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 25 OF 49

Description of Map Units

Nevada Bureau of Mines and Geology

Map 127

GEOLOGY OF THE FRENCHMAN MOUNTAIN QUADRANGLE

CLARK COUNTY, NEVADA

by

S.B. Castor, J.E. Faulds, S.M. Rowland, and C.M. dePolo

The Frenchman Mountain Quadrangle contains exposures of rock units that range in age from the Middle Cambrian Chisholm Shale through Holocene alluvium. Older Cambrian and Proterozoic rocks are not exposed in the quadrangle but crop out just to the west in the Las Vegas NE Quadrangle (Matti and others, 1993). Major breaks in the stratigraphic section include the Ordovician through early Devonian (at least 100 million years), the Late Permian and part of the Early Triassic (perhaps 20 million years), and much of Mesozoic and Cenozoic time (a break of as much as 200 million years). The Paleozoic and Mesozoic strata are conformable, and both the Ordovician/Silurian and Paleozoic/Mesozoic boundaries are disconformities. In contrast, the break between the youngest Mesozoic unit (Early Jurassic Aztec Sandstone) and the oldest Tertiary unit (basal conglomerate of the Horse Spring Formation) is marked by a slight angular unconformity. The base of the Tertiary rests on progressively younger units to the north from a position on the upper part of the Moenkopi Formation (Middle Triassic) in the southern part of the Frenchman Mountain Quadrangle to the Aztec Sandstone in the central part. However, except for local structural complexities, the dip discordance between Mesozoic and Tertiary strata is only a few degrees.

QUATERNARY

Qa Active alluvium Active cobble, gravel, and sand deposits in washes, locally with boulders in proximal reaches; occupies channels inset up to 15 m (~35 m in Las Vegas Wash) and proximal to discharge areas of alluvial fans; anastomosing bar-and-channel surface morphology is nearly ubiquitous. These surfaces have commonly been shaped by the last major discharge event in the channel and have a distinct flood hazard potential. Deposits range from moderately sorted to poorly sorted, poorly to moderately stratified, and non-indurated to weakly cemented by salts (commonly gypsum). Clasts are angular to subrounded. Thickness of the deposits ranges from a few centimeters to ~10 m.

Ql Landfill Sunrise landfill disturbed area. Much of this unit is cover over a decommissioned landfill, but some represents scraped and highly disturbed older units.

Qia Intermittently active alluvium Alluvial surfaces that are intermittently active including low terraces and discharge areas of alluvial fans. Bar-and-channel surface morphology is common, although many of these surfaces have stable vegetation. Deposits range from moderately sorted to poorly sorted, poorly to moderately stratified, and non-indurated to weakly cemented by salts (commonly gypsum). Clasts are angular to subangular.

Qab Basin alluvium of Las Vegas Valley Alluvium of the basin floor of Las Vegas Valley. Surface morphology consists of a series of shallow channels with interfluvial sandy flats. The unit consists of light brown sandy silty clays to silty fine sands; generally poorly to moderately stratified with thin bedding; mostly unconsolidated but locally indurated by clay and weakly cemented with gypsum and other salts.

Qa_1 Young stream-terrace and fan-terrace alluvium Alluvial surfaces forming the lowest set of stream and fan terraces. A smoothed bar-and-swale surface morphology is common where clasts include cobbles; surfaces are more smoothed where clasts are pebbles. Moderately developed etching occurs on limestones and sandstones, and rock varnish is weakly to moderately well developed on small clasts. Soil development includes a 2- to 5-cm-thick eolian silt Av horizon, an incipient cambic horizon that can be up to 15 cm thick, and a stage I to II calcic horizon. Pavements are moderately well developed to well developed. Deposits are commonly weakly to moderately well indurated, poorly to moderately sorted, and are poorly to moderately stratified.

