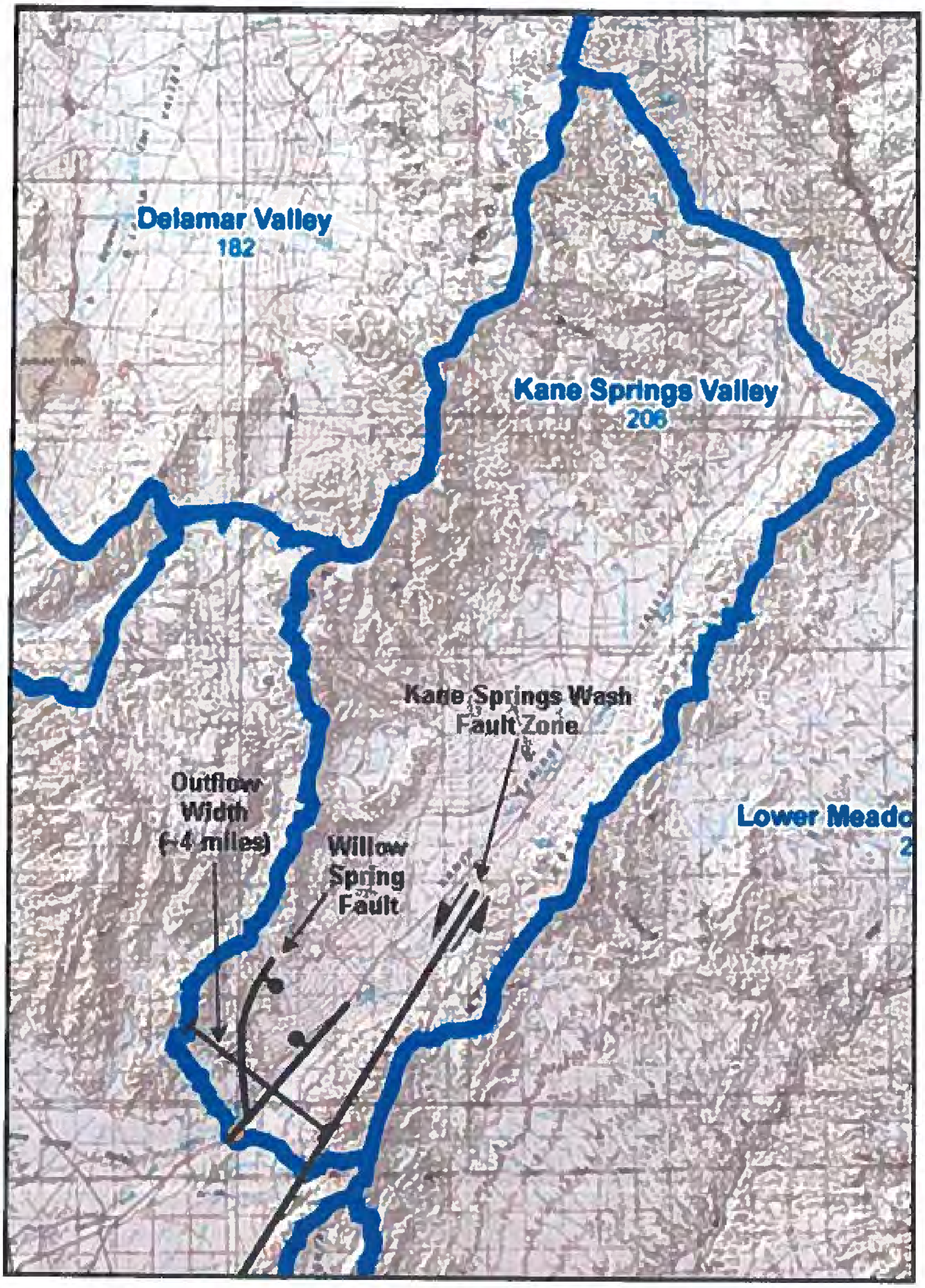


FIGURE 30
Conceptual Groundwater Flow Through Kane Springs Valley

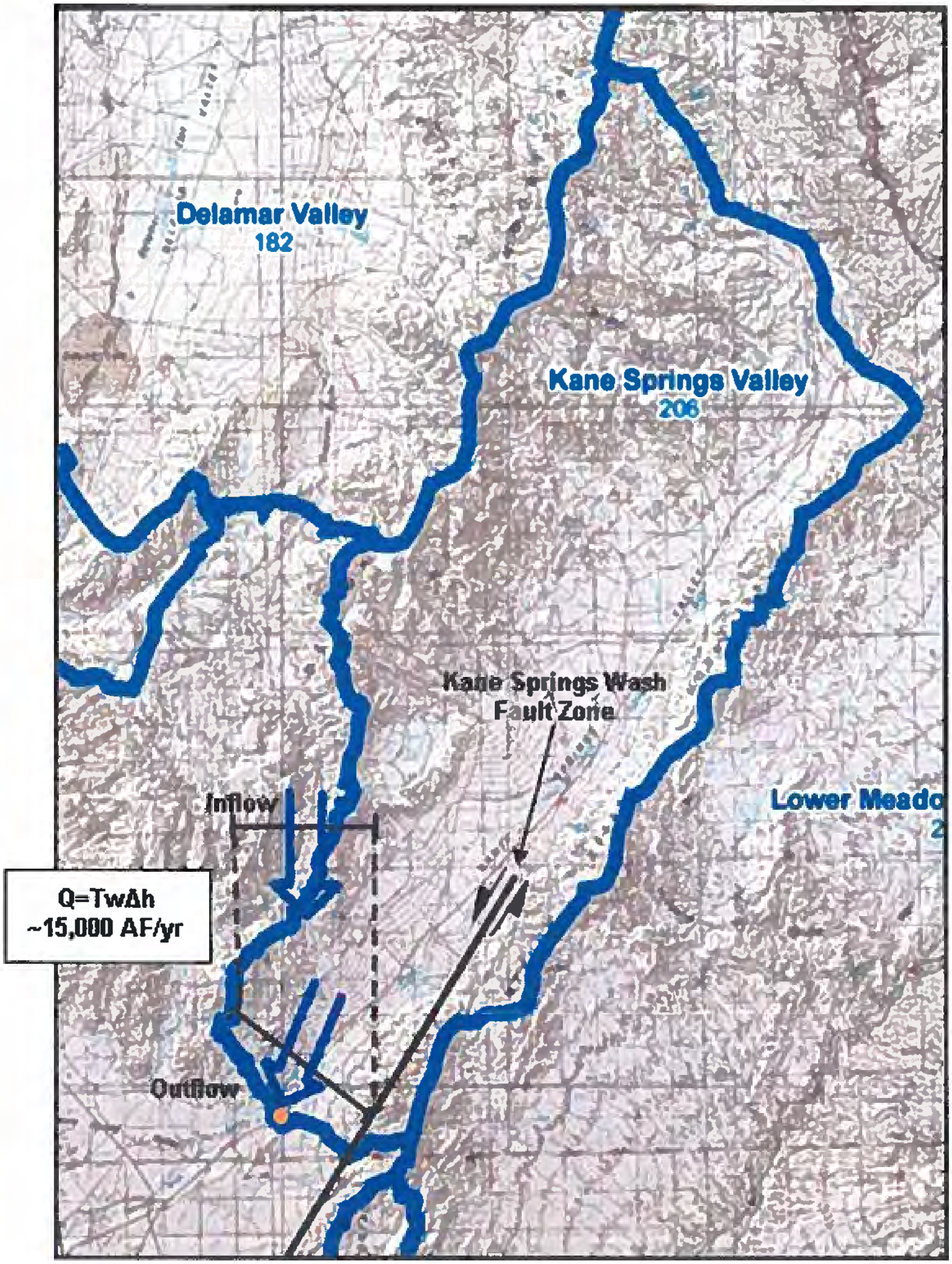


FIGURE 31
Ten-Mile Radius from KPW-1 and Permitted Points of Diversion in the Vicinity of Kane Springs Valley

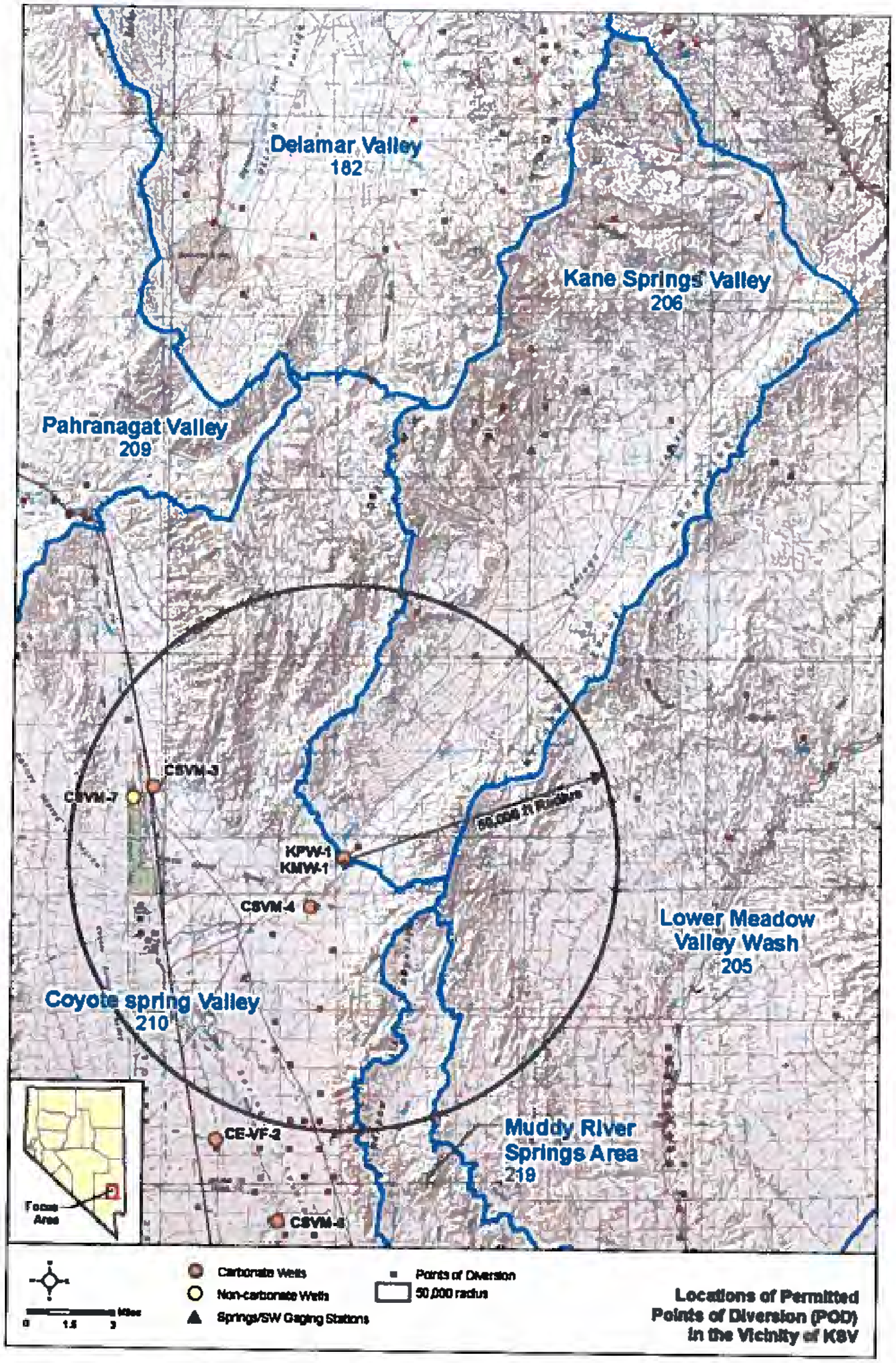
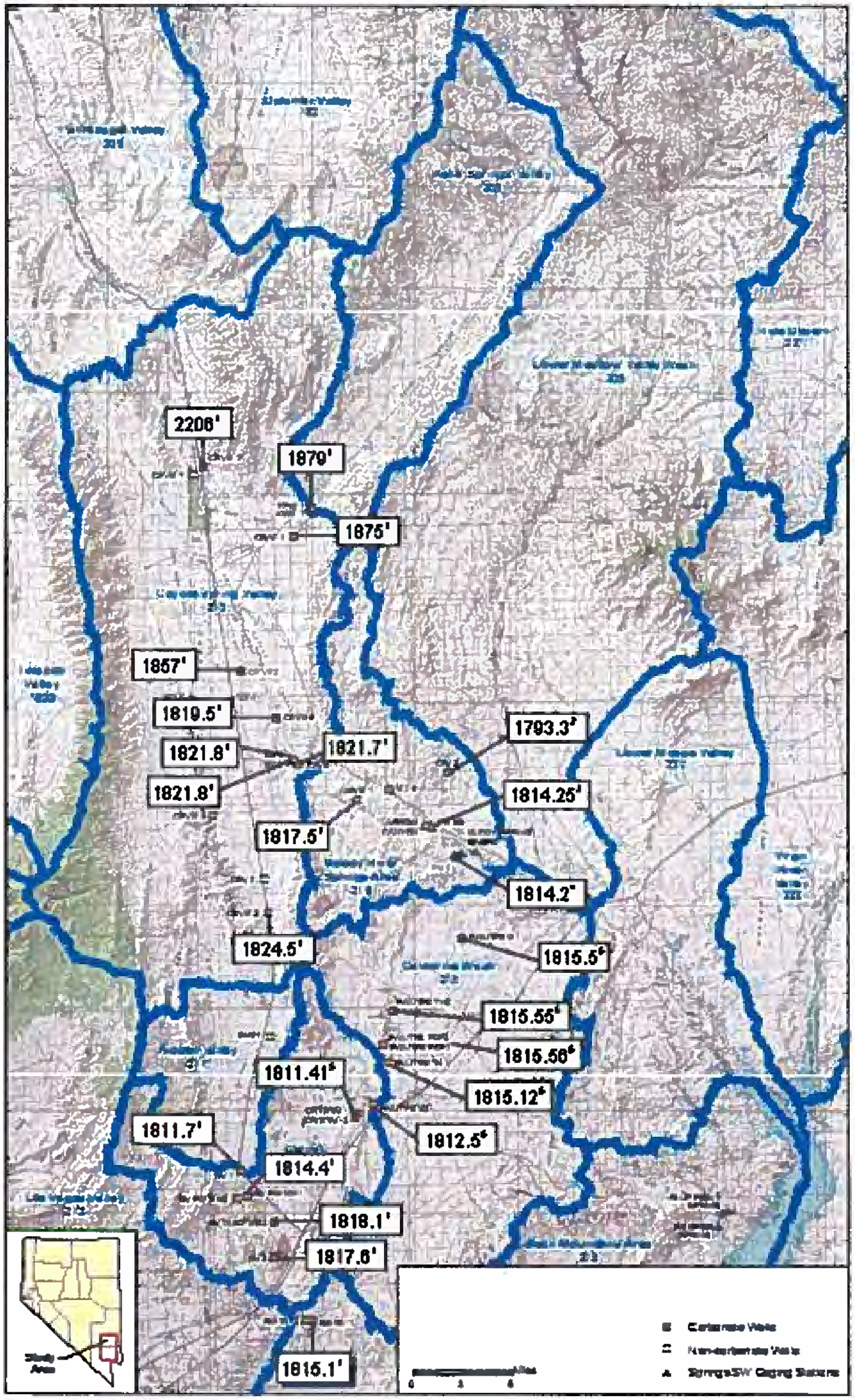


FIGURE 32
Most Recent Groundwater Level Elevations (ft amsl) in Selected Carbonate Wells Within Study Area



[1] Dec 05
[2] June 04
[3] Dec 04
[4] Nov 04
[5] Mar 04
[6] Feb 01

Source: Southern Nevada Water Authority Central Data Repository

FIGURE 33
Hydrographs for Selected Carbonate Wells in the Study Area

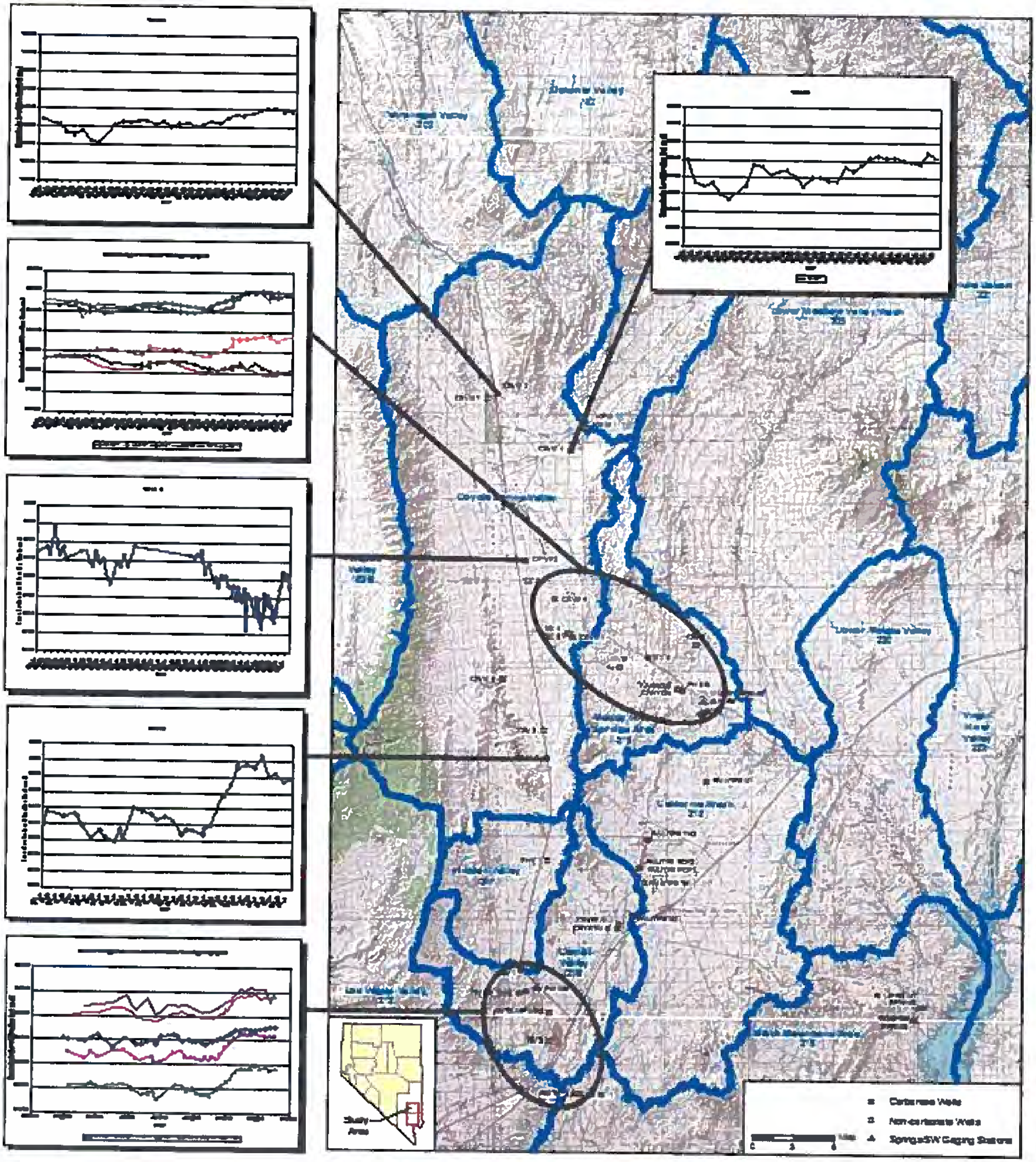


FIGURE 34
Vertical Profile Through Selected Carbonate Wells in Study Area

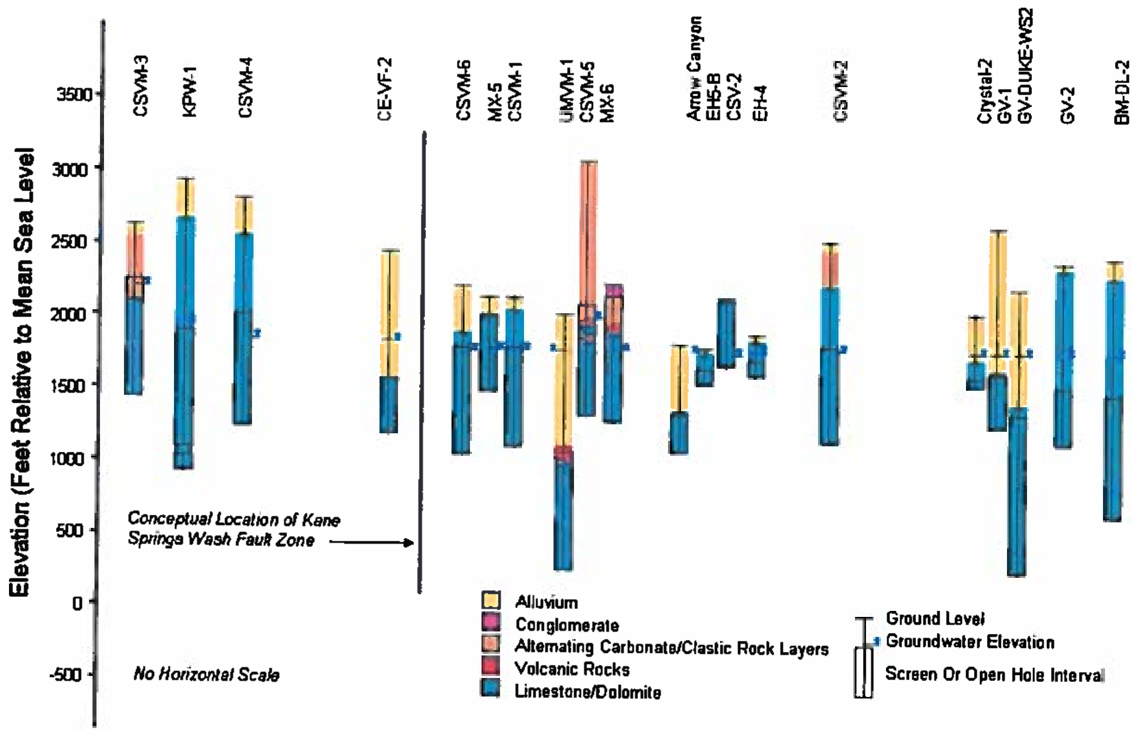
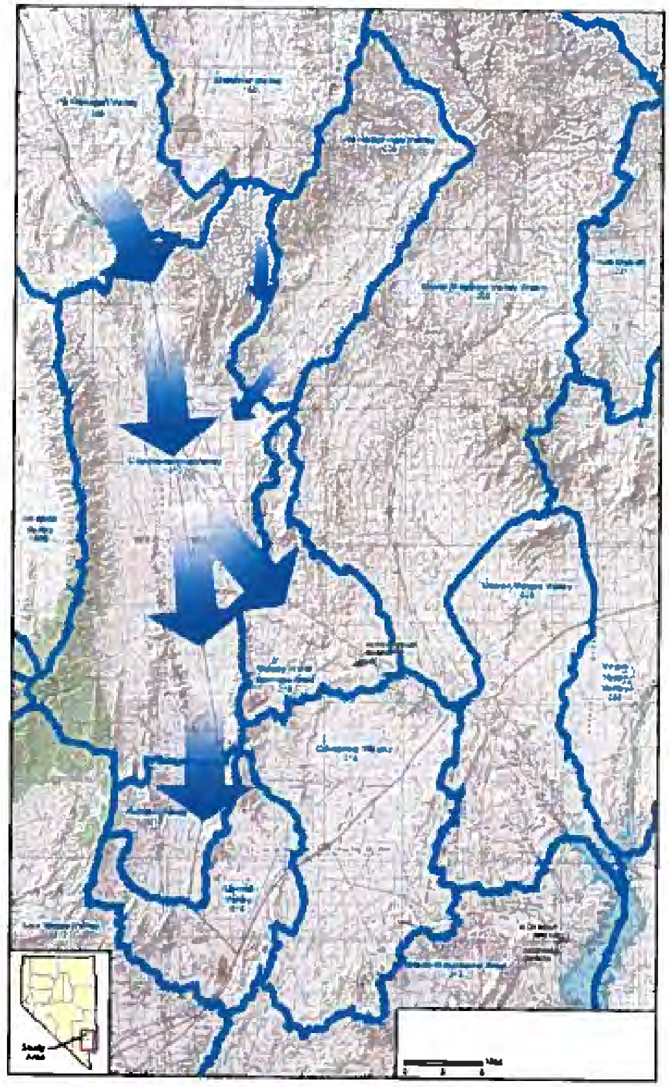


FIGURE 35
Generalized Regional Groundwater Flow in Portion of the Carbonate Aquifer System, Colorado River Basin.



General Direction of Groundwater Flow in Carbonate Aquifer with the Study Area

Groundwater Modeling Evaluation of Coyote Spring Valley, Lincoln and Clark Counties, Nevada

Prepared for

Coyote Springs

Coyote Springs Investment, LLC

Prepared by

IWR

Integrated Water Resources, Inc.
integratedwater.com

July 6, 2001

Copy of Exhibit 26

Table of Contents

List of Figures and Tables

Figures follow main report text.

Executive Summary

This report has been prepared in support of Coyote Springs Investment, LLC (CSI) ground-water applications within the Coyote Spring Valley. CSI currently holds approximately 6,100 acre-feet of water-right permits in Coyote Spring Valley, of which Nevada Power Company may utilize up to 2,500 acre-feet for a 20-year period ending in 2018. CSI also has pending applications to appropriate ground water from the Carbonate Aquifer system.

Southern Nevada Water Authority (SNWA) currently has approximately 7,500 acre-feet of underground water rights in Coyote Spring Valley. Las Vegas Valley Water District (LVVWD) has pending applications to appropriate underground water from the underlying Carbonate Aquifer system totaling 27,512 acre-feet annually (LVVWD, 2001, Applications 54055 through 54059).

CSI's pending applications to appropriate underground water from the Carbonate Aquifer have a combined total of 108,585 acre-feet annually (Applications 63272 through 63276, 63867 through 63876, and 64186 through 64192).

Given the limited information on ground-water flows in the region, it is uncertain how many of the ground water applications in Coyote Springs Valley can be developed without impacting the regional Carbonate Aquifer system down-gradient at Muddy Springs in Upper Moapa Valley. CSI has conducted numerical groundwater modeling to assist in the evaluation of proposed groundwater withdrawals from Coyote Spring Valley. The model is based on the U.S. Geological Survey code "MODFLOW," the most widely-used finite difference groundwater modeling method in the United States. CSI's groundwater model is constructed to model changes in groundwater levels within the Coyote Spring Valley hydrographic basin only.

To evaluate pumping stresses resulting from the proposed groundwater development in Coyote Spring Valley, CSI makes assumptions concerning various physical conditions in the basin as well as for groundwater inflows and groundwater discharges at the basin boundaries. In general, these assumptions are identical to, or consistent with the assumptions and model inputs made for Coyote Spring Valley by LVVWD, as described in the June 2001 groundwater modeling report. CSI's model is a two-layer model, which simulates both the carbonate and the alluvial groundwater conditions.

Because there is little long-term water level data within Coyote Spring Valley, and no significant historical groundwater production, the groundwater modeling effort has been conducted in two stages:

1. Validation of initial basin groundwater conditions. CSI has constructed a model that is consistent with the inflows, outflows and major hydrologic characteristics of the basin, and which produces a steady-state water level very close to the observed levels at existing monitoring points in the basin.

2. Testing of groundwater development impacts. CSI has tested groundwater production equivalent to net production of approximately 60,000 acre-feet per year (AFY), developed in phased increments. Groundwater conditions from the steady-state groundwater model validation exercise are used as the initial condition for transient model analysis of groundwater pumping impacts.

Results of the groundwater modeling effort show that significant natural groundwater flow into and out of Coyote Spring Valley can be maintained while concurrently developing a significant amount of groundwater from both the alluvial and bedrock basin aquifers. In this context, the majority of groundwater produced for the CSI project is derived from groundwater storage, which is assumed to be significant within the upper portion of the Coyote Spring Valley basin. On this basis, drawdown of water levels in the main portion of Coyote Spring Valley basin, the proposed location of CSI's production wells, is anticipated to be on the order of 60 to 70 feet over 60 years. The amount of groundwater level drawdown is different in other portions of the basin, with a lesser amount of drawdown at the basin margins with Pahranagat Valley and at the basin margin with Upper Moapa Valley at Arrow Canyon. The smallest simulated drawdowns are along the western basin margin at the Sheep Range.

The complete simulated groundwater production scenario includes incremental increases in groundwater production over the first 40 years of the project, plus 20 more years of production at the total net production amount 61,200 AFY. Basin-wide drawdown of water levels during the first two increments of groundwater production – the first 20 years of the phased production scenario – are everywhere less than 20 feet.

As initial groundwater development, testing and monitoring occur, CSI anticipates revision of the groundwater model utilizing any new data, together with renewed analysis of groundwater sources and flow regimes. Such information developed concurrently with initial phases of groundwater production will provide a more detailed and quantitative view of basin hydrology and groundwater pumping impacts.

Background

On behalf of CSI, Integrated Water Resources, Inc. has developed a groundwater flow model for Coyote Spring Valley (hydrographic basin #210, herein referred to as "Coyote Spring Valley"), to support development of private property within the Valley. To determine the potential effect of significant groundwater pumping from the basin, a numerical groundwater model was constructed for initial testing of pumping scenarios.

Consistent with the proposed CSI property development plan, the groundwater model production scenarios describe pumping increases in increments, with total, net groundwater production after all increments of 61,200 AFY. Details of the incremental increase in total groundwater production are provided, together with results of the corresponding model scenario in the "Transient Model Scenario" section below.

As initial groundwater development, testing and monitoring occur, CSI anticipates revision of the groundwater model utilizing any such new data, together with renewed analysis of groundwater sources and flow regimes. The information will be developed in accordance with a monitoring plan, which document is separate from this Groundwater Modeling Report.

Purpose

The principal purpose for developing the groundwater model is to provide a semi-quantitative method for evaluating potential changes to groundwater levels within Coyote Spring Valley as groundwater production for the CSI development project occurs. Because there is no significant historical pumping within the basin, the groundwater model can be used as a limited predictive tool for estimating the principal location and magnitude of such impacts. It is important to note that groundwater modeling analysis is a tool that is best used in concert with other methods for evaluating the Coyote Spring Valley groundwater basin. Uncertainties in the model parameters are readily acknowledged by CSI for this model as well as by others for models of Coyote Spring Valley and of the Carbonate Aquifer system.

As the project is developed, new data will become available from staged groundwater production and from monitoring of groundwater conditions that describe the Coyote Spring Valley hydrology in more detail. Such data can be used to refine the groundwater model together with any pumping impacts defined by the model.

Previous Work

Whereas Coyote Spring Valley has not had significant groundwater development, it has been the subject of considerable attention with regard to basin hydrology and in association with other portions of the broader regional carbonate flow system in eastern Nevada (refer also to CSI's monitoring plan report and the reference list therein). Five studies of the basin merit special attention, and have specific importance to the groundwater model development conducted for CSI:

› Eakin's (1964) report on the basin hydrology. During the last several decades, understanding of the Coyote Spring Valley hydrology has improved, but Eakin's work on the basin and the White River flow system (Eakin, 1966) identified and discussed many of the issues and hydrologic characteristics that remain of principal concern today.

› MX missile well drilling program, 1981. Various reports conducted for the MX program provided what to date is the best well production and water level information for the basin and the carbonate aquifer that is the principal groundwater-bearing unit in the basin (e.g, Ertec Western, 1981).

› Las Vegas Valley Water District MODFLOW model of Coyote Spring Valley (Buqo et al., 1992). This was the first basin-specific numerical modeling effort for Coyote Spring Valley and the first comprehensive hydrologic study of the basin following construction of the MX wells. The effort is updated by the Las Vegas Valley Water District (2001) regional modeling analysis using a finite-element modeling method.

› U.S. Geological Survey (1990's) Regional Aquifer System Analysis of the Great Basin region (e.g., Burbey and Prudic, 1991), including the regional carbonate aquifer system of which Coyote Spring Valley bedrock aquifers are a part. This work was a significant MODFLOW modeling effort for the regional carbonate aquifer system, and built on previous work such as Kirk and Compana (1988).

› Isotopic studies of groundwater flows within the regional carbonate province, most recently Thomas et al. (2001). Such methods for tracing provenance and regional flowpaths of groundwater for mass balance and flow rate estimates have been undertaken by several researchers during the last several decades, and provide an important tool for water budget and model input estimates.

These studies and information reports provide the principal basis for CSI's model development and selection of the parameters that define the model behavior.

Consistency with Recent Data and Groundwater Model Analysis

Recent work by Thomas et al. (2001) and LVVWD (2001) provide new analysis of recharge, subsurface inflow and outflow and related hydrogeologic characteristics of several basins in the Carbonate Aquifer system, including Coyote Spring Valley. For most basins evaluated, subsurface flow rates and basin recharge calculated by LVVWD (2001) and used by Thomas et al. (2001) are estimated in these new research reports to be significantly higher than most previous estimates.

For example, the analysis by Thomas et al. (2001) concludes that subsurface groundwater inflow at the northern margin of Coyote Spring Valley is 44,000 AFY, including 16,000 AFY from Delamar Valley. In comparison, most previous work has maintained that subsurface inflow to Coyote Spring Valley is primarily or only from Pahranagat Valley (e.g., Eakin, 1966; Welch and Thomas, 1984; Buqo et al., 1992), and that total inflow to the northern margin of Coyote Spring Valley is approximately 25,000 to 35,000 AFY.

Similarly, LVVWD (2001) has developed new estimates of recharge from precipitation, resulting in generally higher estimates for recharge than previous researchers. In Coyote Spring Valley, recharge from precipitation is estimated to be 4,000 AFY, almost twice the 2,300 AFY estimate that has prevailed previously in the literature (e.g., Eakin, 1964; Harrill et al., 1988).

CSI's hydrogeological framework for groundwater flow modeling is based in part on new research presented in Thomas et al. (2001) and LVVWD (2001). By using data consistent with these new research results, CSI builds on, and is consistent with, this recent, quantitative analysis of the Carbonate Aquifer in the Coyote Spring Valley area.

In addition, by using these data for establishing initial conditions for the CSI groundwater flow model, more direct comparison can be made between the CSI basin-specific analysis, and the analyses conducted for more regional evaluation by LVVWD (2001) and Thomas et al. (2001). Where more detailed groundwater flow characteristics or different basin parameters are used in the CSI groundwater model, as compared with the hydrogeology presented in Thomas et al. (2001) and LVVWD (2001), such differences are discussed in this report.

Groundwater Flow Model

CSI's numerical groundwater model encompasses the complete Coyote Spring Valley hydrographic basin, together with the west flank of the Sheep Range (Figure 1). The model simulates groundwater conditions in: (1) an upper alluvial aquifer that exists in the main Coyote Spring Valley lowland, and (2) the regional carbonate aquifer which outcrops along the basin's ridges and highlands and underlies the alluvial sediments elsewhere in the basin.

The carbonate stratigraphic sequence is well described in existing literature (e.g., Longwell et al., 1965; Tschantz and Pampeyan, 1970; Schmidt and Dixon, 1995) and is represented in the CSI model in a manner that is consistent with the carbonate aquifer description of LVVWD (2001) in the vicinity of Coyote Spring Valley.

Hydrogeological Framework

The conceptual model for CSI's numerical groundwater flow model includes a stratigraphic sequence of the carbonates that is consistent with the regional stratigraphy (and is consistent with LVVWD, 2001), an alluvial sequence that is of varying thickness in the basin, and the presence of basin-scale fault and fracture zones that are likely conduits for relatively high rates and volumes of groundwater flow.

The prominent features of CSI's conceptual model for Coyote Spring Valley are:

- A carbonate bedrock aquifer unit that is:
    i. Thick; CSI models a 12,000 foot thickness based on regional and basin-specific geological studies, corresponding with the average thickness of Paleozoic carbonates in the vicinity of Coyote Spring Valley. This value is similar to the thickness of the primary carbonate unit used by LVVWD (2001);
    ii. Locally highly hydraulically conductive, but modestly conductive outside zones of localized groundwater flow;
    iii. The primary conduit (as opposed to the alluvial aquifer) through which groundwater migrates within the basin; and
    iv. Only modestly recharged by local precipitation.
- An alluvial aquifer unit that is:
    i. Important to the project because of two deep alluvial basins underlying and adjacent to the project property, with alluvial basin fill up to 3,000 feet thick;
    ii. Mostly unsaturated except in the two regions of significant sedimentary thickness;
    iii. Assumed to be unconfined; and
    iv. Available to the project for conjunctive use and artificial recharge project augmentation opportunities at the two deep basins and along Pahranagat Wash.
- Local zones of high groundwater flow rate, principally along structural features such as fault and fracture zones; and
- Basin boundaries with local zones of large subsurface flows. These basin groundwater fluxes dominate the basin hydrology, whereas in-basin recharge from local precipitation is relatively minor.

Young sedimentary deposits that make up the alluvial stratigraphic sequence ("Layer 1" of the model) exist in locally thick accumulations (Refer to cross-sections in Figure 2, cross section locations are shown in Figure 3; Phelps et al., 2000), and are in places also displaced by the Basin-Range normal faults. These sediments are likely unconfined in most of their extent, and are known from limited drilling to be unsaturated in the top several hundred feet.

Geologic Structures

There is considerable structural complexity within the carbonate strata, associated both with regionally-prevalent low-angle faults of older geologic age, and the more topographically dominant normal faults and associated extensional deformation of the Basin-Range geologic province (e.g., Wernicke, 1991). The structural deformation creates portions of the carbonate sequence in Coyote Spring Valley that are likely to favor migration of groundwater, and other regions that impede groundwater flow, or redirect it horizontally or vertically.

The geometry and extent of low-angle structures beneath Coyote Spring Valley is not well understood. However, the bulk behavior of the carbonate strata that make up the primary aquifer sequence (refer to LVVWD, 2001) can be reasonably estimated because of the significant cumulative thickness of the carbonate rocks and their regional extent. For this reason, the CSI model, like previous work, groups the carbonate sequence into a single, thick layer, and does not account for variations in flow that might occur, for example, along a low-angle fault complex at 8,000 feet depth. Instead, the model accounts for such features through bulk characteristics of the carbonate rock over a cumulative thickness of 12,000 feet (Figure 2).

In contrast, the Basin-Range normal faults that make up the basin-bounding structures for many of the White River system hydrographic basins provide specific zones along which groundwater may migrate at high rate. In particular, CSI confirms the importance of features identified in other work, such as the north-south structures which cross the structural boundary between Pahranagat and Coyote Spring Valleys (Jayko, 1990) and the prominent fault and fracture zones that define the east margin of the valley floor in Coyote Spring Valley and the location of Arrow Canyon in Upper Moapa Valley (e.g., Johnson et al., 2000). These features are reflected by increased hydraulic conductivity in CSI's groundwater flow model, in zones that correspond with the location of principal structures in Coyote Spring Valley (Figure 3). Specific zones of inferred high hydraulic conductivity include fault and fracture zones that:

- Extend from southern Pahranagat Valley into northern Coyote Spring Valley;
- Extend from southern Delamar Valley into northern Coyote Spring Valley;
- Exist in Kane Spring Valley and terminate at the east-margin Coyote Spring basin-bounding fault;
- Extending from southern Coyote Spring Valley into Hidden Valley and Garnet Valley;
- Extend from Pahranagat Wash in Coyote Spring Valley into Upper Moapa Valley along Arrow Canyon; and

- Provide direct hydraulic connection between the region of greatest subsurface basin inflow (at the northern boundary of Coyote Spring Valley) and the location of greatest outflow (through Arrow Canyon to Upper Moapa Valley).

These zones of assumed high hydraulic conductivity are defined in the model by different hydrologic properties than other portions of the basin (Figure 3 and Table 1).

Subsurface Groundwater Flow

For groundwater modeling of Coyote Spring Valley, CSI's estimate for the amount of subsurface flow into and out of Coyote Spring Valley basin is based on recent isotope-based mass balance calculations (Thomas et al., 2001) and are consistent with the subsurface flow rates used by LVVWD in its recent modeling of the Coyote Spring Valley and nearby basins (LVVWD, 2001). The amounts of interbasin flow for the model are summarized in Figure 4 and Table 2.

The large rates of groundwater migration believed to occur within the carbonate aquifer of Coyote Spring Valley are likely concentrated within the structurally-controlled regions that connect the northern basin margin with the eastern basin margin and Upper Moapa Valley near Arrow Canyon. The presence of regional fault and fracture zones that extend to the southern portion of Coyote Spring Valley are consistent with the Thomas et al. (2001) finding that a significant groundwater flow also occurs southward from Coyote Spring Valley into Hidden Valley.

Prominent basin-bounding faults are likely conduits for a substantial amount of the groundwater flow that migrates into Coyote Spring Valley from Kane Spring Valley. The amount of this flow represented in CSI's groundwater model is taken from Thomas et al., (2001) (6,000 AFY, see Figure 4 and Table 2).

Springs

The vertical migration of significant bedrock groundwater flow is commonly a reason for surface spring discharge of water or the presence of hot water in wells or springs. Upwelling of groundwater in the carbonate aquifer in Coyote Spring Valley may be responsible for surface and near-surface water occurrence at Coyote Spring in the north-central part of the basin, just as hydrothermal upwelling apparently has some impact on groundwater temperatures recorded for MX-4 and MX-5 wells farther downgradient along Pahranagat Wash in Coyote Spring Valley (~30°C water sampled from wells; Buqo et al., 1992). Coyote Spring is not known to have a strong thermal component, and it is estimated by LVVWD (2001) be the site of most of the Valley's evapotranspiration, estimated at approximately 1,000 AFY. The spring may represent a perched water system, as discussed by Buqo et al. (1992).

Other small, ungaged springs are known in the Sheep Range, on the west margin of Coyote Spring Valley. Most of these springs are ephemeral and are likely to be principally associated with precipitation and recharge to bedrock in high elevation portions of the Sheep Range. None of the mountain springs are known to have discharge greater than a few gallons per minute. A more detailed description of spring locations in the Sheep Range is provided in Buqo et al. (1992).

Model Construction

The groundwater model constructed for Coyote Spring Valley utilizes MODFLOW, a modular, three-dimensional finite difference flow model. MODFLOW has been used previously for the carbonate aquifer province by the U.S. Geological Survey (e.g., Prudic et al., 1993; Schaeffer and Harrill, 1995), and by Buqo et al. (1992) for specific analysis of Coyote Spring Valley. The MODFLOW code is the most widely used numerical groundwater flow modeling method in the U.S.

Within each grid cell, MODFLOW calculates hydrogeological characteristics, inflows, outflows and cumulative changes, subject to the initial conditions developed for the model region. MODFLOW was executed within the Boss GMS modeling interface. The MODFLOW modules used for the simulation include: the basic package, running MODFLOW96 (Harbaugh and McDonald, 1996); block centered flow package; general head package; well package; and recharge package. The strongly implicit procedure was the solver used.

Layer 1 was modeled as Type 1, unconfined, and Layer 2 was modeled as Type 2, Confined/Unconfined. Cell wetting was allowed to occur for Layer 1, with a wetting factor of 1.0, and a wet/dry flag of -1 (McDonald et al., 1992). The head change criterion for both steady state and transient models was set at 0.001 feet. Both the steady state and transient models converged quickly with cumulative water budget errors less than 0.1%.

Stress periods for the transient model follow the pumping scenarios outlined below, and correspond to five stress periods. Within each stress period 10 time steps were used, with a multiplier of 1.4 for the time step lengths for the first four stress periods, and a multiplier of 1.0 for the fifth and last stress period which does not have any additional pumping stress. The first four stress periods are 10 years in length. The final stress period is 20 years in length for a cumulative transient model length of 60 years.

The model grid used for Coyote Spring Valley analysis consists of 100 rows x 50 columns x 2 layers (2,700' x 2,600' row and column cell dimension). Considering the low data density for the basin, this grid spacing is relatively detailed. Accordingly, the model provides the ability to map and constrict certain groundwater movements along those geological features that are believed to concentrate the majority of subsurface flow, particularly within the carbonate bedrock units (Figure 3).

Layer 1 corresponds to the alluvial aquifer, and Layer 2 corresponds to the carbonate bedrock aquifer. Layer 1 has a variable thickness (Figure 2). Layer 2 has a constant thickness of 12,000', corresponding to the average thickness of the Lower Paleozoic carbonate aquifer in the vicinity of Coyote Spring Valley.

Because CSI's groundwater flow model uses many of the same input parameters as the LVVWD (2001) model, it is also useful to compare the two models. The LVVWD model is a finite-element model that extends over several basins, and includes significant consideration of surface flows such as discharges from Muddy River Springs. In contrast, the CSI finite-difference (MODFLOW) model is constructed with boundaries specific to Coyote Spring Valley and the groundwater system within it. Even so, the models are quite similar in inflow boundary conditions at the north margin of Coyote Spring Valley: groundwater flow from Pahranagat and Delamar Valleys for the two models are represented at identical rates, taken from the work of Thomas et al. (2001).

Both models provide for a very thick carbonate aquifer of 10,000 to 15,000 feet thick (12,000 feet thick for the CSI model), with locally high hydraulic conductivity. The ability to provide detail in hydraulic conductivity based on the presence of geological structures is greater in the CSI model, as is the detail in the alluvial layer of the CSI model, by virtue of the more limited geographic focus of the CSI model. Because the representations of hydrogeologic conditions in Coyote Spring Valley are different for the two models, they can be considered complementary for understanding the possible effects of significant groundwater production in Coyote Spring Valley, and from groundwater production on a more regional basis.