Qa_2 Intermediate stream-terrace and fan-terrace alluvium (late Pleistocene) Alluvial surfaces forming an intermediate level of stream and fan terraces. Alluvial surfaces are present in the cobbly units but are smoothed from surficial reworking and eolian deposition. In pebbly deposits little or no surface may remain. Edges of deposits are commonly eroded or dissected. Pavements are well developed and rock varnish is moderately to strongly developed on siliciclastic, cherty, and granitoid rocks. Limestones and sandstones are moderately well to well etched. Soil development includes a 5- to 15-cm-thick eolian silt Av horizon overlying a reddish argillic horizon up to 80 cm thick, and a stage I to III calcic horizon or a gypsiferous horizon up to 40 cm thick at the base of the profile. Deposits are made up of sandy gravels to gravely cobbles. Deposits are moderately well indurated, poorly to moderately sorted, and poorly to moderately stratified. Clasts are angular to subangular. Deposit thicknesses range from 0.5 to 5 m.

Qsg Intermediate alluvium of Las Vegas Wash (late Pleistocene) Interbedded silty fine sands and gravels locally inset into the channel of Las Vegas Wash. Deposits are moderately to well stratified, non-indurated, have a badlands-erosional character, and lack surfaces and soils.

Qa_3 Older stream-terrace and fan-terrace alluvium (Pleistocene) Alluvial surfaces forming the highest recognizable stream- and fan-terrace remnants. These units either lack surfaces or are erosionally stripped down to resistant calcic horizons. Areas that lack surfaces are eroded slopes or ballenas. Surfaces have moderately to well developed pavements with abundant pedogenic carbonate litter. Rock varnish is moderately well to well developed. Soils are generally truncated above calcic horizons that have stage III to IV carbonate development, overlain by an up to 20-cm-thick eolian silt cap (Av). Calcic horizons are >1 m thick, and carbonate rinds are up to 2 cm thick and are commonly micritic in character. Some buried paleosols exist. Deposits are sandy gravels to gravelly cobbles, moderately well to well indurated, poorly to moderately sorted, and poorly to moderately stratified. Clasts are angular to subangular. Deposit thicknesses range from 2 to >5 m.

QTcg Older cemented conglomerate of Las Vegas Wash (Quaternary or late Tertiary) Sandy pebble to cobble conglomerate composed of rounded and subrounded limestone, volcanic, granitic, and gneissic clasts cemented into a sandy calcareous matrix. Moderately to well sorted, generally well stratified with large-scale fluvial cross-bedding. The deposit is a well indurated, cliff-forming unit that is generally restricted to the channel walls of Las Vegas Wash, and is 10 m to 30 m thick. The deposit represents a paleochannel along Las Vegas Wash.

QTa Older alluvium and lag gravels (Quaternary or late Tertiary) Gravel deposits that have the highest geomorphic position of any alluvium, capping low ridges; no surfaces are preserved. Relict carbonate horizons occur locally, with up to stage IV carbonate development and >1-m-thick gypsic horizons with stage V salt development. Carbonate rinds on some clasts exceed 2 cm in thickness and are commonly micritic in character. The deposits are poorly stratified and consist of pebble to boulder gravels that are poorly to moderately sorted and poorly to moderately indurated. The clasts are mostly angular to subangular and have very dark surfaces. They are dominantly of Tertiary porphyry (Td) and Proterozoic metamorphic rock and granite but also include a little Tertiary limestone and local Paleozoic carbonate. These gravels, which are as much as 20 m thick, mainly overlie Tertiary deposits, commonly sandstones and conglomerates of the Muddy Creek Formation. In places, they are lag gravels resting on conglomerates in the Muddy Creek Formation.

QTa_n Older alluvium of Nellis basin (Quaternary or late Tertiary) Reddish brown, thin-bedded (2 to 25 cm thick), poorly to moderately sorted pebble conglomerate and lesser interbedded medium-grained sandstone. Conglomerate is generally matrix supported but includes clast-supported beds. Pebbles are subangular to subrounded. Clast compositions are dominated by Paleozoic lithologies but include sparse Proterozoic gneiss. Thickness is as much as 20 m.