Data Selected for Use in CSI Model

CSI's groundwater model flow budget is based in large part on new isotopic data interpretations (Thomas et al., 2001), and the use of such data by Las Vegas Valley Water District in its regional finite-element groundwater model (LVVWD, 2001). Whereas previous work has commonly assumed somewhat lower values for groundwater inflow and outflow for Coyote Spring Valley, such estimates are typically poorly-constrained by direct sampling and measurement of water levels, flows, pumping tests and similar data at key locations.

Similarly, the isotopic data interpretations have limitations resulting from sampling locations and mass balance uncertainties among other issues, but CSI has favored the isotopically-derived results for the current groundwater modeling exercise for 2 reasons:

1. The results are based on mass balance as well as regional hydrogeological data, and
2. The results form the basis for LVVWD's 2001 modeling exercise, which is an important comparative benchmark for CSI's work in Coyote Spring Valley.

Hydrogeologic data separate from flowrates and amounts as defined by the isotopic analysis are derived from various sources, including the five research topics named in the

"Previous Work" section above. Other work, such as Johnson et al. (2000) analysis of the "Arrow Canyon Cell" provide analysis of data and data sources overlapping with or near to Coyote Spring Valley. CSI has attempted to evaluate all such available research and to establish reasonable ranges for important hydrologic parameters such as storativity, hydraulic conductivity and hydraulic head conditions.

Other data types, and sources for data used in the CSI basin evaluation and model construction include:

- Digital Elevation Model. USGS National Elevation Dataset (NED's) redistributed by University of Nevada, Reno. NED has a resolution of one arc-second (approximately 30 meters).
- Basin Boundaries. Nevada Division of Water Resources.
- Well Locations (see also Appendix B). Various sources, including:
  - i. Berger et al., 1988;
  - ii. Tumbusch and Schaeffer, 1996;
  - iii. Schaeffer et al., 1992;
  - iv. Burbey, 1995;
  - v. Southern Nevada Water Authority / Las Vegas Valley Water District information sheets and data
  - vi. LVVWD, 1992
  - vii. Mifflin and Associates, Inc., 2001;
  - viii. Johnson et al., 2000;
  - ix. Nevada Division of Water Resources, Well Log Database (Digital), http://ndwr.state.nv.us;
  - x. USGS Water Resources for Nevada, (Internet), http://water.usgs.gov/nv/nwis/nwis;
  - xi. Groundwater Network in Southern Nevada, (Internet), http://nevada.usgs.gov/gw.
- Water Levels. Various sources, including:
  - i. USGS ground-water levels retrieved from digital sources;
  - ii. Nevada Department of Water Resources Well Log Database; and
  - iii. Other sources as listed in the "Well Locations" item above.
- Property Boundary. Coyote Springs Investment, LLC.
- Water Rights Points-of-Diversion. Nevada Division of Water Resources Water Rights Database, Hydrographic Abstract Ground Water Report.
- Other administrative, cultural, and Landsat data. Various public agency sources as needed and available.

Summary information concerning groundwater model input parameters are provided in Tables 1 and 2.

Table 1: General Physical and Hydrologic Model Parameters

Groundwater Model Parameter	Use	Low Range	High Range	Typical or Fixed Value
Physical Model				
Alluvium, thickness (feet)	"Layer 1"	0	3,500	-
Carbonate Bedrock, thickness (feet)	"Layer 2"	-	-	12,000 feet
Surface Elevation		~2,000	~9,000	
Alluvium				
Hydraulic Conductivity, horizontal (ft/day)	Model Validation; Model Scenario Evaluation	-	-	10
Hydraulic Conductivity, vertical (ft/day)	Model Validation; Model Scenario Evaluation	-	-	0.5
Specific Yield	Model Scenario Evaluation	-	-	0.1
Piezometric Surface (Historic elevation in feet)	Model Validation	1,815 [a]	[b]	1,850 [c]
Bedrock (Carbonate)				
Hydraulic Conductivity, horizontal (ft/day)	Model Validation; Model Scenario Evaluation	0.03	45	2
Hydraulic Conductivity, vertical (ft/day)	Model Validation; Model Scenario Evaluation	0.005	1	0.01
Specific Storage (1/ft)	Model Scenario Evaluation	1x10e-6	1x10e-5	
Specific Yield	Model Scenario Evaluation	0.01	0.1	
Piezometric Surface (Historic elevation in feet)	Model Validation	1,815 [a]	[b]	1,850 [c]

[a] Typical value at southern end of Coyote Spring Valley basin; assumes alluvium, where thick enough, is in hydraulic connection with upper, unconfined portion of carbonate aquifer

[b] Maximum historic elevations are not well known. In general, hydrographs for Coyote Spring Valley wells are unchanged over the period of record. Model validation procedure includes testing of high water levels. Water elevations in Pahranagat Valley near the boundary with Coyote Spring Valley are approximately 3,100 feet.

[c] Typical value at central portion of project site; ; assumes alluvium, where thick enough, is in hydraulic connection with upper, unconfined portion of carbonate aquifer

Boundary Conditions

In addition to the hydrologic parameters for the model grid cells, boundary conditions must also be defined for the model; these are the flow conditions imposed on the model edges. All inflow and outflow across the model boundary occurs within Layer 2 (carbonate aquifer). Two types of boundary conditions are incorporated into the CSI model for Coyote Spring Valley: (1) flow boundaries, along which a constant rate of flow occurs, either into or out of the model grid space, simulated with injection or extraction wells; and (2) general head boundaries, in which head and flow across the boundary may vary, according to defined conditions for conductance.

The major inflows and outflows for the steady state model (Figure 4 and Table 2) equal 50,000 AFY interbasin groundwater flow from the north, 53,000 AFY interbasin outflow to the south. Combining the inflows with 4,000 AFY basin recharge and 1,000 AFY basinwide ET results in zero sum water balance for the steady state conditions, and initial conditions for the transient model.

The general head boundary was used to simulate connection of the carbonate aquifer within Coyote Spring Basin with the regional carbonate aquifer. Conductance was set to a small value in order to minimize flow across these boundaries, in order to simulate storage capacity of the carbonate aquifer outside the basin.

Geographic Information System

In addition to data management within the MODFLOW software package, a significant amount of the associated resource data is maintained in a Geographic Information System (GIS). The GIS was specifically constructed to organize and maintain project-related geospatial data using ESRI's most recent Arc/Info software and data storage schema. The system is used in conjunction with published reports and maps for analyses and modeling support.

There are two general types of data in the GIS: base map data, and project data. The base map data consist of the cultural, administrative, hydrography, transportation, cadastral, physical and image backdrop layers. The project data consist of the well locations, water rights points-of-diversion, CSI property boundary, water levels, basin profiles, and groundwater model data. The GIS was used to compile and utilize different geospatial information, and to help reconcile myriad and contradictory sources describing well locations in the project area. The GIS also provides a link to groundwater flow model digital data sources and spatial presentation of model results.

Table 2: Basin Water Balance Summary

Flow or Condition	Flow From	Flow To	Amount (AFY)
In-Basin Bedrock Recharge	Sheep Range	Coyote Spring Valley	4,000
Pahranagat Subsurface Flow*	Pahranagat Valley	Coyote Spring Valley	28,000
Delamar Subsurface Flow*	Delamar Valley	Coyote Spring Valley	16,000
Kane Spring Valley Subsurface Flow*	Kane Spring Valley	Coyote Spring Valley	6,000
Arrow Canyon Subsurface Flow*	Coyote Spring Valley	Upper Moapa Valley via Arrow Canyon	37,000
Hidden Valley Subsurface Flow*	Coyote Spring Valley	Hidden Valley and Garnet Valley	16,000
Model Boundary (West)**	Tikapoo Valley / Sheep Range	Coyote Spring Valley	40
Model Boundary (Southeast)**	Coyote Spring Valley	California Wash and Upper Moapa Valley	0.2
Model Boundary (East-Central)**	Coyote Spring Valley	Upper Moapa Valley	2
Model Boundary (Northeast)**	Delamar Valley / Kane Spring Valley	Coyote Spring Valley	24
Water Rights Points-of-Diversion (Proposed Groundwater Production)	Coyote Spring Valley	Net Consumptive	Phased production increments; up to 61,200 AFY net
Evapotranspiration	Basin-Wide	Consumed	1,000
*Flow focused along geological features			
**Boundary-distributed flow, based on general head boundary			

Model Validation – Steady-State Model Evaluation

The steady-state model has been calibrated by an iterative process to water levels in the wells CE-VF-2, MX-4 and MX-5, with calculated residuals less than 10 feet. This process is referred to as a validation process in view of the inability to calibrate the transient model with time-variant stresses on the hydrologic system. This inability reflects the paucity of data available for Coyote Spring Valley, and particularly the absence of measured aquifer stress conditions. It may be possible in the future to complete a calibration of the transient model after a period of groundwater production and associated monitoring within the basin.

The validation is a steady-state equilibrium analysis, based upon the physical model construction and hydrologic assumptions for the basin. The completion of the steady-state analysis was conducted through an iterative process of testing different model parameters for sensitivity and effect on the overall simulated basin conditions. A comparison of simulated basin conditions from the final steady-state model parameters and observed groundwater levels from available monitoring data provides a very close match for key monitoring wells in the basin (see "Water Level Data" section below).

The result of the validation exercise provides the initial condition for transient modeling to estimate changing groundwater conditions that result from the project's proposed pumping (see section "Transient Model Scenario" below).

Water Level Data

Water level data used in the model validation are derived from a variety of sources, and include a small number of monitoring points with several decades of relatively frequent water level measurements (a summary of water level data are provided in Appendix A, and the location and details of wells in the Coyote Spring Valley area are shown in Appendix B).

CSI's model validation is based on the most recent water levels observed, and is keyed in particular to a well at the northern margin of the project area, CE-VF-2, and to two wells near the intersection of important regional geological structures linking Coyote Spring Valley and Arrow Canyon, at wells MX-4 and MX-5. Simulated water levels from the groundwater model steady-state produce residuals of 9 feet for CE-VF-2 and –7 feet for MX-4 and MX-5. The simulated results are also consistent basin-wide with other data available for Coyote Spring Valley (Figure 4).

Limitations and Implications

Because the data do not provide for transient-state model calibration, emphasis has been placed on model development and testing to incorporate and utilize information currently available on the Coyote Spring Valley basin groundwater flow system:

- Physical model construction is a realistic generalization of the alluvial and bedrock geology;
- Distribution of hydraulic conductivity in the model region is a realistic generalization of the primary groundwater flowpaths into, within and out of the basin;
- Steady-state model validation provides simulated water levels in close match with observed water levels at key wells;
- Model boundary conditions match subsurface inflow and outflow rates assumed for the basin, based on existing research;

- Model boundary conditions away from the primary inflow and outflow regions provide realistic (and very small) flows across the basin boundary; and
- Steady-state model provides a meaningful platform for evaluating groundwater changes that could result from new groundwater production within Coyote Spring Valley.

Whereas parameters such as storativity and specific yield are important to the transient model and the associated evaluation of proposed new groundwater production, it is not possible to test sensitivity for storage coefficients in the steady-state validation process.

In contrast, hydraulic conductivity has a large and important impact on simulated groundwater conditions, and CSI has determined that the distribution of hydraulic conductivity presented in the model is relatively well constrained. Without changing the complete hydraulic conductivity distribution for all portions of the model, relative changes in hydraulic conductivity between the zones shown in Figure 3 cannot vary by more than 10% without producing unrealistic steady-state simulated conditions.

The range of hydraulic conductivity values used by CSI are representative of realistic geologic variations, and are consistent with other research (e.g., Mifflin, 2001; LVVWD, 2001). To the extent that specific areas that are narrower than the CSI model hydraulic conductivity zones (such as individual faults or local zones of pervasive mineralization) may have hydraulic conductivity that ranges even higher or lower than the values used by CSI, the CSI model averages these variations.

On this basis, the selection of model parameters used in the CSI groundwater modeling is reasonable based on:

- Limited sensitivity testing of model parameters;
- Existing literature and research;
- Results of other modeling (such as LVVWD, 2001; Mifflin, 2001), and
- Requirement that the steady-state model simulation match existing, observed water levels.

Transient Model Scenario

CSI has utilized the steady-state model result to analyze potential changes in groundwater conditions within Coyote Spring Valley for a pumping scenario for the CSI project. This analysis is based on transient modeling of the basin, with staged increases in project pumping over several decades, and a total period of analysis of 60 years. Results of the analysis provide simulations of anticipated water levels and associated drawdown resulting from the groundwater production.

The scenario utilizes the same model parameters as the steady-state model exercise. Accordingly, groundwater flow rates into and out of the basin remain constant throughout the duration of the simulated production, including the 37,000 AFY outflow from Coyote Spring Valley to Upper Moapa Valley at Arrow Canyon.

Production Scenario

Simulated basin groundwater conditions associated with CSI project development are summarized in the following groundwater use scenario:

- Groundwater Production Increment 1: 15,000 AFY, for first ten years, of which 9,000 AFY is in the northernmost portion of development property, and 6,000 AFY just south of the Lincoln-Clark County line;
- Groundwater Production Increment 2: Additional 15,000 AFY, for next ten years, proportionately distributed as in Increment 1 (9,000 AFY in Lincoln County, 6,000 AFY in Clark County);
- Groundwater Production Increment 3: Additional 19,000 AFY, for next ten years, proportionately distributed as in previous increments (11,400 AFY in Lincoln County, 7,600 AFY in Clark County);
- Groundwater Production Increment 4: Last 12,200 AFY, for ten years, in and around MX wells and approximately distributed as in previous increments (7,200 AFY in Lincoln County, 5,000 AFY in Clark County);
- Groundwater Production Net production of 61,200 AFY (Table 3) for twenty additional years, with total transient model length of 60 years.

Table 3: Groundwater Production Scenario for CSI Project – Total Amounts after All Increments of Use

Net Groundwater Use – CSI Model Scenario, Total Use After All Increments	
Clark County:	
Net Groundwater Use*:	24,600 AFY
Lincoln County:	
Net Groundwater Use*:	36,600 AFY
Coyote Springs Investment Development Total:	
Total Net Groundwater Use*:	61,200 AFY
*Amount of groundwater production simulated using groundwater model	

Simulation Results

Results of the simulation show that the amount of modeled groundwater pumping produces lowering of the water table in Coyote Spring Valley, with constant subsurface groundwater inflow and outflow, including flow from the basin to Upper Moapa Valley via Arrow Canyon. Accordingly, the model simulates a large amount of groundwater production from storage, within both the alluvial and carbonate units. Figures 5 through 12 show water levels and drawdown for Layer 2 only (carbonate unit) associated with cumulative impact after progressive production increments. Water level changes within Layer 1, which is hydraulically isolated within Coyote Spring Valley, are controlled by the changes in the Layer 2 carbonate aquifer, and change in concert with the Layer 2 water level changes.

Incremental drawdown of the water table within Coyote Spring Valley is small after the first two increments of pumping; refer to Figures 5 – 6 (first groundwater production increment) and Figures 7 – 8 (second production increment). Decline in water levels basin-wide is less than 20 feet after the second increment of groundwater production.

In the region of highest hydraulic conductivity, along the prominent geological structures that focus groundwater flow in the carbonate aquifer, groundwater level drawdown after the 60-year model test period is approximately 70 feet. In regions of the basin closer to the southern boundary with Hidden Valley and the northern boundary with Pahranagat and Kane Spring Valley, total drawdown is less – approximately 50 feet. Along the western basin boundary, at the Sheep Range, the least amount of potential groundwater drawdown is expected – approximately 10 to 30 feet (see Figure 12 for drawdown results and Figure 11 for corresponding water levels).

Discussion

CSI's groundwater model for the Coyote Spring Valley is a numerical estimation of potential impact to groundwater levels within the basin resulting from 60 years of production for the proposed CSI development. The production is staged, with initial net groundwater production of 15,000 AFY for 10 years, and additional increments occurring over the next 30 years. The simulation considers groundwater production over a total 60-year period, with final, net groundwater production of 61,200 AFY.

The simulated groundwater level drawdowns are reasonable and consistent with existing knowledge of the hydrogeology of the Coyote Spring Valley, and suggest that groundwater withdrawals from Coyote Spring Valley may result in lowering of the basin water table in the vicinity of the proposed project approximately 70 feet over 60 years, with constant flow of groundwater in the carbonate aquifer both into and out of Coyote Spring Valley. Groundwater level declines in other portions of the basin are estimated to be as little as 30 feet or less at the Sheep Range along the western basin boundary, and approximately 50 feet at the boundaries with Pahranagat, Delamar and Hidden Valleys.

During the first increments of pumping, drawdown is relatively small: after 20 years, at the conclusion of the second pumping increment, simulated water levels are no more than 20 feet below pre-development water levels at the CSI project area, and are less than 10 feet below pre-development water levels in other portions of the basin.

It is CSI's intent that groundwater modeling will be revised as new hydrologic data become available for the basin, such that the estimates of hydrologic response to pumping and potential impacts to groundwater levels in the basin are revised to reflect new information that is gathered from monitoring of new pumping stresses to the aquifer system.

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Figures

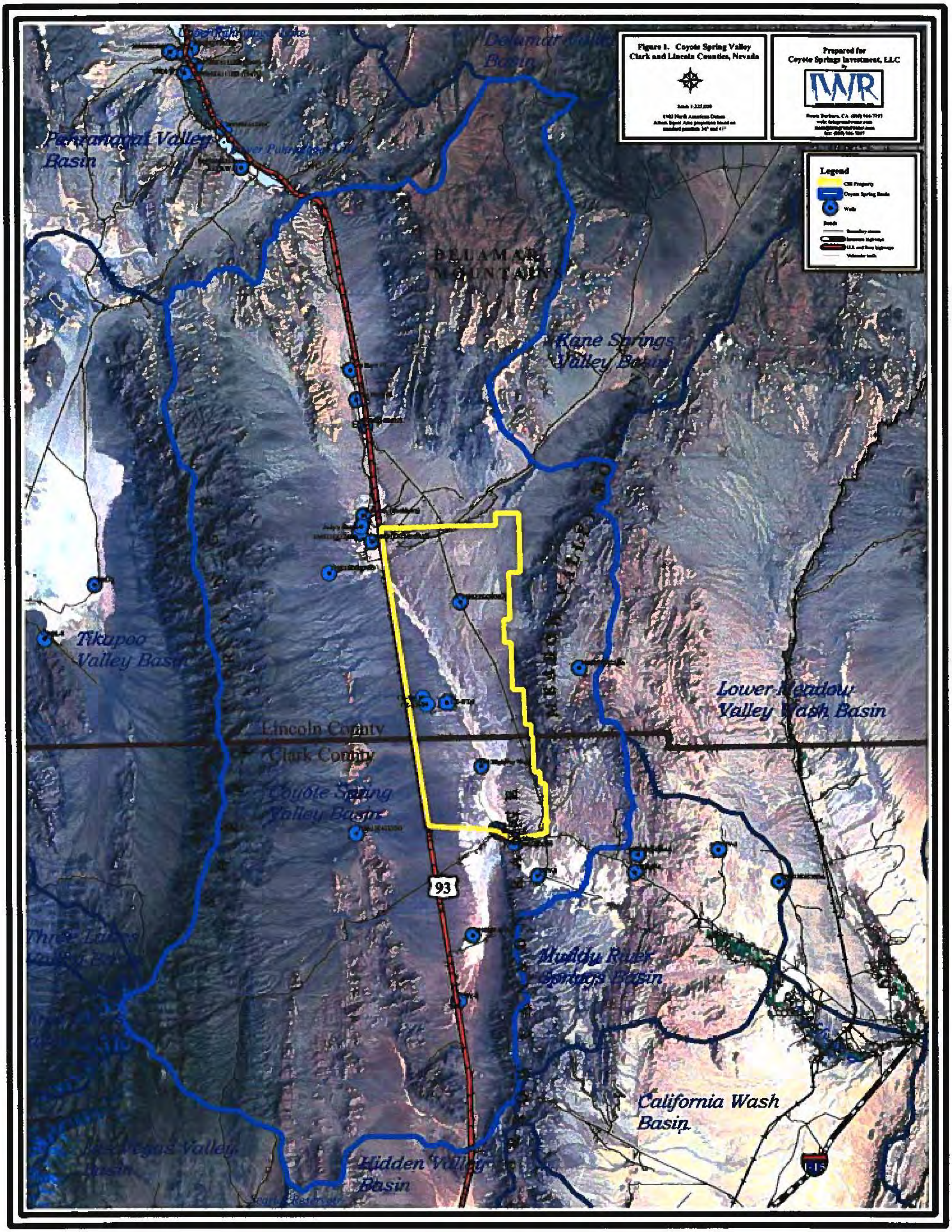

Figure 1. Coyote Spring Valley
Clark and Lincoln Counties, Nevada
Prepared for
Coyote Springs Investment, LLC
IWR
Legend
Wells
Delamar Valley Basin
Pahranagat Valley Basin
DELAMAR MOUNTAINS
Kane Springs Valley Basin
Tikapoo Valley Basin
Lower Meadow Valley Wash Basin
Lincoln County
Clark County
Coyote Spring Valley Basin
93
Muddy River Springs Basin
California Wash Basin
Hidden Valley Basin

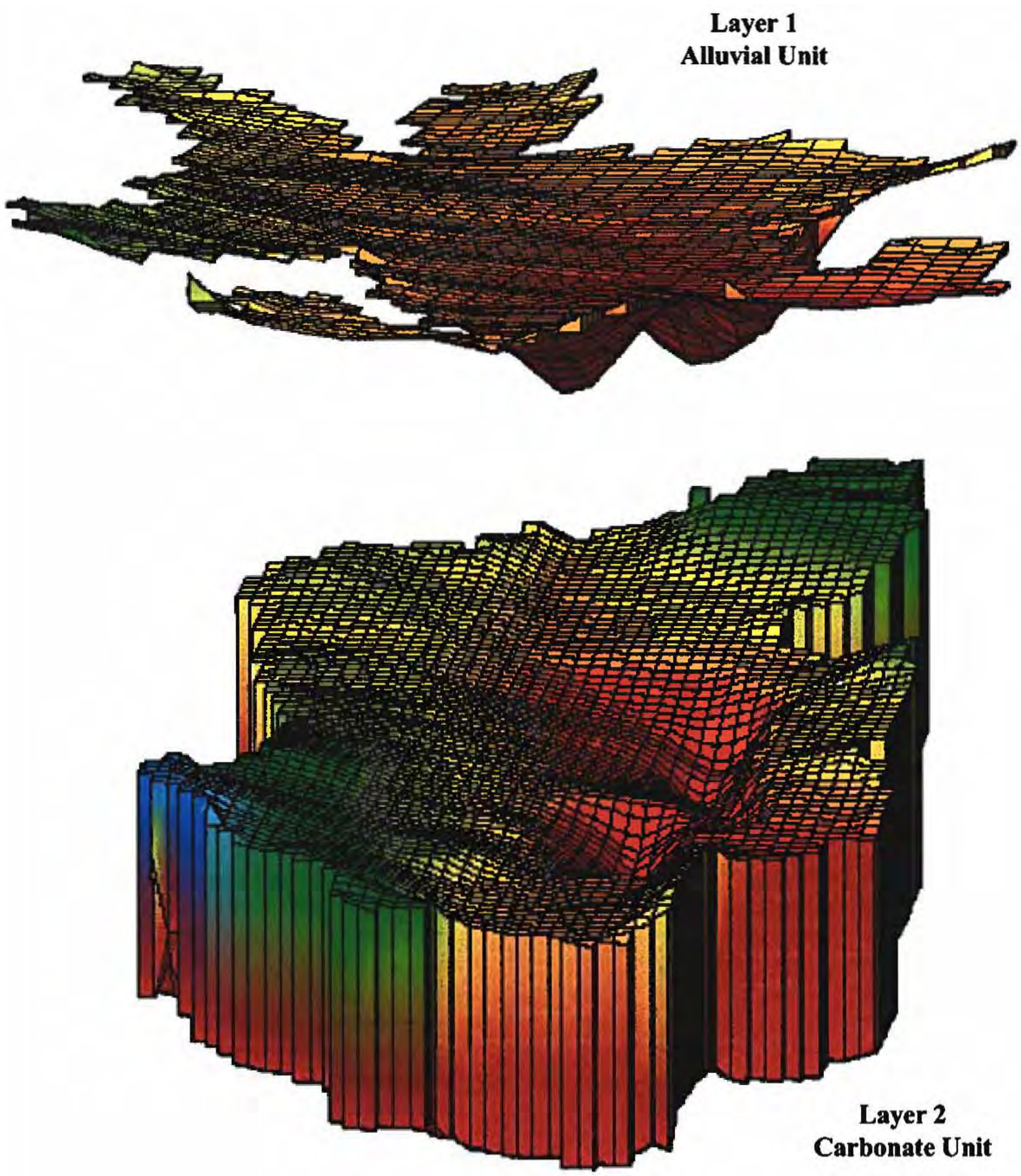

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Figure 2a. Three-dimensional rendering, looking from SSE to NNW, of model construction showing layer thickness. Refer to text for discussion.

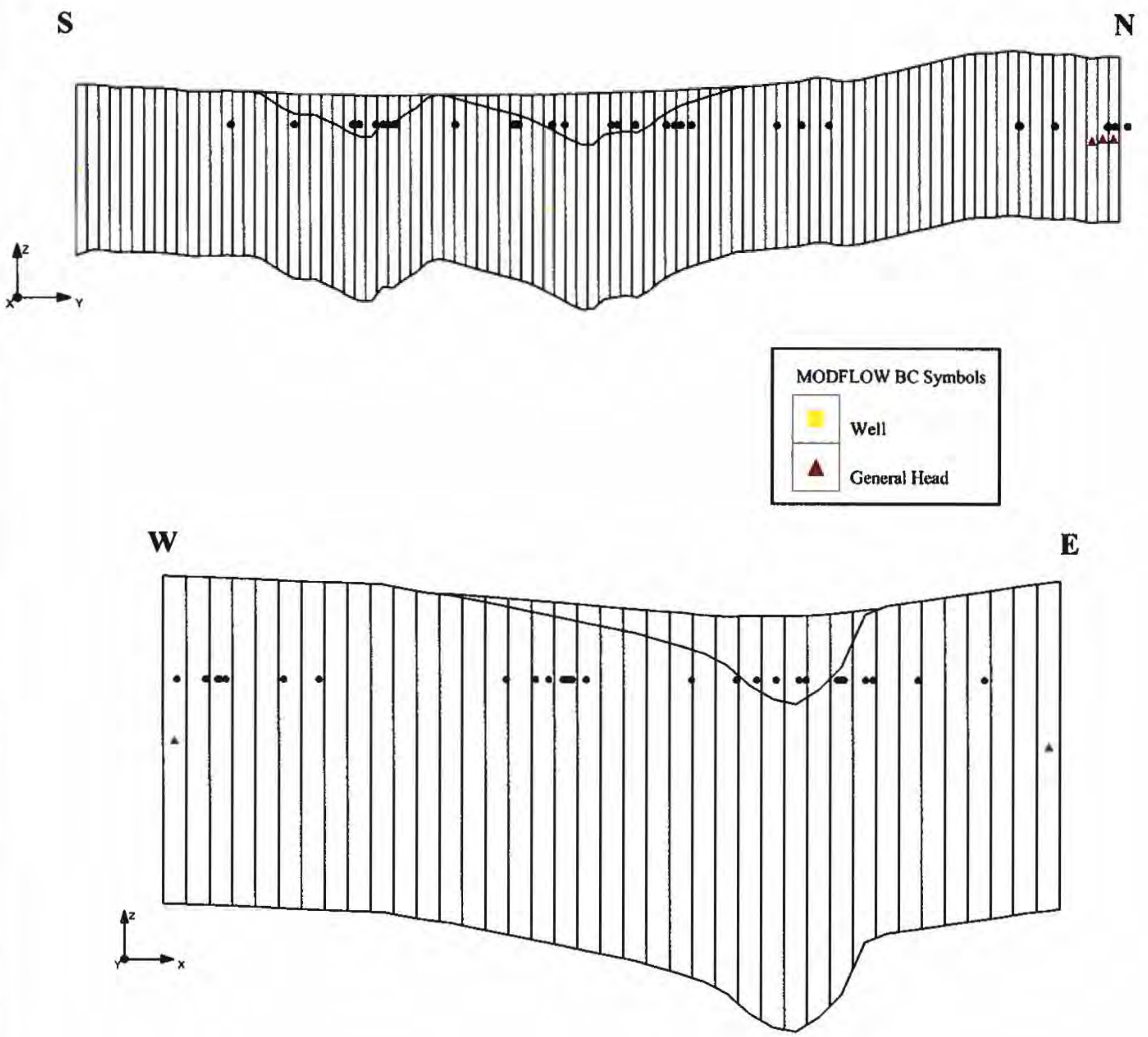

Figure 2b. Cross section of model construction. See Figure 3c for cross-section locations.

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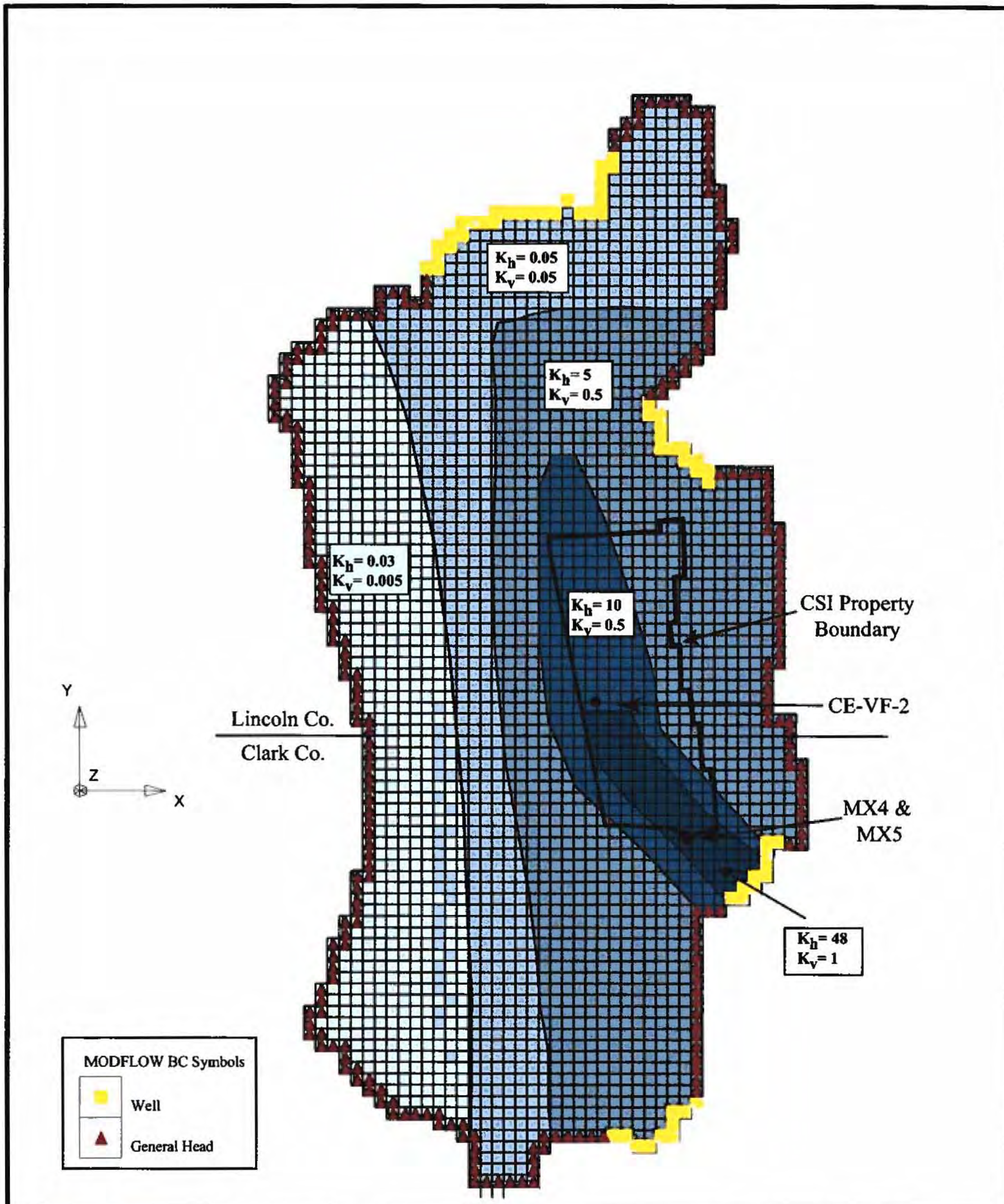

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Figure 3a. Distribution of hydraulic conductivity zones for Layer 2 (carbonate bedrock).

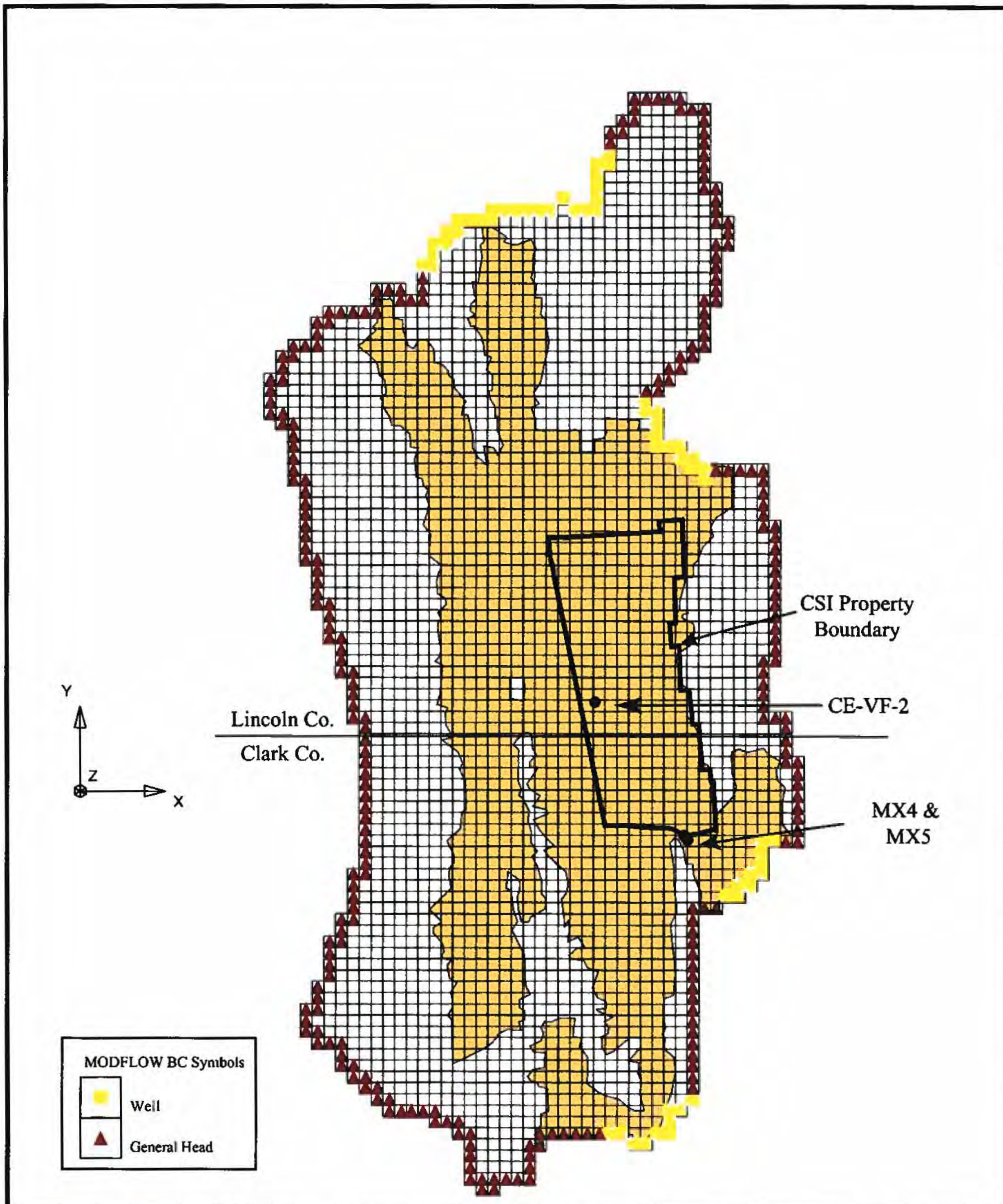

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Figure 3b. Distribution of Layer 1 (alluvium).

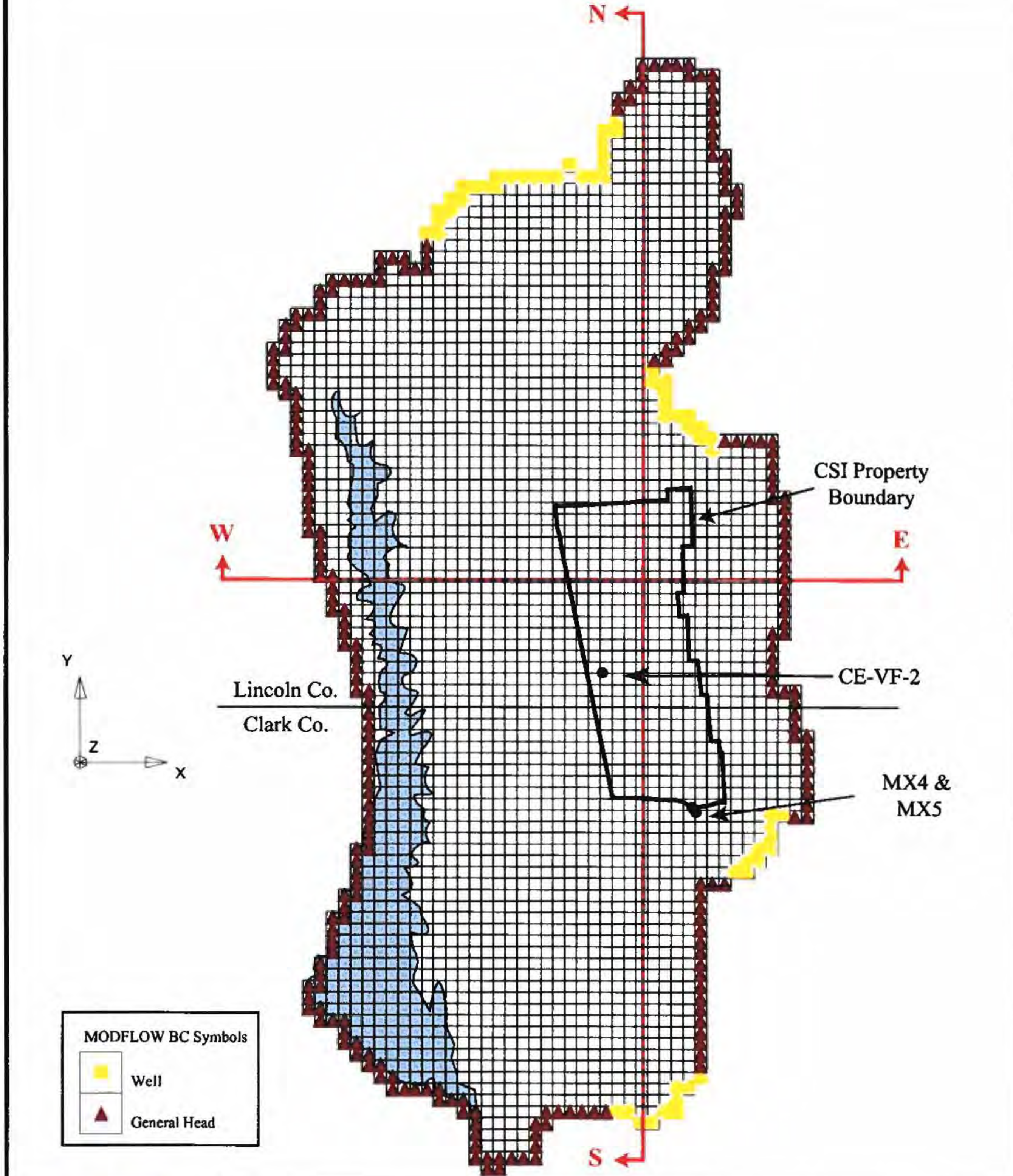

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Figure 3c. Area over which 4,000 AFY recharge in Sheep Range is distributed. Cross sections denoted by W-E and N-S are shown in Figure 2(b).

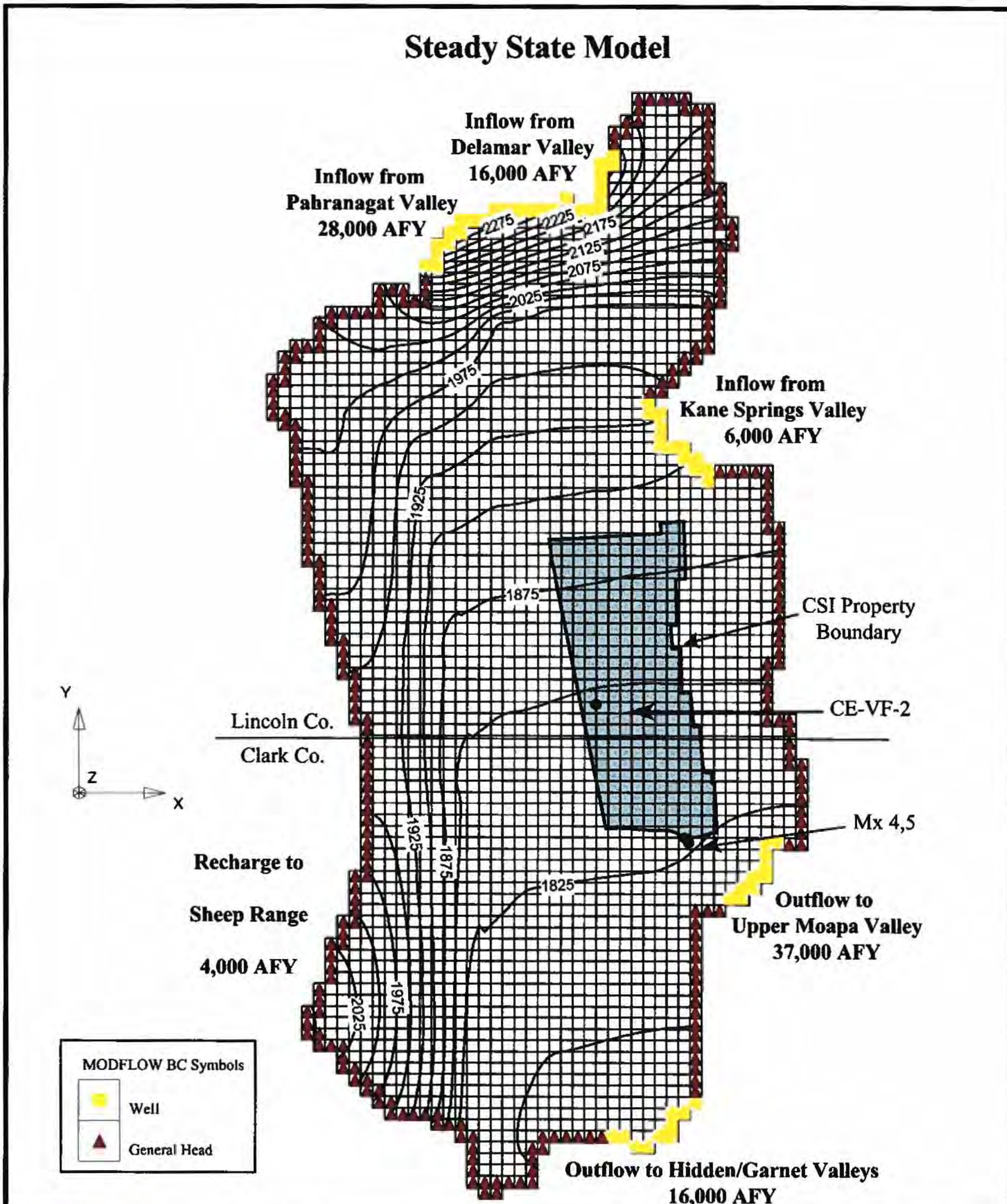

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Figure 4. Steady-state model simulation, showing in-flows, outflows and boundary conditions.

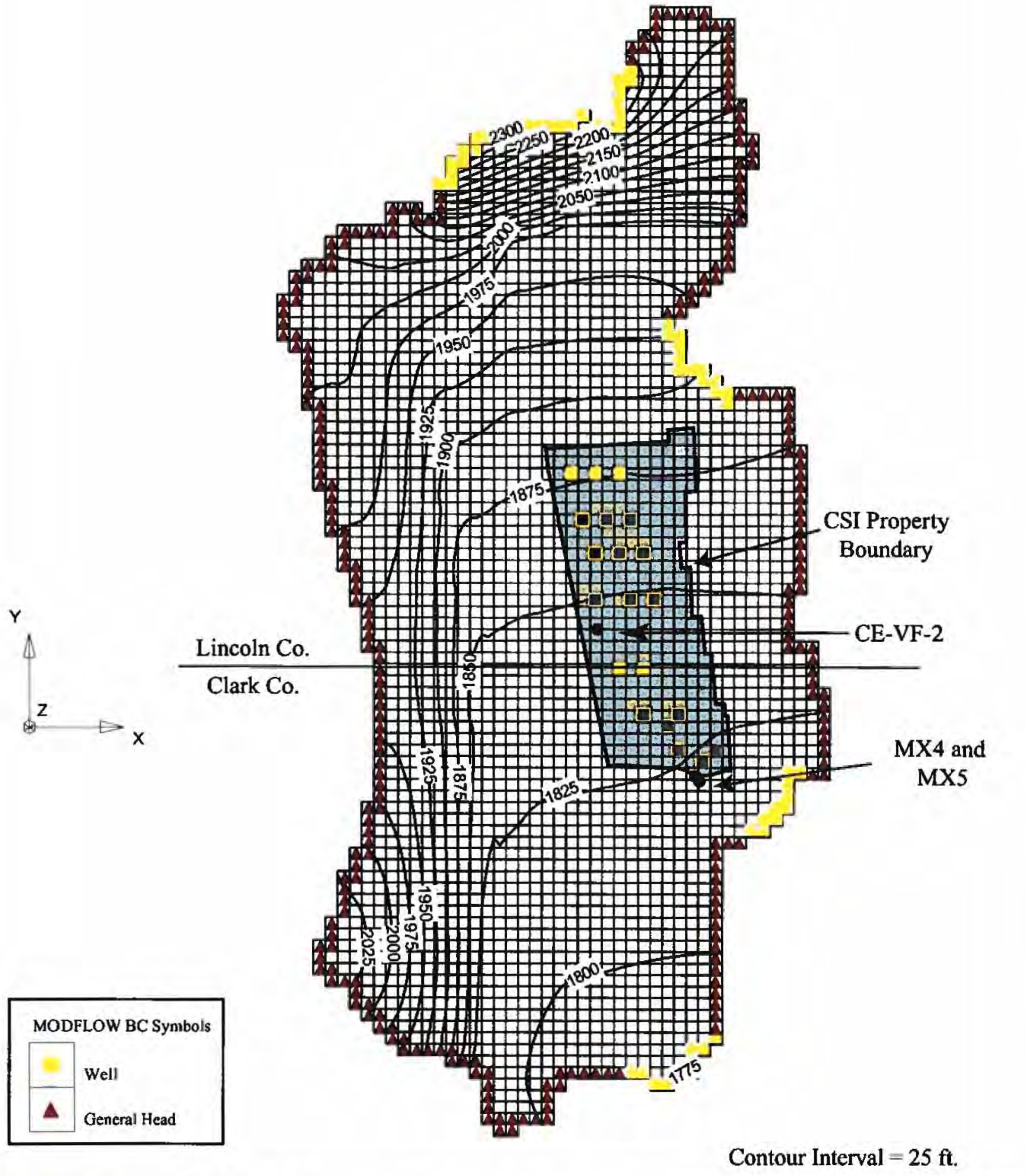

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Figure 5. Simulated water levels after first pumping increment (15,000 AFY for 10 years). Active pumping cells shown in yellow.

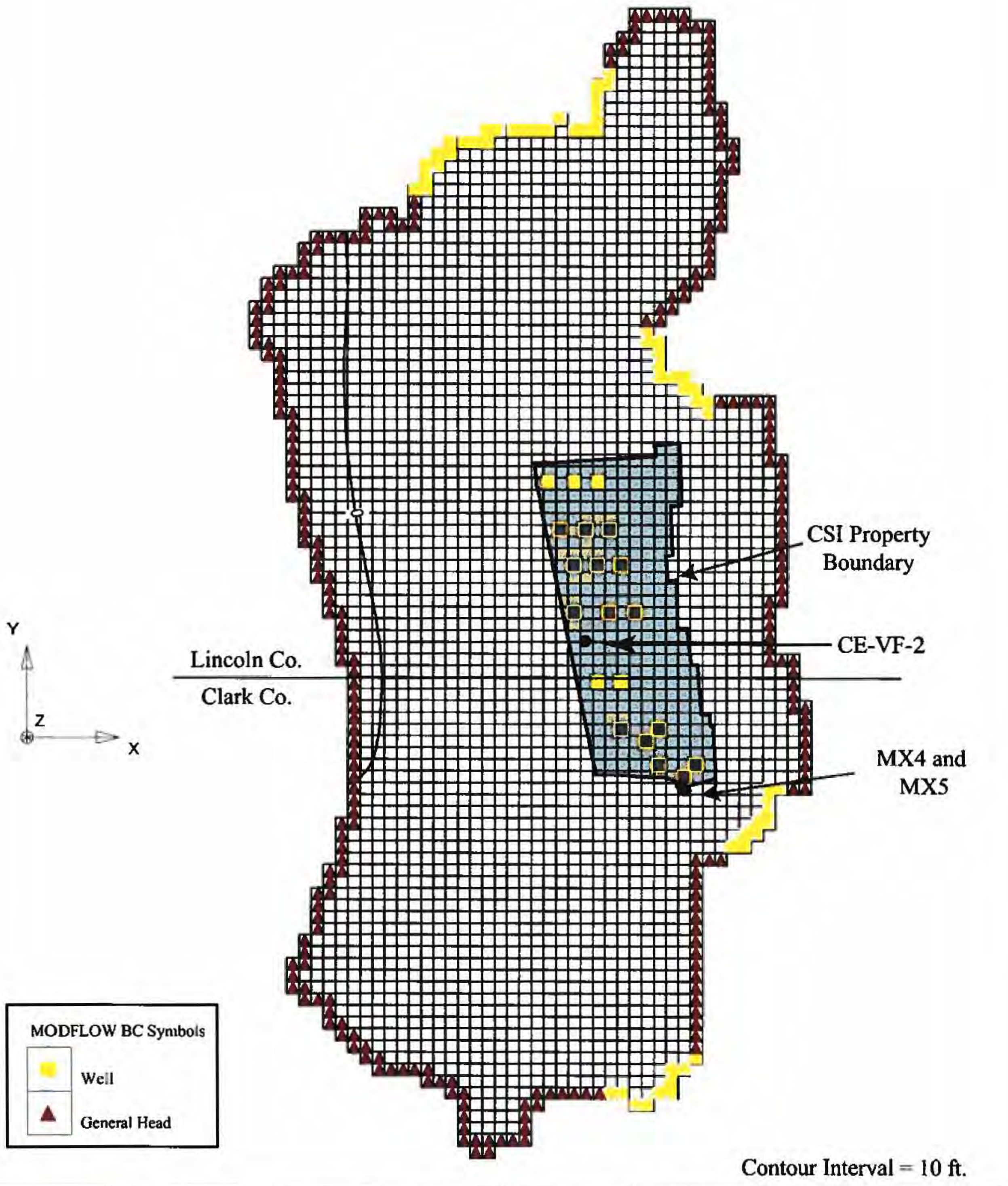

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Figure 6. Simulated drawdown after first pumping increment (15,000 AFY for 10 years). Active pumping cells shown in yellow.

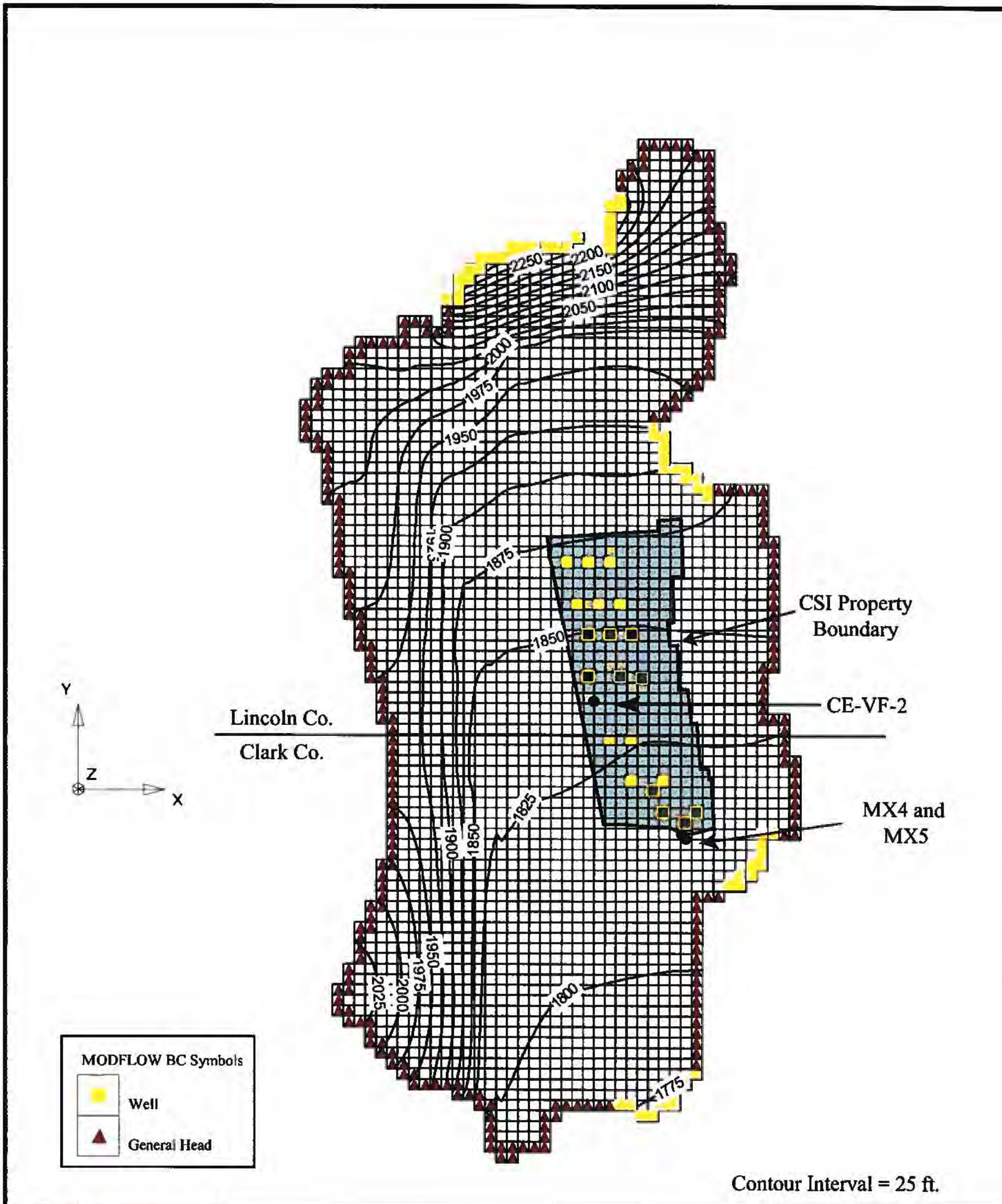

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Figure 7. Cumulative, simulated water levels after second pumping increment (15,000 AFY for 10 years). Active pumping cells shown in yellow.

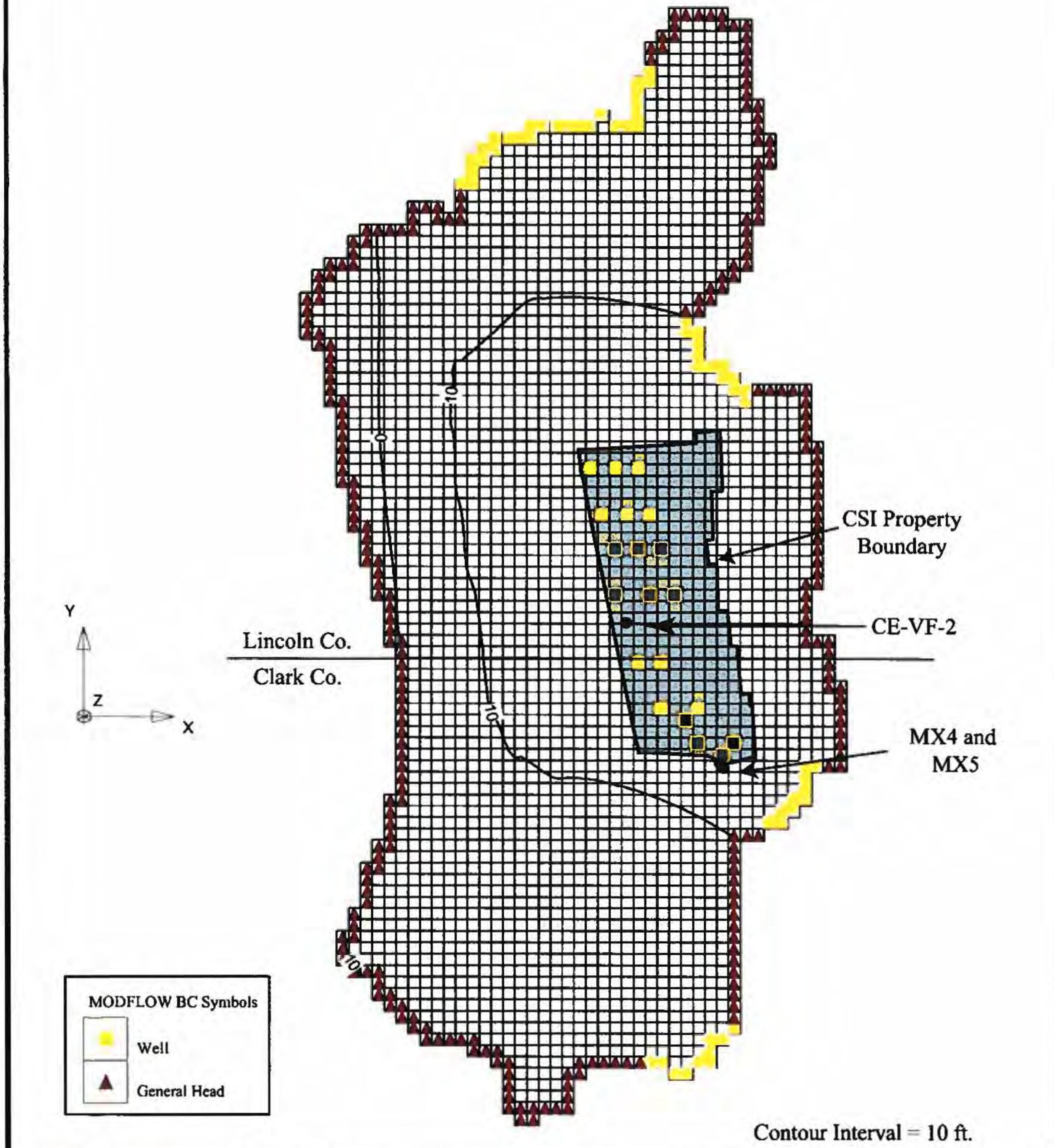

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Figure 8. Cumulative, simulated drawdown after second pumping increment (15,000 AFY for 10 years). Active pumping cells shown in yellow.

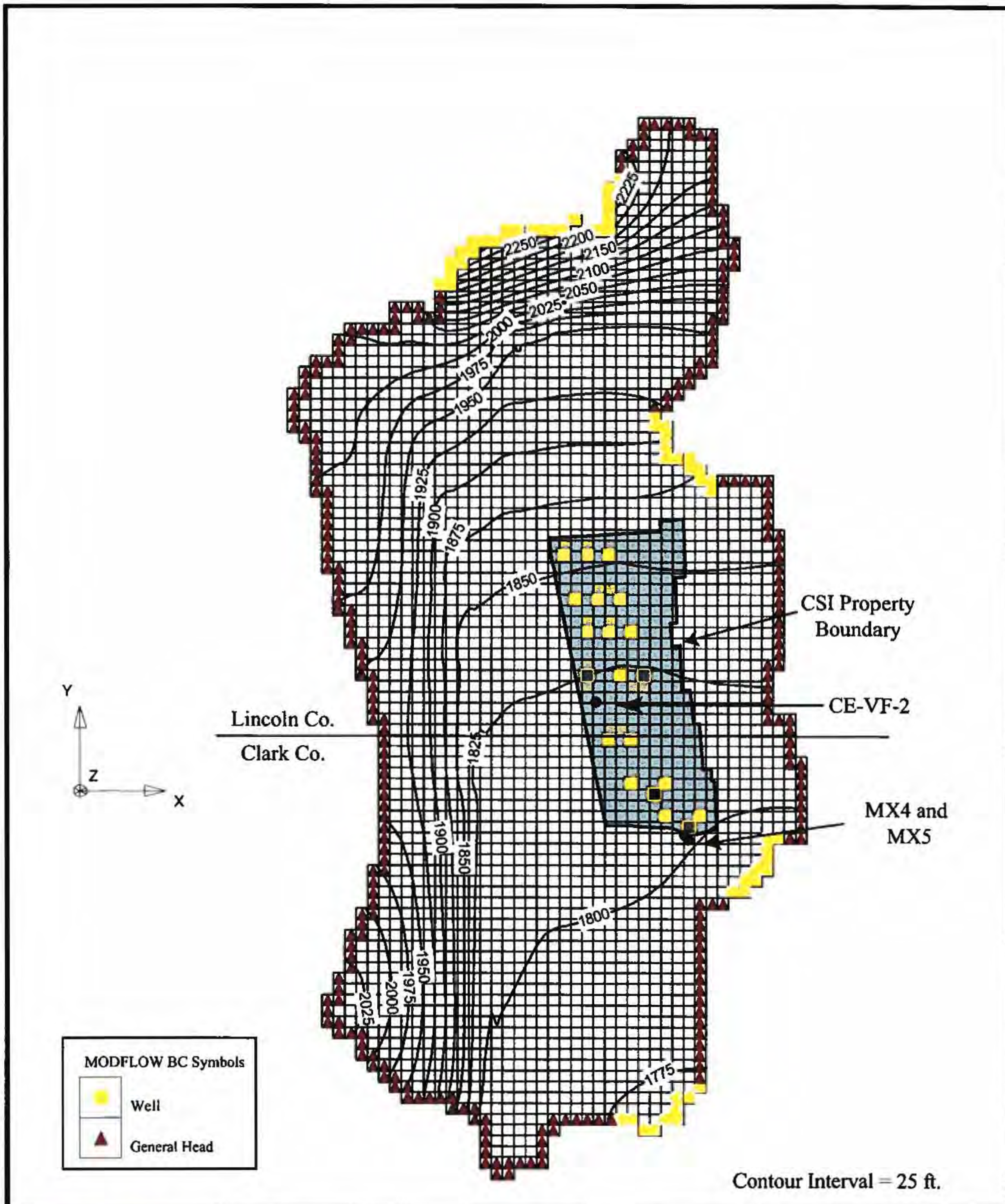

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Figure 9. Cumulative, simulated water levels after third pumping increment (19,000 AFY for 10 years). Active pumping cells shown in yellow.

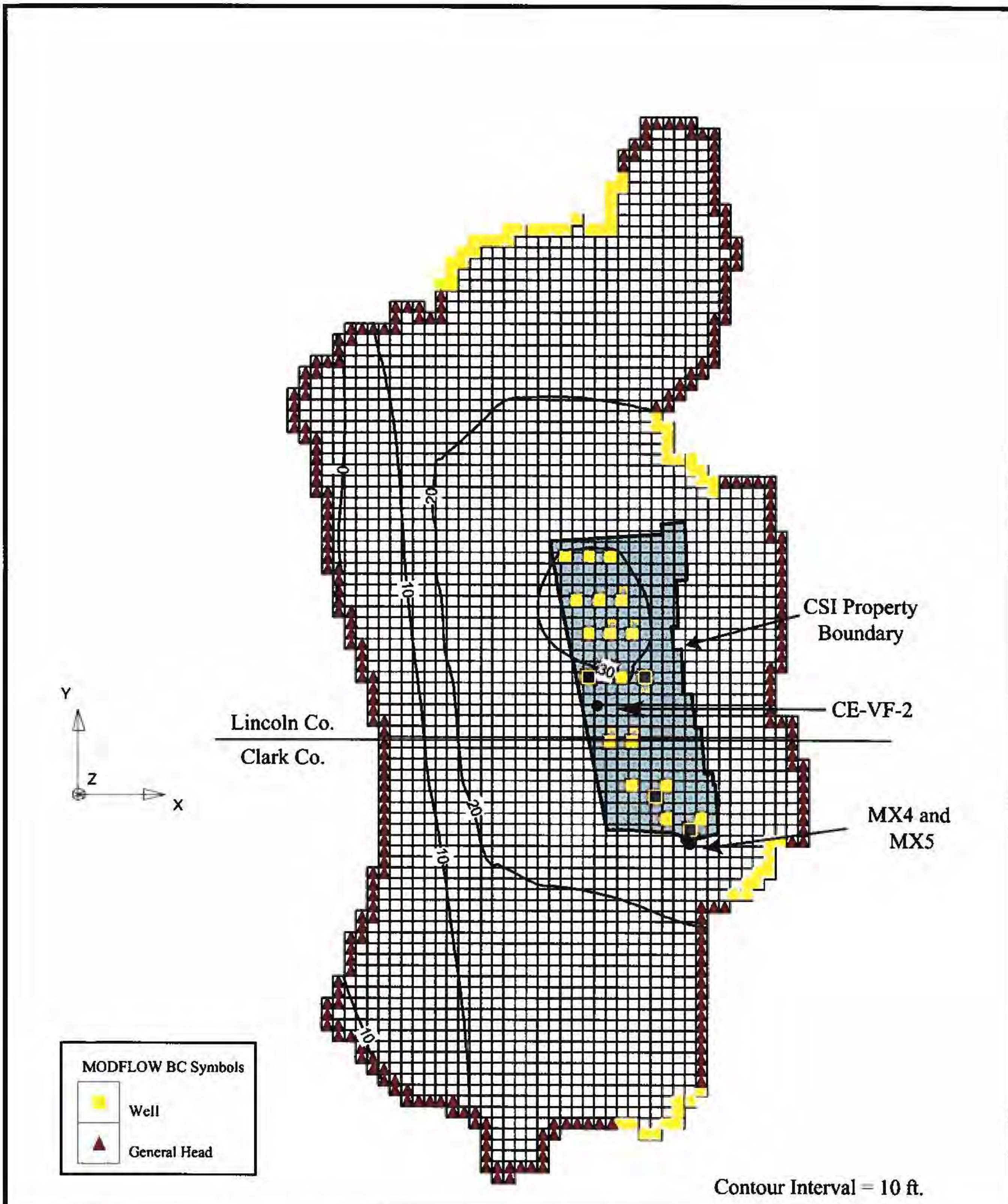

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Figure 10. Cumulative, simulated drawdown after third pumping increment (19,000 AFY for 10 years). Active pumping cells are shown in yellow.

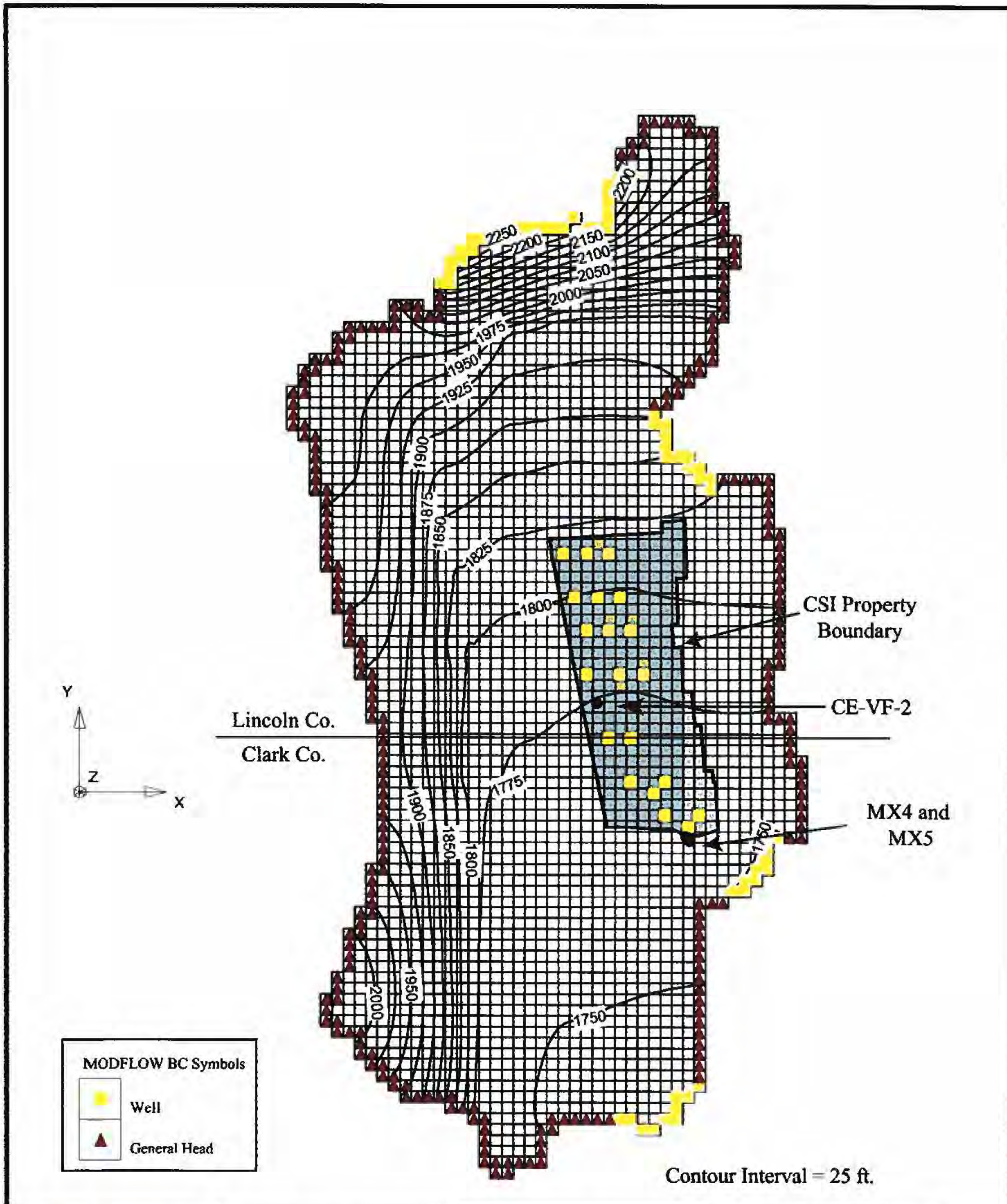

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Figure 11. Cumulative, simulated water levels after fourth pumping increment (12,100 AFY for 10 years), plus 20 years at full net pumping (60 year total transient model simulation period). Active pumping cells shown in yellow.

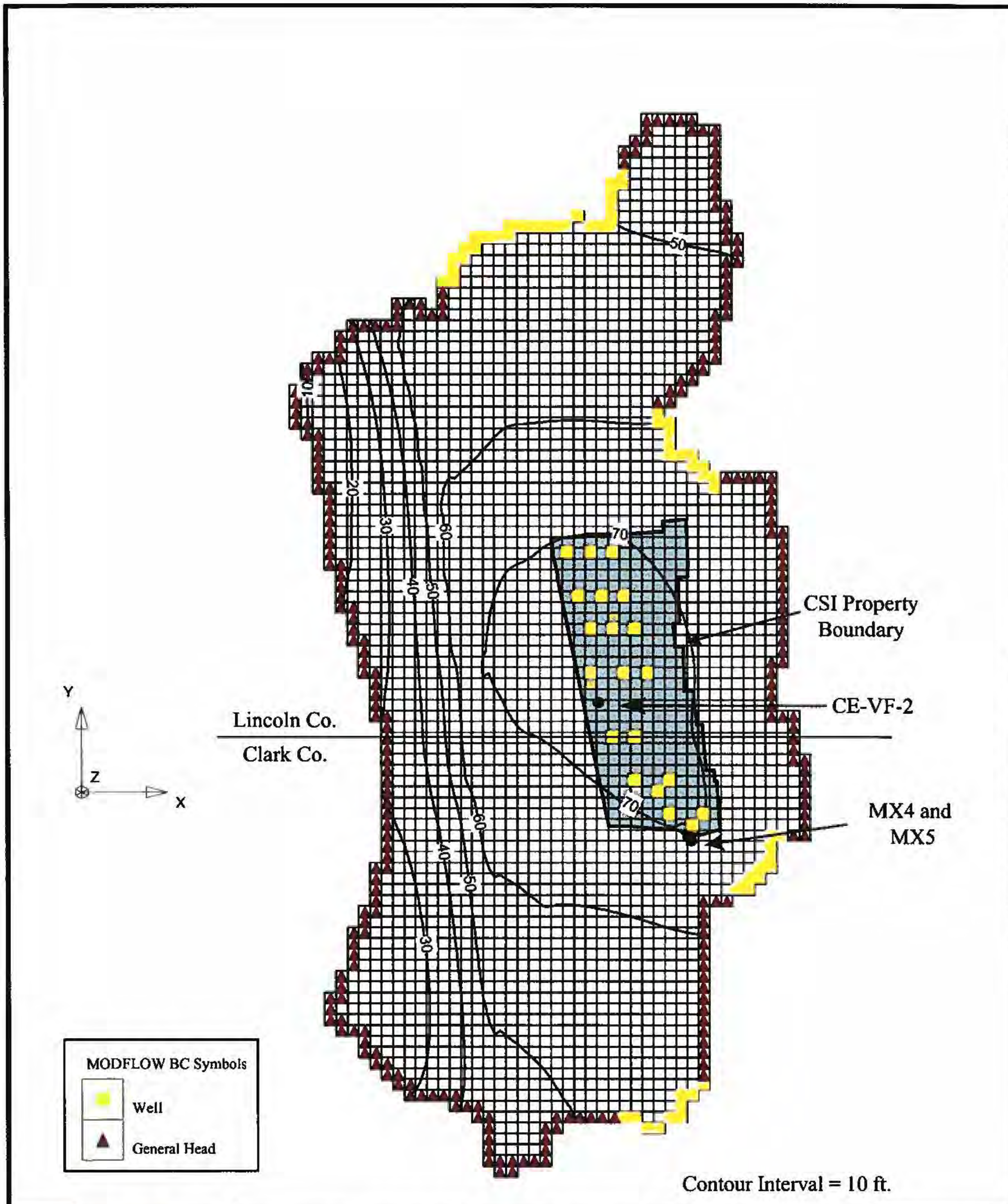

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Figure 12. Cumulative, simulated drawdown after fourth pumping increment (12,100 AFY for 10 years), plus 20 years at full net pumping (60-year total transient model simulation period). Active pumping cells shown in yellow.

Appendix A – Water Level Data

Appendix A – Water Level Data

Appendix A: Coyote Spring Valley Water Level Data								
Well Site ID	Well Name	Reading Date	Ground Elevation (ft)	Well Depth (ft)	Water Level (feet below surface)	Water Level (ft mean sea level)	Comments	USGS Well ID
217S16E6309DDAB1	SHV-1	12/30/85	2648.8	920	833.2	1815.6		363308114553001
217S16E6309DDAB1	SHV-1	9/13/87	2648.8	920	831	1817.8		363308114553001
217S16E6309DDAB1	SHV-1	1/31/89	2648.8	920	831	1817.8		363308114553001
217S16E6309DDAB1	SHV-1	3/28/89	2648.8	920	831	1817.8		363308114553001
217S16E6309DDAB1	SHV-1	5/30/89	2648.8	920	830.3	1818.5		363308114553001
217S16E6309DDAB1	SHV-1	7/26/89	2648.8	920	830.7	1818.1		363308114553001
217S16E6309DDAB1	SHV-1	9/12/89	2648.8	920	830.9	1817.9		363308114553001
217S16E6309DDAB1	SHV-1	8/12/99	2648.8	920	831.7	1817.1		363308114553001
217S16E6309DDAB1	SHV-1	7/7/00	2648.8	920	831.31	1817.49		363308114553001
217S16E6309DDAB1	SHV-1	8/17/00	2648.8	920	834.6	1814.2		363308114553001
217S16E6309DDAB1	SHV-1	10/24/00	2648.8	920	831.55	1817.25		363308114553001
217S16E6309DDAB1	SHV-1	1/5/01	2648.8	920	831.5	1817.3		363308114553001
210S14E6328ACDC1	CSV-3	12/20/85	2414.3	780	585	1829.3		364127114553001
210S14E6328ACDC1	CSV-3	2/19/86	2414.3	780	587.5	1826.8		364127114553001
210S14E6328ACDC1	CSV-3	9/13/87	2414.3	780	589.45	1824.85		364127114553001
210S14E6328ACDC1	CSV-3	5/18/88	2414.3	780	589.3	1825		364127114553001
210S14E6328ACDC1	CSV-3	8/4/88	2414.3	780	589.4	1824.9		364127114553001
210S14E6328ACDC1	CSV-3	12/13/88	2414.3	780	589.02	1825.28		364127114553001
210S14E6328ACDC1	CSV-3	1/31/89	2414.3	780	589.5	1824.8		364127114553001
210S14E6328ACDC1	CSV-3	3/28/89	2414.3	780	588.7	1825.6		364127114553001
210S14E6328ACDC1	CSV-3	5/30/89	2414.3	780	588.6	1825.7		364127114553001
210S14E6328ACDC1	CSV-3	7/26/89	2414.3	780	588.6	1825.7		364127114553001
210S14E6328ACDC1	CSV-3	9/12/89	2414.3	780	588.8	1825.5		364127114553001
210S14E6328ACDC1	CSV-3	11/13/90	2414.3	780	589.6	1824.7		364127114553001
210S14E6328ACDC1	CSV-3	3/19/91	2414.3	780	589.3	1825		364127114553001
210S14E6328ACDC1	CSV-3	6/18/91	2414.3	780	589.6	1824.7		364127114553001
210S14E6328ACDC1	CSV-3	9/12/91	2414.3	780	589.9	1824.4		364127114553001

210S14E6328ACDC1	CSV-3	12/10/91	2414.3	780	589.6	1824.7		364127114553001
210S14E6328ACDC1	CSV-3	3/11/92	2414.3	780	589.7	1824.6		364127114553001
210S14E6328ACDC1	CSV-3	6/17/92	2414.3	780	589.5	1824.8		364127114553001
210S14E6328ACDC1	CSV-3	9/8/92	2414.3	780	589.6	1824.7		364127114553001
210S14E6328ACDC1	CSV-3	12/21/92	2414.3	780	589.9	1824.4		364127114553001
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210S14E6328ACDC1	CSV-3	6/7/93	2414.3	780	589.5	1824.8		364127114553001
210S14E6328ACDC1	CSV-3	9/7/93	2414.3	780	589.8	1824.5		364127114553001
210S14E6328ACDC1	CSV-3	12/15/93	2414.3	780	589.6	1824.7		364127114553001
210S14E6328ACDC1	CSV-3	3/31/94	2414.3	780	589.2	1825.1		364127114553001
210S14E6328ACDC1	CSV-3	7/7/94	2414.3	780	589.02	1825.28		364127114553001
210S14E6328ACDC1	CSV-3	9/20/94	2414.3	780	590.16	1824.14		364127114553001
210S14E6328ACDC1	CSV-3	7/7/00	2414.3	780	590.06	1824.24		364127114553001
210S14E6328ACDC1	CSV-3	8/17/00	2414.3	780	593.39	1820.91		364127114553001
210S14E6328ACDC1	CSV-3	1/5/01	2414.3	780	590.41	1823.89		364127114553001
209S08E6102BD	209S08E6102BD	6/29/71	3600	245	13	3587	WL from Driller's log, ground elev from DEM	
209S08E6103	209S08E6103	6/16/62	3434	350	9	3425	WL from Driller's log, ground elev from DEM	
209S08E6111BD	209S08E6111BD	10/10/00	3356	190	34	3322	WL from Driller's log, ground elev from DEM	
210S10E6225	210S10E6225	7/11/77	2618	500	360	2258	WL from Driller's log, ground elev from DEM	
210S14E6310	210S14E6310	5/4/44	2315	353	332	1983		364352114544701
210S11E6213BD	C.S. Inc. (Buckhorn)	6/24/70	2577	100	37	2540	WL from Driller's log, ground elev from DEM	
210S11E6224BD	210S11E6224BD	11/21/99	2573	213	63	2510	WL from Driller's log, ground elev from DEM	
210S11E6227DD	210S11E6227DD	12/19/96	2775	80	72	2703	WL from Driller's log, ground elev from DEM	

217S16E6315AA	217S16E6315AA	9/19/95	2867	70	46	2821	WL from Driller's log, ground elev from DEM	
217S16E6315AA	217S16E6315AA	9/19/95	2867	70	46	2821	WL from Driller's log, ground elev from DEM	
217S16E6315AA	217S16E6315AA	9/19/95	2867	70	46	2821	WL from Driller's log, ground elev from DEM	
219S13E6431DAAD1	CSV-1	11/11/85	2158.6	765	343.9	1814.7		364601114514301
219S13E6431DAAD1	CSV-1	12/17/85	2158.6	765	344.68	1813.92		364601114514301
219S13E6431DAAD1	CSV-1	9/11/87	2158.6	765	344.44	1814.16		364601114514301
219S13E6431DAAD1	CSV-1	5/18/88	2158.6	765	344.33	1814.27		364601114514301
219S13E6431DAAD1	CSV-1	8/3/88	2158.6	765	344.49	1814.11		364601114514301
219S13E6431DAAD1	CSV-1	12/8/88	2158.6	765	344.58	1814.02		364601114514301
219S13E6431DAAD1	CSV-1	1/20/89	2158.6	765	344.66	1813.94		364601114514301
219S13E6431DAAD1	CSV-1	1/31/89	2158.6	765	344.52	1814.08		364601114514301
219S13E6431DAAD1	CSV-1	3/28/89	2158.6	765	344.6	1814		364601114514301
219S13E6431DAAD1	CSV-1	5/30/89	2158.6	765	344.38	1814.22		364601114514301
219S13E6431DAAD1	CSV-1	7/26/89	2158.6	765	344.46	1814.14		364601114514301
219S13E6431DAAD1	CSV-1	9/12/89	2158.6	765	344.72	1813.88		364601114514301
219S13E6431DAAD1	CSV-1	11/13/90	2158.6	765	345.1	1813.5		364601114514301
219S13E6431DAAD1	CSV-1	3/26/91	2158.6	765	344.44	1814.16		364601114514301
219S13E6431DAAD1	CSV-1	6/13/91	2158.6	765	344.8	1813.8		364601114514301
219S13E6431DAAD1	CSV-1	9/12/91	2158.6	765	344.07	1814.53		364601114514301
219S13E6431DAAD1	CSV-1	12/10/91	2158.6	765	344.59	1814.01		364601114514301
219S13E6431DAAD1	CSV-1	3/18/92	2158.6	765	345.1	1813.5		364601114514301
219S13E6431DAAD1	CSV-1	6/15/92	2158.6	765	344.4	1814.2		364601114514301
219S13E6431DAAD1	CSV-1	9/14/92	2158.6	765	344.9	1813.7		364601114514301
219S13E6431DAAD1	CSV-1	12/9/92	2158.6	765	343.87	1814.73		364601114514301
219S13E6431DAAD1	CSV-1	3/30/93	2158.6	765	344.3	1814.3		364601114514301
219S13E6431DAAD1	CSV-1	6/8/93	2158.6	765	344.1	1814.5		364601114514301
219S13E6431DAAD1	CSV-1	9/9/93	2158.6	765	344.4	1814.2		364601114514301
219S13E6431DAAD1	CSV-1	12/17/93	2158.6	765	344.5	1814.1		364601114514301
219S13E6431DAAD1	CSV-1	3/31/94	2158.6	765	344.5	1814.1		364601114514301
219S13E6431DAAD1	CSV-1	6/16/94	2158.6	765	344.56	1814.04		364601114514301
219S13E6431DAAD1	CSV-1	9/8/94	2158.6	765	344.83	1813.77		364601114514301

219S13E6431DAAD1	CSV-1	7/7/00	2158.6	765	346.07	1812.53		364601114514301
219S13E6431DAAD1	CSV-1	8/17/00	2158.6	765	347.36	1811.24		364601114514301
219S13E6431DAAD1	CSV-1	1/5/01	2158.6	765	346.11	1812.49		364601114514301
219S13E6435ACAA1	CE-DT-6	6/3/81	2274.6	937	458	1816.6		364604114471301
219S13E6435ACAA1	CE-DT-6	6/6/81	2274.6	937	457	1817.6		364604114471301
219S13E6435ACAA1	CE-DT-6	7/11/81	2274.6	937	457	1817.6		364604114471301
219S13E6435ACAA1	CE-DT-6	8/11/81	2274.6	937	458	1816.6		364604114471301
219S13E6435ACAA1	CE-DT-6	3/14/85	2274.6	937	457.4	1817.2		364604114471301
219S13E6435ACAA1	CE-DT-6	6/18/85	2274.6	937	457.3	1817.3		364604114471301
219S13E6435ACAA1	CE-DT-6	9/11/87	2274.6	937	459.2	1815.4		364604114471301
219S13E6435ACAA1	CE-DT-6	9/13/87	2274.6	937	459.5	1815.1		364604114471301
219S13E6435ACAA1	CE-DT-6	8/3/88	2274.6	937	457.63	1816.97		364604114471301
219S13E6435ACAA1	CE-DT-6	12/8/88	2274.6	937	461.96	1812.64		364604114471301
219S13E6435ACAA1	CE-DT-6	1/20/89	2274.6	937	457.77	1816.83		364604114471301
219S13E6435ACAA1	CE-DT-6	1/31/89	2274.6	937	457.95	1816.65		364604114471301
219S13E6435ACAA1	CE-DT-6	3/28/89	2274.6	937	457.7	1816.9		364604114471301
219S13E6435ACAA1	CE-DT-6	5/30/89	2274.6	937	457.66	1816.94		364604114471301
219S13E6435ACAA1	CE-DT-6	3/18/92	2274.6	937	458.1	1816.5		364604114471301
219S13E6435ACAA1	CE-DT-6	6/15/92	2274.6	937	457.8	1816.8		364604114471301
219S13E6435ACAA1	CE-DT-6	9/14/92	2274.6	937	458.2	1816.4		364604114471301
219S13E6435ACAA1	CE-DT-6	12/9/92	2274.6	937	458.3	1816.3		364604114471301
219S13E6435ACAA1	CE-DT-6	3/30/93	2274.6	937	457.5	1817.1		364604114471301
219S13E6435ACAA1	CE-DT-6	12/17/93	2274.6	937	457.9	1816.7		364604114471301
219S13E6435ACAA1	CE-DT-6	10/18/95	2274.6	937	457.8	1816.8		364604114471301
219S13E6435ACAA1	CE-DT-6	1/16/96	2274.6	937	457.7	1816.9		364604114471301
219S13E6435ACAA1	CE-DT-6	2/1/96	2274.6	937	459	1815.6		364604114471301
219S13E6435ACAA1	CE-DT-6	4/1/96	2274.6	937	440	1834.6		364604114471301
219S13E6435ACAA1	CE-DT-6	12/31/96	2274.6	937	459	1815.6		364604114471301
219S13E6435ACAA1	CE-DT-6	1/31/97	2274.6	937	458.9	1815.7		364604114471301
219S13E6435ACAA1	CE-DT-6	2/28/97	2274.6	937	458.5	1816.1		364604114471301
219S13E6435ACAA1	CE-DT-6	4/1/97	2274.6	937	458.8	1815.8		364604114471301
219S13E6435ACAA1	CE-DT-6	11/3/97	2274.6	937	459.4	1815.2		364604114471301
219S13E6435ACAA1	CE-DT-6	12/31/97	2274.6	937	460	1814.6		364604114471301
219S13E6435ACAA1	CE-DT-6	6/1/98	2274.6	937	460	1814.6		364604114471301
219S13E6435ACAA1	CE-DT-6	12/31/98	2274.6	937	460	1814.6		364604114471301
219S13E6435ACAA1	CE-DT-6	4/1/99	2274.6	937	459	1815.6		364604114471301
219S13E6435ACAA1	CE-DT-6	4/30/99	2274.6	937	459	1815.6		364604114471301

219S13E6435ACAA1	CE-DT-6	6/1/99	2274.6	937	460	1814.6		364604114471301
219S13E6435ACAA1	CE-DT-6	7/1/99	2274.6	937	459	1815.6		364604114471301
219S13E6435ACAA1	CE-DT-6	8/2/99	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	9/1/99	2274.6	937	459	1815.6		364604114471301
219S13E6435ACAA1	CE-DT-6	10/1/99	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	10/29/99	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	12/1/99	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	12/30/99	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	2/1/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	3/1/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	4/3/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	5/2/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	6/1/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	10/26/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	11/30/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	12/28/00	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	2/1/01	2274.6	937	461	1813.6		364604114471301
219S13E6435ACAA1	CE-DT-6	2/28/01	2274.6	937	461	1813.6		364604114471301
219S13E6528BDAC1	CSV-2	2/6/85	2185.9	478	391.8	1794.1		364650114432001
219S13E6528BDAC1	CSV-2	10/27/85	2185.9	478	391.8	1794.1		364650114432001
219S13E6528BDAC1	CSV-2	12/30/85	2185.9	478	390.21	1795.69		364650114432001
219S13E6528BDAC1	CSV-2	6/7/86	2185.9	478	390.76	1795.14		364650114432001
219S13E6528BDAC1	CSV-2	9/11/87	2185.9	478	390.94	1794.96		364650114432001
219S13E6528BDAC1	CSV-2	5/17/88	2185.9	478	390.59	1795.31		364650114432001
219S13E6528BDAC1	CSV-2	8/3/88	2185.9	478	390.99	1794.91		364650114432001
219S13E6528BDAC1	CSV-2	12/21/88	2185.9	478	390.95	1794.95		364650114432001
219S13E6528BDAC1	CSV-2	1/20/89	2185.9	478	390.96	1794.94		364650114432001
219S13E6528BDAC1	CSV-2	1/31/89	2185.9	478	390.9	1795		364650114432001
219S13E6528BDAC1	CSV-2	3/28/89	2185.9	478	391.2	1794.7		364650114432001
219S13E6528BDAC1	CSV-2	5/30/89	2185.9	478	390.85	1795.05		364650114432001
219S13E6528BDAC1	CSV-2	7/26/89	2185.9	478	390.99	1794.91		364650114432001
219S13E6528BDAC1	CSV-2	9/12/89	2185.9	478	391.23	1794.67		364650114432001
219S13E6528BDAC1	CSV-2	3/29/90	2185.9	478	390.94	1794.96		364650114432001
219S13E6528BDAC1	CSV-2	6/8/90	2185.9	478	391.04	1794.86		364650114432001
219S13E6528BDAC1	CSV-2	8/14/90	2185.9	478	390.24	1795.66		364650114432001
219S13E6528BDAC1	CSV-2	9/28/90	2185.9	478	392.4	1793.5		364650114432001
219S13E6528BDAC1	CSV-2	10/29/90	2185.9	478	391.5	1794.4		364650114432001

219S13E6528BDAC1	CSV-2	2/6/91	2185.9	478	391.4	1794.5		364650114432001
219S13E6528BDAC1	CSV-2	3/26/91	2185.9	478	391.28	1794.62		364650114432001
219S13E6528BDAC1	CSV-2	4/9/91	2185.9	478	391.4	1794.5		364650114432001
219S13E6528BDAC1	CSV-2	5/30/91	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	7/30/91	2185.9	478	391.8	1794.1		364650114432001
219S13E6528BDAC1	CSV-2	9/4/91	2185.9	478	392	1793.9		364650114432001
219S13E6528BDAC1	CSV-2	9/4/91	2185.9	478	391.7	1794.2		364650114432001
219S13E6528BDAC1	CSV-2	10/8/91	2185.9	478	392	1793.9		364650114432001
219S13E6528BDAC1	CSV-2	11/8/91	2185.9	478	391.8	1794.1		364650114432001
219S13E6528BDAC1	CSV-2	1/10/92	2185.9	478	391.4	1794.5		364650114432001
219S13E6528BDAC1	CSV-2	1/14/92	2185.9	478	391.5	1794.4		364650114432001
219S13E6528BDAC1	CSV-2	2/12/92	2185.9	478	391.2	1794.7		364650114432001
219S13E6528BDAC1	CSV-2	3/18/92	2185.9	478	391.3	1794.6		364650114432001
219S13E6528BDAC1	CSV-2	4/21/92	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	4/29/92	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	5/12/92	2185.9	478	391.1	1794.8		364650114432001
219S13E6528BDAC1	CSV-2	5/19/92	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	5/20/92	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	6/15/92	2185.9	478	391.2	1794.7		364650114432001
219S13E6528BDAC1	CSV-2	6/18/92	2185.9	478	391.5	1794.4		364650114432001
219S13E6528BDAC1	CSV-2	7/29/92	2185.9	478	391.4	1794.5		364650114432001
219S13E6528BDAC1	CSV-2	8/18/92	2185.9	478	391.4	1794.5		364650114432001
219S13E6528BDAC1	CSV-2	9/14/92	2185.9	478	391.5	1794.4		364650114432001
219S13E6528BDAC1	CSV-2	10/7/92	2185.9	478	391.8	1794.1		364650114432001
219S13E6528BDAC1	CSV-2	12/9/92	2185.9	478	391.6	1794.3		364650114432001
219S13E6528BDAC1	CSV-2	2/25/93	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	3/30/93	2185.9	478	390.6	1795.3		364650114432001
219S13E6528BDAC1	CSV-2	4/26/93	2185.9	478	390.4	1795.5		364650114432001
219S13E6528BDAC1	CSV-2	6/8/93	2185.9	478	390.5	1795.4		364650114432001
219S13E6528BDAC1	CSV-2	7/2/93	2185.9	478	390.7	1795.2		364650114432001
219S13E6528BDAC1	CSV-2	7/15/93	2185.9	478	390.9	1795		364650114432001
219S13E6528BDAC1	CSV-2	7/29/93	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	9/9/93	2185.9	478	391.1	1794.8		364650114432001
219S13E6528BDAC1	CSV-2	10/14/93	2185.9	478	391	1794.9		364650114432001
219S13E6528BDAC1	CSV-2	11/18/93	2185.9	478	390.9	1795		364650114432001
219S13E6528BDAC1	CSV-2	12/17/93	2185.9	478	391.2	1794.7		364650114432001
219S13E6528BDAC1	CSV-2	2/14/94	2185.9	478	391.3	1794.6		364650114432001

219S13E6528BDAC1	CSV-2	3/1/94	2185.9	478	391.6	1794.3		364650114432001
219S13E6528BDAC1	CSV-2	4/5/94	2185.9	478	392.1	1793.8		364650114432001
219S13E6528BDAC1	CSV-2	6/15/94	2185.9	478	391.21	1794.69		364650114432001
219S13E6528BDAC1	CSV-2	9/8/94	2185.9	478	391.5	1794.4		364650114432001
219S13E6528BDAC1	CSV-2	3/29/96	2185.9	478	390.8	1795.1		364650114432001
219S13E6528BDAC1	CSV-2	2/26/97	2185.9	478	390.6	1795.3		364650114432001
219S13E6528BDAC1	CSV-2	7/8/97	2185.9	478	391.1	1794.8		364650114432001
219S13E6528BDAC1	CSV-2	10/20/97	2185.9	478	391.4	1794.5		364650114432001
219S13E6528BDAC1	CSV-2	12/15/97	2185.9	478	391.1	1794.8		364650114432001
219S13E6528BDAC1	CSV-2	4/28/98	2185.9	478	390.9	1795		364650114432001
219S13E6528BDAC1	CSV-2	10/27/98	2185.9	478	392.16	1793.74		364650114432001
219S13E6528BDAC1	CSV-2	12/17/98	2185.9	478	392.06	1793.84		364650114432001
219S13E6528BDAC1	CSV-2	4/8/99	2185.9	478	391.84	1794.06		364650114432001
219S13E6528BDAC1	CSV-2	7/28/99	2185.9	478	392.56	1793.34		364650114432001
219S13E6528BDAC1	CSV-2	10/14/99	2185.9	478	392.44	1793.46		364650114432001
219S13E6528BDAC1	CSV-2	12/13/99	2185.9	478	392.28	1793.62		364650114432001
219S13E6528BDAC1	CSV-2	4/5/00	2185.9	478	392.04	1793.86		364650114432001
219S13E6528BDAC1	CSV-2	7/7/00	2185.9	478	392.85	1793.05		364650114432001
219S13E6528BDAC1	CSV-2	8/17/00	2185.9	478	391.15	1794.75		364650114432001
219S13E6528BDAC1	CSV-2	10/24/00	2185.9	478	393.25	1792.65		364650114432001
219S13E6528BDAC1	CSV-2	11/29/00	2185.9	478	392.77	1793.13		364650114432001
219S13E6528BDAC1	CSV-2	12/18/00	2185.9	478	393	1792.9		364650114432001
219S13E6528BDAC1	CSV-2	12/21/00	2185.9	478	392.76	1793.14		364650114432001
219S13E6528BDAC1	CSV-2	2/1/01	2185.9	478	392.76	1793.14		364650114432001
219S13E6528BDAC1	CSV-2	2/14/01	2185.9	478	392.75	1793.15		364650114432001
210S13E6325BDAA1	Perkins	5/4/44	2159	353	332	1827		364726114525501
210S13E6325A	210S13E6325A	4/1/44	2518		332	2186		364730114524501
210S13E6326AAAA1	CE-DT-5	5/6/81	2170	628	352	1818		364741114532801
210S13E6326AAAA1	CE-DT-5	7/4/81	2170	628	349	1821		364741114532801
210S13E6326AAAA1	CE-DT-5	8/13/81	2170	628	349	1821		364741114532801
210S13E6326AAAA1	CE-DT-5	3/14/85	2170	628	347.84	1822.16		364741114532801
210S13E6326AAAA1	CE-DT-5	12/3/85	2170	628	348.5	1821.5		364741114532801
210S13E6326AAAA1	CE-DT-5	9/11/87	2170	628	348.72	1821.28		364741114532801
210S13E6326AAAA1	CE-DT-5	9/13/87	2170	628	348.86	1821.14		364741114532801
210S13E6326AAAA1	CE-DT-5	5/18/88	2170	628	348.57	1821.43		364741114532801
210S13E6326AAAA1	CE-DT-5	8/3/88	2170	628	348.72	1821.28		364741114532801
210S13E6326AAAA1	CE-DT-5	12/8/88	2170	628	348.8	1821.2		364741114532801

210S13E6326AAAA1	CE-DT-5	1/20/89	2170	628	348.73	1821.27		364741114532801
210S13E6326AAAA1	CE-DT-5	1/30/89	2170	628	348.97	1821.03		364741114532801
210S13E6326AAAA1	CE-DT-5	1/31/89	2170	628	348.88	1821.12		364741114532801
210S13E6326AAAA1	CE-DT-5	3/28/89	2170	628	348.98	1821.02		364741114532801
210S13E6326AAAA1	CE-DT-5	5/30/89	2170	628	348.83	1821.17		364741114532801
210S13E6326AAAA1	CE-DT-5	7/26/89	2170	628	350.48	1819.52		364741114532801
210S13E6326AAAA1	CE-DT-5	8/14/89	2170	628	349.01	1820.99		364741114532801
210S13E6326AAAA1	CE-DT-5	9/12/89	2170	628	349.1	1820.9		364741114532801
210S13E6326AAAA1	CE-DT-5	11/13/90	2170	628	349.02	1820.98		364741114532801
210S13E6326AAAA1	CE-DT-5	3/26/91	2170	628	349	1821		364741114532801
210S13E6326AAAA1	CE-DT-5	6/13/91	2170	628	348.8	1821.2		364741114532801
210S13E6326AAAA1	CE-DT-5	9/12/91	2170	628	349.03	1820.97		364741114532801
210S13E6326AAAA1	CE-DT-5	12/10/91	2170	628	349.14	1820.86		364741114532801
210S13E6326AAAA1	CE-DT-5	3/18/92	2170	628	350.12	1819.88		364741114532801
210S13E6326AAAA1	CE-DT-5	6/15/92	2170	628	348.73	1821.27		364741114532801
210S13E6326AAAA1	CE-DT-5	9/14/92	2170	628	349.1	1820.9		364741114532801
210S13E6326AAAA1	CE-DT-5	12/9/92	2170	628	349.04	1820.96		364741114532801
210S13E6326AAAA1	CE-DT-5	3/30/93	2170	628	348.49	1821.51		364741114532801
210S13E6326AAAA1	CE-DT-5	6/8/93	2170	628	348.15	1821.85		364741114532801
210S13E6326AAAA1	CE-DT-5	9/9/93	2170	628	348.46	1821.54		364741114532801
210S13E6326AAAA1	CE-DT-5	12/17/93	2170	628	348.6	1821.4		364741114532801
210S13E6326AAAA1	CE-DT-5	3/31/94	2170	628	348.6	1821.4		364741114532801
210S13E6326AAAA1	CE-DT-5	6/16/94	2170	628	348.62	1821.38		364741114532801
210S13E6326AAAA1	CE-DT-5	9/8/94	2170	628	348.96	1821.04		364741114532801
210S13E6326AAAA1	CE-DT-5	8/13/99	2170	628	349.81	1820.19		364741114532801
210S13E6323DDDC1	CE-DT-4	12/12/80	2172.6	669	354	1818.6		364743114533101
210S13E6323DDDC1	CE-DT-4	6/28/81	2172.6	669	352	1820.6		364743114533101
210S13E6323DDDC1	CE-DT-4	3/14/85	2172.6	669	351.77	1820.83		364743114533101
210S13E6323DDDC1	CE-DT-4	12/4/85	2172.6	669	350	1822.6		364743114533101
210S13E6323DDDC1	CE-DT-4	7/9/86	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	7/10/86	2172.6	669	351.74	1820.86		364743114533101
210S13E6323DDDC1	CE-DT-4	7/14/86	2172.6	669	351.66	1820.94		364743114533101
210S13E6323DDDC1	CE-DT-4	8/20/86	2172.6	669	351.77	1820.83		364743114533101
210S13E6323DDDC1	CE-DT-4	9/18/86	2172.6	669	351.69	1820.91		364743114533101
210S13E6323DDDC1	CE-DT-4	11/17/86	2172.6	669	351.87	1820.73		364743114533101
210S13E6323DDDC1	CE-DT-4	2/10/87	2172.6	669	351.77	1820.83		364743114533101
210S13E6323DDDC1	CE-DT-4	3/3/87	2172.6	669	351.94	1820.66		364743114533101

210S13E6323DDDC1	CE-DT-4	3/13/87	2172.6	669	351.66	1820.94		364743114533101
210S13E6323DDDC1	CE-DT-4	5/7/87	2172.6	669	351.7	1820.9		364743114533101
210S13E6323DDDC1	CE-DT-4	6/3/87	2172.6	669	351.75	1820.85		364743114533101
210S13E6323DDDC1	CE-DT-4	7/10/87	2172.6	669	352	1820.6		364743114533101
210S13E6323DDDC1	CE-DT-4	8/27/87	2172.6	669	352.09	1820.51		364743114533101
210S13E6323DDDC1	CE-DT-4	9/11/87	2172.6	669	351.99	1820.61		364743114533101
210S13E6323DDDC1	CE-DT-4	9/13/87	2172.6	669	351.95	1820.65		364743114533101
210S13E6323DDDC1	CE-DT-4	9/30/87	2172.6	669	352.06	1820.54		364743114533101
210S13E6323DDDC1	CE-DT-4	10/29/87	2172.6	669	351.95	1820.65		364743114533101
210S13E6323DDDC1	CE-DT-4	12/18/87	2172.6	669	351.81	1820.79		364743114533101
210S13E6323DDDC1	CE-DT-4	1/29/88	2172.6	669	351.79	1820.81		364743114533101
210S13E6323DDDC1	CE-DT-4	2/12/88	2172.6	669	351.82	1820.78		364743114533101
210S13E6323DDDC1	CE-DT-4	4/7/88	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	5/12/88	2172.6	669	351.85	1820.75		364743114533101
210S13E6323DDDC1	CE-DT-4	5/18/88	2172.6	669	351.72	1820.88		364743114533101
210S13E6323DDDC1	CE-DT-4	8/3/88	2172.6	669	351.88	1820.72		364743114533101
210S13E6323DDDC1	CE-DT-4	12/8/88	2172.6	669	352.04	1820.56		364743114533101
210S13E6323DDDC1	CE-DT-4	1/17/89	2172.6	669	352.06	1820.54		364743114533101
210S13E6323DDDC1	CE-DT-4	1/30/89	2172.6	669	351.99	1820.61		364743114533101
210S13E6323DDDC1	CE-DT-4	1/31/89	2172.6	669	352.89	1819.71		364743114533101
210S13E6323DDDC1	CE-DT-4	3/28/89	2172.6	669	351.98	1820.62		364743114533101
210S13E6323DDDC1	CE-DT-4	5/30/89	2172.6	669	351.82	1820.78		364743114533101
210S13E6323DDDC1	CE-DT-4	7/3/89	2172.6	669	351.93	1820.67		364743114533101
210S13E6323DDDC1	CE-DT-4	7/26/89	2172.6	669	351.29	1821.31		364743114533101
210S13E6323DDDC1	CE-DT-4	8/14/89	2172.6	669	351.9	1820.7		364743114533101
210S13E6323DDDC1	CE-DT-4	9/12/89	2172.6	669	352.1	1820.5		364743114533101
210S13E6323DDDC1	CE-DT-4	3/29/90	2172.6	669	353.25	1819.35		364743114533101
210S13E6323DDDC1	CE-DT-4	8/14/90	2172.6	669	352.09	1820.51		364743114533101
210S13E6323DDDC1	CE-DT-4	9/27/90	2172.6	669	350.9	1821.7		364743114533101
210S13E6323DDDC1	CE-DT-4	10/29/90	2172.6	669	352.4	1820.2		364743114533101
210S13E6323DDDC1	CE-DT-4	12/3/90	2172.6	669	352.5	1820.1		364743114533101
210S13E6323DDDC1	CE-DT-4	2/7/91	2172.6	669	352.4	1820.2		364743114533101
210S13E6323DDDC1	CE-DT-4	3/26/91	2172.6	669	352.3	1820.3		364743114533101
210S13E6323DDDC1	CE-DT-4	4/9/91	2172.6	669	352.4	1820.2		364743114533101
210S13E6323DDDC1	CE-DT-4	5/30/91	2172.6	669	352.1	1820.5		364743114533101
210S13E6323DDDC1	CE-DT-4	7/30/91	2172.6	669	352	1820.6		364743114533101
210S13E6323DDDC1	CE-DT-4	9/5/91	2172.6	669	352.7	1819.9		364743114533101

210S13E6323DDDC1	CE-DT-4	10/8/91	2172.6	669	352.8	1819.8		364743114533101
210S13E6323DDDC1	CE-DT-4	11/8/91	2172.6	669	352.8	1819.8		364743114533101
210S13E6323DDDC1	CE-DT-4	11/14/91	2172.6	669	352.2	1820.4		364743114533101
210S13E6323DDDC1	CE-DT-4	1/10/92	2172.6	669	352.5	1820.1		364743114533101
210S13E6323DDDC1	CE-DT-4	2/12/92	2172.6	669	352.3	1820.3		364743114533101
210S13E6323DDDC1	CE-DT-4	2/21/92	2172.6	669	352.4	1820.2		364743114533101
210S13E6323DDDC1	CE-DT-4	3/18/92	2172.6	669	352.3	1820.3		364743114533101
210S13E6323DDDC1	CE-DT-4	4/21/92	2172.6	669	352	1820.6		364743114533101
210S13E6323DDDC1	CE-DT-4	4/29/92	2172.6	669	352.1	1820.5		364743114533101
210S13E6323DDDC1	CE-DT-4	5/12/92	2172.6	669	352.1	1820.5		364743114533101
210S13E6323DDDC1	CE-DT-4	6/15/92	2172.6	669	351.94	1820.66		364743114533101
210S13E6323DDDC1	CE-DT-4	6/18/92	2172.6	669	352.3	1820.3		364743114533101
210S13E6323DDDC1	CE-DT-4	7/29/92	2172.6	669	352.2	1820.4		364743114533101
210S13E6323DDDC1	CE-DT-4	9/14/92	2172.6	669	352.2	1820.4		364743114533101
210S13E6323DDDC1	CE-DT-4	10/7/92	2172.6	669	352.5	1820.1		364743114533101
210S13E6323DDDC1	CE-DT-4	12/9/92	2172.6	669	352.5	1820.1		364743114533101
210S13E6323DDDC1	CE-DT-4	3/30/93	2172.6	669	351.7	1820.9		364743114533101
210S13E6323DDDC1	CE-DT-4	6/8/93	2172.6	669	351.4	1821.2		364743114533101
210S13E6323DDDC1	CE-DT-4	8/4/93	2172.6	669	351.6	1821		364743114533101
210S13E6323DDDC1	CE-DT-4	9/9/93	2172.6	669	351.6	1821		364743114533101
210S13E6323DDDC1	CE-DT-4	10/14/93	2172.6	669	351.7	1820.9		364743114533101
210S13E6323DDDC1	CE-DT-4	10/19/93	2172.6	669	351.9	1820.7		364743114533101
210S13E6323DDDC1	CE-DT-4	11/10/93	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	11/18/93	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	12/17/93	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	2/14/94	2172.6	669	351.9	1820.7		364743114533101
210S13E6323DDDC1	CE-DT-4	3/31/94	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	6/16/94	2172.6	669	351.84	1820.76		364743114533101
210S13E6323DDDC1	CE-DT-4	8/9/94	2172.6	669	352.08	1820.52		364743114533101
210S13E6323DDDC1	CE-DT-4	10/4/95	2172.6	669	351.9	1820.7		364743114533101
210S13E6323DDDC1	CE-DT-4	12/12/95	2172.6	669	351.7	1820.9		364743114533101
210S13E6323DDDC1	CE-DT-4	1/19/96	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	1/26/96	2172.6	669	351.9	1820.7		364743114533101
210S13E6323DDDC1	CE-DT-4	3/5/96	2172.6	669	351.7	1820.9		364743114533101
210S13E6323DDDC1	CE-DT-4	3/12/96	2172.6	669	351.6	1821		364743114533101
210S13E6323DDDC1	CE-DT-4	4/16/96	2172.6	669	351.38	1821.22		364743114533101
210S13E6323DDDC1	CE-DT-4	5/31/96	2172.6	669	351.7	1820.9		364743114533101

210S13E6323DDDC1	CE-DT-4	7/11/96	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	8/15/96	2172.6	669	351.8	1820.8		364743114533101
210S13E6323DDDC1	CE-DT-4	10/4/96	2172.6	669	352	1820.6		364743114533101
210S13E6323DDDC1	CE-DT-4	3/7/97	2172.6	669	351.6	1821		364743114533101
210S13E6323DDDC1	CE-DT-4	7/8/97	2172.6	669	351.7	1820.9		364743114533101
210S13E6323DDDC1	CE-DT-4	10/20/97	2172.6	669	352.3	1820.3		364743114533101
210S13E6323DDDC1	CE-DT-4	5/7/98	2172.6	669	351.6	1821		364743114533101
210S13E6323DDDC1	CE-DT-4	10/27/98	2172.6	669	352.48	1820.12		364743114533101
210S13E6323DDDC1	CE-DT-4	12/17/98	2172.6	669	352.66	1819.94		364743114533101
210S13E6323DDDC1	CE-DT-4	2/19/99	2172.6	669	352.48	1820.12		364743114533101
210S13E6323DDDC1	CE-DT-4	3/2/99	2172.6	669	352.47	1820.13		364743114533101
210S13E6323DDDC1	CE-DT-4	3/11/99	2172.6	669	352.42	1820.18		364743114533101
210S13E6323DDDC1	CE-DT-4	4/12/99	2172.6	669	352.37	1820.23		364743114533101
210S13E6323DDDC1	CE-DT-4	5/7/99	2172.6	669	352.42	1820.18		364743114533101
210S13E6323DDDC1	CE-DT-4	7/2/99	2172.6	669	352.46	1820.14		364743114533101
210S13E6323DDDC1	CE-DT-4	8/12/99	2172.6	669	352.84	1819.76		364743114533101
210S13E6323DDDC1	CE-DT-4	10/7/99	2172.6	669	353.16	1819.44		364743114533101
210S13E6323DDDC1	CE-DT-4	10/8/99	2172.6	669	353.11	1819.49		364743114533101
210S13E6323DDDC1	CE-DT-4	12/13/99	2172.6	669	353.01	1819.59		364743114533101
210S13E6323DDDC1	CE-DT-4	1/11/00	2172.6	669	352.95	1819.65		364743114533101
210S13E6323DDDC1	CE-DT-4	2/9/00	2172.6	669	352.7	1819.9		364743114533101
210S13E6323DDDC1	CE-DT-4	4/5/00	2172.6	669	352.74	1819.86		364743114533101
210S13E6323DDDC1	CE-DT-4	7/7/00	2172.6	669	353.09	1819.51		364743114533101
210S13E6323DDDC1	CE-DT-4	8/17/00	2172.6	669	353.35	1819.25		364743114533101
210S13E6323DDDC1	CE-DT-4	10/24/00	2172.6	669	353.64	1818.96		364743114533101
210S13E6323DDDC1	CE-DT-4	12/5/00	2172.6	669	353.41	1819.19		364743114533101
210S13E6323DDDC1	CE-DT-4	1/5/01	2172.6	669	353.41	1819.19		364743114533101
210S13E6323DDDC1	CE-DT-4	2/14/01	2172.6	669	353.33	1819.27		364743114533101
210S13E6323DDDC1	CE-DT-4	2/16/01	2172.6	669	353.39	1819.21		364743114533101
210S13E6311BACD1	Old Highway Well	7/19/81	2220	170	165	2055		365008114541101
210S13E6311BACD1	Old Highway Well	9/29/81	2220	170	164	2056		365008114541101
210S13E6311BACD1	Old Highway Well	3/14/85	2220	170	166.34	2053.66		365008114541101
210S13E6311BACD1	Old Highway Well	8/12/99	2220	170	163.44	2056.56		365008114541101
210S12E6329DABC1	CE-VF-2	7/11/81	2466.9	1221	612	1854.9		365227114554401
210S12E6329DABC1	CE-VF-2	9/29/81	2466.9	1221	609	1857.9		365227114554401
210S12E6329DABC1	CE-VF-2	2/5/85	2466.9	1221	603.1	1863.8		365227114554401
210S12E6329DABC1	CE-VF-2	11/25/85	2466.9	1221	602	1864.9		365227114554401

210S12E6329DABC1	CE-VF-2	1/28/86	2466.9	1221	604.6	1862.3		365227114554401
210S12E6329DABC1	CE-VF-2	1/29/86	2466.9	1221	604.1	1862.8		365227114554401
210S12E6329DABC1	CE-VF-2	2/4/86	2466.9	1221	604.3	1862.6		365227114554401
210S12E6329DABC1	CE-VF-2	2/5/86	2466.9	1221	604.3	1862.6		365227114554401
210S12E6329DABC1	CE-VF-2	9/13/87	2466.9	1221	609.7	1857.2		365227114554401
210S12E6329DABC1	CE-VF-2	5/17/88	2466.9	1221	609.6	1857.3		365227114554401
210S12E6329DABC1	CE-VF-2	8/4/88	2466.9	1221	609.8	1857.1		365227114554401
210S12E6329DABC1	CE-VF-2	12/13/88	2466.9	1221	609.02	1857.88		365227114554401
210S12E6329DABC1	CE-VF-2	1/31/89	2466.9	1221	609.5	1857.4		365227114554401
210S12E6329DABC1	CE-VF-2	3/28/89	2466.9	1221	609.8	1857.1		365227114554401
210S12E6329DABC1	CE-VF-2	5/30/89	2466.9	1221	609.7	1857.2		365227114554401
210S12E6329DABC1	CE-VF-2	7/26/89	2466.9	1221	609.6	1857.3		365227114554401
210S12E6329DABC1	CE-VF-2	9/12/89	2466.9	1221	609.9	1857		365227114554401
210S12E6329DABC1	CE-VF-2	11/13/90	2466.9	1221	609.7	1857.2		365227114554401
210S12E6329DABC1	CE-VF-2	3/26/91	2466.9	1221	609.7	1857.2		365227114554401
210S12E6329DABC1	CE-VF-2	6/13/91	2466.9	1221	610	1856.9		365227114554401
210S12E6329DABC1	CE-VF-2	9/12/91	2466.9	1221	610.1	1856.8		365227114554401
210S12E6329DABC1	CE-VF-2	12/10/91	2466.9	1221	609.7	1857.2		365227114554401
210S12E6329DABC1	CE-VF-2	3/18/92	2466.9	1221	610	1856.9		365227114554401
210S12E6329DABC1	CE-VF-2	6/17/92	2466.9	1221	609.9	1857		365227114554401
210S12E6329DABC1	CE-VF-2	9/8/92	2466.9	1221	610.3	1856.6		365227114554401
210S12E6329DABC1	CE-VF-2	12/21/92	2466.9	1221	610.6	1856.3		365227114554401
210S12E6329DABC1	CE-VF-2	3/31/93	2466.9	1221	610.3	1856.6		365227114554401
210S12E6329DABC1	CE-VF-2	6/7/93	2466.9	1221	610	1856.9		365227114554401
210S12E6329DABC1	CE-VF-2	9/7/93	2466.9	1221	610.1	1856.8		365227114554401
210S12E6329DABC1	CE-VF-2	12/15/93	2466.9	1221	609.8	1857.1		365227114554401
210S12E6329DABC1	CE-VF-2	3/31/94	2466.9	1221	610.1	1856.8		365227114554401
210S12E6329DABC1	CE-VF-2	7/7/94	2466.9	1221	609.79	1857.11		365227114554401
210S12E6329DABC1	CE-VF-2	9/20/94	2466.9	1221	609.56	1857.34		365227114554401
210S12E6329DABC1	CE-VF-2	8/12/99	2466.9	1221	609.65	1857.25		365227114554401
210S12E6329DABC1	CE-VF-2	7/7/00	2466.9	1221	610.52	1856.38		365227114554401
210S12E6329DABC1	CE-VF-2	8/17/00	2466.9	1221	610.4	1856.5		365227114554401
210S12E6329DABC1	CE-VF-2	10/24/00	2466.9	1221	610.64	1856.26		365227114554401
210S12E6329DABC1	CE-VF-2	1/5/01	2466.9	1221	610.34	1856.56		365227114554401
210S12E6329ADCC2	CE-DT-1	11/22/80	2464.2	570	547	1917.2		365231114564302
210S12E6329ADCC2	CE-DT-1	1/29/86	2464.2	570	542.2	1922		365231114564302
210S12E6329ADCC2	CE-DT-1	2/6/86	2464.2	570	542.1	1922.1		365231114564302

210S12E6329ADCC1	CE-VF-1	11/22/80	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	2/1/81	2464.2	714	627	1837.2		365232114554401
210S12E6329ADCC1	CE-VF-1	7/14/81	2464.2	714	548	1916.2		365232114554401
210S12E6329ADCC1	CE-VF-1	9/29/81	2464.2	714	548	1916.2		365232114554401
210S12E6329ADCC1	CE-VF-1	6/6/85	2464.2	714	547.77	1916.43		365232114554401
210S12E6329ADCC1	CE-VF-1	1/28/86	2464.2	714	543	1921.2		365232114554401
210S12E6329ADCC1	CE-VF-1	1/29/86	2464.2	714	543	1921.2		365232114554401
210S12E6329ADCC1	CE-VF-1	2/5/86	2464.2	714	542.8	1921.4		365232114554401
210S12E6329ADCC1	CE-VF-1	2/6/86	2464.2	714	542.7	1921.5		365232114554401
210S12E6329ADCC1	CE-VF-1	9/13/86	2464.2	714	548.8	1915.4		365232114554401
210S12E6329ADCC1	CE-VF-1	5/17/88	2464.2	714	548.5	1915.7		365232114554401
210S12E6329ADCC1	CE-VF-1	8/4/88	2464.2	714	548.9	1915.3		365232114554401
210S12E6329ADCC1	CE-VF-1	12/13/88	2464.2	714	548.48	1915.72		365232114554401
210S12E6329ADCC1	CE-VF-1	1/31/89	2464.2	714	549.1	1915.1		365232114554401
210S12E6329ADCC1	CE-VF-1	3/28/89	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	5/30/89	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	7/26/89	2464.2	714	549.1	1915.1		365232114554401
210S12E6329ADCC1	CE-VF-1	9/12/89	2464.2	714	549.1	1915.1		365232114554401
210S12E6329ADCC1	CE-VF-1	11/13/90	2464.2	714	548.9	1915.3		365232114554401
210S12E6329ADCC1	CE-VF-1	3/26/91	2464.2	714	548.4	1915.8		365232114554401
210S12E6329ADCC1	CE-VF-1	6/13/91	2464.2	714	548.6	1915.6		365232114554401
210S12E6329ADCC1	CE-VF-1	9/12/91	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	12/10/91	2464.2	714	548.7	1915.5		365232114554401
210S12E6329ADCC1	CE-VF-1	3/18/92	2464.2	714	548.6	1915.6		365232114554401
210S12E6329ADCC1	CE-VF-1	6/17/92	2464.2	714	548.7	1915.5		365232114554401
210S12E6329ADCC1	CE-VF-1	9/8/92	2464.2	714	548.9	1915.3		365232114554401
210S12E6329ADCC1	CE-VF-1	12/21/92	2464.2	714	549.3	1914.9		365232114554401
210S12E6329ADCC1	CE-VF-1	3/31/93	2464.2	714	549.2	1915		365232114554401
210S12E6329ADCC1	CE-VF-1	6/7/93	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	9/7/93	2464.2	714	549.3	1914.9		365232114554401
210S12E6329ADCC1	CE-VF-1	12/15/93	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	3/31/94	2464.2	714	548	1916.2		365232114554401
210S12E6329ADCC1	CE-VF-1	7/7/94	2464.2	714	548.65	1915.55		365232114554401
210S12E6329ADCC1	CE-VF-1	9/20/94	2464.2	714	548.71	1915.49		365232114554401
210S12E6329ADCC1	CE-VF-1	7/19/99	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	10/19/99	2464.2	714	549	1915.2		365232114554401
210S12E6329ADCC1	CE-VF-1	2/9/00	2464.2	714	550	1914.2		365232114554401

169S12E6010AD	DDL-2	1/21/89	3300	460	216	3084		365502115134101
169S12E6010AD	DDL-2	2/5/89	3300	460	216.1	3083.9		365502115134101
169S12E6010AD	DDL-2	4/26/90	3300	460	214.2	3085.8		365502115134101
169S12E6010AD	DDL-2	11/28/90	3300	460	214.2	3085.8		365502115134101
169S12E6010AD	DDL-2	4/25/91	3300	460	213.9	3086.1		365502115134101
169S12E6010AD	DDL-2	9/30/91	3300	460	213.9	3086.1		365502115134101
169S12E6010AD	DDL-2	5/13/92	3300	460	213.8	3086.2		365502115134101
169S12E6010AD	DDL-2	12/16/92	3300	460	213.8	3086.2		365502115134101
169S12E6010AD	DDL-2	5/28/93	3300	460	213.6	3086.4		365502115134101
169S12E6010AD	DDL-2	10/19/93	3300	460	213.56	3086.44		365502115134101
169S12E6010AD	DDL-2	6/3/94	3300	460	213.45	3086.55		365502115134101
169S12E6010AD	DDL-2	11/30/94	3300	460	213.52	3086.48		365502115134101
169S12E6010AD	DDL-2	6/13/95	3300	460	213.34	3086.66		365502115134101
169S12E6010AD	DDL-2	1/10/96	3300	460	213.34	3086.66		365502115134101
169S12E6010AD	DDL-2	9/13/96	3300	460	213.18	3086.82		365502115134101
169S12E6010AD	DDL-2	6/24/97	3300	460	213.06	3086.94		365502115134101
169S12E6010AD	DDL-2	11/25/97	3300	460	213.1	3086.9		365502115134101
169S12E6010AD	DDL-2	7/28/98	3300	460	212.91	3087.09		365502115134101
169S12E6010AD	DDL-2	12/15/98	3300	460	212.99	3087.01		365502115134101
169S12E6010AD	DDL-2	6/16/99	3300	460	212.78	3087.22		365502115134101
169S12E6010AD	DDL-2	11/18/99	3300	460	212.88	3087.12		365502115134101
169S12E6010AD	DDL-2	5/24/00	3300	460	212.74	3087.26		365502115134101
169S11E6036AAAD1	DDL-1	10/1/86	3208	420	159.6	3048.4		365711115115201
169S11E6036AAAD1	DDL-1	5/6/87	3208	420	161	3047		365711115115201
169S11E6036AAAD1	DDL-1	9/13/87	3208	420	158.44	3049.56		365711115115201
169S11E6036AAAD1	DDL-1	5/17/88	3208	420	158.38	3049.62		365711115115201
169S11E6036AAAD1	DDL-1	4/26/90	3208	420	158.4	3049.6		365711115115201
169S11E6036AAAD1	DDL-1	11/28/90	3208	420	158.6	3049.4		365711115115201
169S11E6036AAAD1	DDL-1	4/8/91	3208	420	160.7	3047.3		365711115115201
169S11E6036AAAD1	DDL-1	4/25/91	3208	420	158.3	3049.7		365711115115201
169S11E6036AAAD1	DDL-1	6/12/91	3208	420	165.7	3042.3		365711115115201
169S11E6036AAAD1	DDL-1	9/13/91	3208	420	167.66	3040.34		365711115115201
169S11E6036AAAD1	DDL-1	9/30/91	3208	420	158.3	3049.7		365711115115201
169S11E6036AAAD1	DDL-1	12/13/91	3208	420	167.24	3040.76		365711115115201
169S11E6036AAAD1	DDL-1	3/31/92	3208	420	158.64	3049.36		365711115115201
169S11E6036AAAD1	DDL-1	5/13/92	3208	420	158.2	3049.8		365711115115201
169S11E6036AAAD1	DDL-1	6/30/92	3208	420	158.2	3049.8		365711115115201

169S11E6036AAAD1	DDL-1	9/18/92	3208	420	158.16	3049.84		365711115115201
169S11E6036AAAD1	DDL-1	12/16/92	3208	420	158.2	3049.8		365711115115201
169S11E6036AAAD1	DDL-1	12/29/92	3208	420	158.11	3049.89		365711115115201
169S11E6036AAAD1	DDL-1	4/2/93	3208	420	159.09	3048.91		365711115115201
169S11E6036AAAD1	DDL-1	5/28/93	3208	420	158.1	3049.9		365711115115201
169S11E6036AAAD1	DDL-1	6/10/93	3208	420	160.45	3047.55		365711115115201
169S11E6036AAAD1	DDL-1	9/7/93	3208	420	158.16	3049.84		365711115115201
169S11E6036AAAD1	DDL-1	10/19/93	3208	420	158.2	3049.8		365711115115201
169S11E6036AAAD1	DDL-1	12/10/93	3208	420	158.1	3049.9		365711115115201
169S11E6036AAAD1	DDL-1	3/29/94	3208	420	158.06	3049.94		365711115115201
169S11E6036AAAD1	DDL-1	6/3/94	3208	420	158.04	3049.96		365711115115201
169S11E6036AAAD1	DDL-1	6/23/94	3208	420	158.08	3049.92		365711115115201
169S11E6036AAAD1	DDL-1	9/23/94	3208	420	158	3050		365711115115201
169S11E6036AAAD1	DDL-1	11/30/94	3208	420	157.06	3050.94		365711115115201
169S11E6036AAAD1	DDL-1	6/13/95	3208	420	157.96	3050.04		365711115115201
169S11E6036AAAD1	DDL-1	1/10/96	3208	420	157.99	3050.01		365711115115201
169S11E6036AAAD1	DDL-1	9/13/96	3208	420	157.89	3050.11		365711115115201
169S11E6036AAAD1	DDL-1	6/24/97	3208	420	157.83	3050.17		365711115115201
169S11E6036AAAD1	DDL-1	11/25/97	3208	420	157.83	3050.17		365711115115201
169S11E6036AAAD1	DDL-1	12/15/98	3208	420	157.73	3050.27		365711115115201
210S11E6224DBAD1	Unnamed #1	3/14/85	2490	149	89.42	2400.58		365834114590001
210S11E6213DBCB1	Judy's Ranch	6/24/70	2520	100	37	2483		365926114591301
209S08E6231CAAB1	VSF&W #2	5/10/63	3200	64	20.45	3179.55		371243115050601
209S08E6231CAAB1	VSF&W #2	4/6/90	3200	64	22.27	3177.73		371243115050601
209S08E6231CAAB1	VSF&W #2	12/29/98	3200	64	22.67	3177.33		371243115050601
209S08E6124DC	209S08E6124DC	2/25/62	4000		3.37	3996.63		371418115055101

Appendix B – Well Data

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Well Name	Well Site ID	Well Depth (ft)	Drill Date	Ground Elevation (ft)	Comments	PLSS	Latitude	Longitude	Hydrologic Unit
205S12E6421BA	205S12E6421BA	360	1970-12-27		Basin number portion of ID suggests well is in Lower Meadow Valley Wash	T12S-R64E-21	36.90	-114.83	205
209S08E6102BD	209S08E6102BD	245	1971-06-29			T08S-R61E-02	37.28	-115.11	209
209S08E6103	209S08E6103	350	1962-06-16			T08S-R61E-03	37.28	-115.13	209
209S08E6111BD	209S08E6111BD	60	1947-01-01			T08S-R61E-11	37.27	-115.11	209
209S08E6111BD	209S08E6111BD	190	2000-10-10			T08S-R61E-11	37.27	-115.11	209
209S08E6124DC	209S08E6124DC			4000	USGS. Lat-Long puts it in section 25 rather than 24 as the ID indicates. Location updated to section 24.	T08S-R61E-24	37.23	-115.09	
209S08E6231BD	209S08E6231BD	85	1947-01-01			T08S-R62E-31	37.21	-115.08	209
210S10E6225	210S10E6225	500	1977-07-11			T10S-R62E-25	37.05	-114.99	210
210S11E6224BD	210S11E6224BD	213	1999-11-21			T11S-R62E-24	36.98	-114.99	210
210S11E6227DD	210S11E6227DD	80	1996-12-19			T11S-R62E-27	36.96	-115.02	210
210S12E6303BA	210S12E6303BA	170	1992-05-28			T12S-R63E-03	36.94	-114.92	210
210S13E6223DD	210S13E6223DD	628	1981-09-27			T13S-R62E-23	36.80	-115.00	210
210S13E6325A	210S13E6325A			2518	USGS	T13S-R63E-25	36.79	-114.88	210
210S13E6435AA	210S13E6435AA	917	1981-06-03		Lat-Long has been adjusted due to	T13S-R64E-35	36.78	-114.78	210

					inconsistentcy with PLSS.				
210S14E6310	210S14E6310	353		2315	USGS	T14S-R63E-10	36.73	-114.91	210
217S16E6315AA	217S16E6315AA	70	1995-09-19			T16S-R63E-15	36.55	-114.91	217
217S16E6315AA	217S16E6315AA	70	1995-09-19			T16S-R63E-15	36.55	-114.91	217
217S16E6315AA	217S16E6315AA	70	1995-09-19			T16S-R63E-15	36.55	-114.91	217
219S13E6535DA	219S13E6535DA	620	1986-11-10			T13S-R65E-35	36.76	-114.68	219
BHG-1	212S16E5908CC1	430	1987-02-18			T16S-R59E-08	36.57	-115.36	212
C.S. Inc. (Buckhorn)	210S11E6213BD	100	1970-06-24			T11S-R62E-13	36.99	-114.99	210
CC-1	212S16E5908CC2	1403	1987-08-01			T16S-R59E-08	36.57	-115.36	212
CE-DT-1	210S12E6329ADCC2	570	1980	2464.2	Alternate depth: 710 LVVWD source, 714 USGS source.	T12S-R63E-29	36.88	-114.93	210
CE-DT-4	210S13E6323DDDC1	669	1980-12-12	2172.6	Alternate ID: 210S13E6323DD	T13S-R63E-23	36.80	-114.89	210
CE-DT-5	210S13E6326AAAA1	628	1981-04-14	2169.1	Alternate ID: 210S13E6323DDD D1	T13S-R63E-23	36.79	-114.89	210
CE-DT-6	219S13E6435ACAA1	937	1981-05-21	2274.6	Basin number was incorrect in DWR database.	T13S-R64E-35	36.77	-114.79	210
CE-VF-1	210S12E6329ADCC1	714	1981-02-01	2464.2	Alternate Ids: 210S12E6329A, 210S12E6329DDC C1	T12S-R63E-29	36.88	-114.95	210
CE-VF-2	210S12E6329DABC1	1221	1981-12-15	2466.9		T12S-R63E-29	36.87	-114.93	210
CSV-1	219S13E6431DAAD1	765	1985-10-16	2158.6		T13S-R64E-31	36.77	-114.86	219
CSV-2	219S13E6528BDAC1	478	1985-10-26	2185.9		T13S-R65E-28	36.78	-114.72	219

CSV-3	210S14E6328ACDC1	780	1987-02-07	2414.3	Alternate ID: 210S14E6328AD, 210S14E6328ADDD. Lat-Long from USGS. DWR Lat-Long puts well in wrong section.	T14S-R63E-28	36.69	-114.93	210
DDL-1	169S11E6036AAAD1	420	1986-10-01	3208	Alternate ID: 169S11E6036AA	T11S-R60E-36	36.95	-115.20	169
DDL-2	169S12E6010AD	460	1989-01-21	3300	Alternate ID: 169BS12E6011	T12S-R60E-10	36.92	-115.24	169
DR-1	212S16E5814A	930	1989-01-26			T16S-R58E-14	36.56	-115.41	212
Judy's Ranch	210S11E6213DBCB1	100		2520	Alternate ID: 210S11E6213DB, Alternate ground elev: 2540	T11S-R62E-13	36.99	-114.99	210
Lamb	209S08E6102CB	92	1947-01-01			T08S-R61E-02	37.28	-115.12	209
Old Highway Well	210S13E6311BACD1	170	1954	2220	USBLM Well. Alternate ground elev: 2222	T13S-R63E-11	36.84	-114.90	210
Perkins	210S13E6325BDAA1	353	1944-05-04	2159	Alternate ID: 210S13E6325, Adjusted lat-long to USGS values.	T13S-R63E-25	36.79	-114.88	210
SBH-1	212S16E5823DDD	720	1987-02-24			T16S-R58E-23	36.54	-115.40	212
SHV-1	217S16E6309DDAB1	920		2648.8		T16S-R63E-09	36.55	-114.93	217
Unnamed #1	210S11E6224DBAD1	149		2490	Lat-Long from USGS, DWR Lat-Long not consistent with PLSS	T11S-R62E-24	36.98	-114.98	210
Van Horn #1	210S10E6214AA	510	1958-04-23	2712	Alternate ID: 210S10E6214A, alternate ground	T10S-R62E-14	37.08	-115.00	210

					elev: 3000				
Van Horn #2	210S10E6224BC	231	1958-05-02	2685	Alternated ID: 210S10E6224B1	T10S-R62E-24	37.06	-114.99	210
VSF&W #1	209S08E6111BB			3322	Unknown well depth	T08S-R61E-11	37.27	-115.12	209
VSF&W #2	209S08E6231CAAB1	64		3200	Alternate ID: 209S08E6231CC, Incorrect location from report, use USGS lat long for USGS well 209S08E6231CAA B1, ground elev 3193	T08S-R62E-31	37.21	-115.08	209