QTbl Limestone megabreccia(?) (Quaternary or late Tertiary) Possible landslide deposit composed primarily of anomalous west-dipping Callville Limestone but includes minor Pakoon Formation on the east (**QTblp**) and possibly, near the southwest margin of the exposure, slivers of the Redwall Limestone. The margins of this deposit are generally fault-bounded and brecciated, whereas internal parts are relatively coherent. This unit may be a large landslide block derived from the high terrain of Sunrise Mountain to the south and southeast.

TERTIARY

Tertiary sedimentary units mapped in the Frenchman Mountain Quadrangle include the Horse Spring Formation, which is subdivided into four members following the terminology of Bohannon (1984); the informal red sandstone unit of Bohannon (1984); and the Muddy Creek Formation as designated by Longwell and others (1965) from the “Muddy Creek beds” of Stock (1921). All are considered to be of Miocene age, although tuff that lies beneath the Horse Spring Formation near Logandale has yielded a late Oligocene age (Bohannon, 1984).

Muddy Creek Formation

Four subunits in the Muddy Creek Formation were defined in the Frenchman Mountain Quadrangle. In the northeast part of the quadrangle, limestone, gypsite, and gypsiferous gravel subunits (Tml, Tmg, and Tmgg, respectively) compose the upper part of the Muddy Creek Formation. The most extensive subunit (Tm) consists of siltstone to conglomerate; coarse detritus in this subunit appears to have been derived from local sources.

We originally placed the limestone unit (Tml) in the Muddy Creek Formation on the basis of its stratigraphic position. On Nellis Air Force Base, this limestone lies on redbeds that have been placed in the red sandstone unit of Bohannon (1984) on the basis of an 11.6 Ma $^{40}Ar/^{39}Ar$ date of an interbedded tuff (sample JF99-452). In addition, the limestone unit directly overlies tuffaceous marl that may be equivalent to or overlie Muddy Creek gypsite near a gas pipeline road at 36° 14' 35"N, 114° 54' 04"W. During subsequent work, a sample of vitric waterlaid tuff collected just north of the Frenchman Mountain Quadrangle (JF99-455, table 1) yielded a tephrochronologic age of 6.0 Ma (M. Perkins, written commun., 1999). Strata mapped as the Muddy Creek Formation may be as old as 10.4 Ma as constrained by associated volcanic rocks in the Callville Mesa area and are as young as 5.9 Ma on the basis of associated volcanic rocks at Fortification Hill (Wallin and others, 1993).

Although locally tilted as much as 70° adjacent to faults, the Muddy Creek Formation is predominantly flat-lying to very gently tilted and, thus, largely postdates tectonism. R.E. Anderson (personal commun., 1999) has proposed a large, open syncline in the unit with a northeast-trending hingeline that crosses Lake Mead Boulevard about 1 km southeast of the Muddy Creek/red sandstone contact. Our structural data support this, but the fold hinge is not shown because dips are too shallow and variable to define an exact location. Anderson further suggested that Muddy Creek conglomerate and conglomerate in the underlying red sandstone may have been deposited continuously on the north limb of a local syntectonic depocenter in this area.

Tml Limestone Mostly moderately resistant pale-orange limestone with light-gray to light-brownish-gray weathered surfaces; limestone is laminated to thick bedded with finely crystalline dense to porous textures. Some porous beds have cm-scale crustiform algal textures. Well-preserved ostracods have been noted in thin section, but identifiable macrofossils were not observed. The limestone is as much as 50 m thick. Friable, commonly dolomitic, pale-olive to yellowish-gray or white marl is locally exposed beneath the limestone. The limestone and marl are interbedded with or overlie gypsite along the contact with Tmg. The base of the unit also includes minor gypsum in the northwest part of the map area.

Tmg Gypsum Gypsite unit that caps a very gently southward-dipping plateau in the northeast part of the quadrangle and thins to the south and west; isolated remnants of this unit (many too small to be mapped) occur along Gypsum Wash north of the Paleozoic buttress that includes Gypsum Cave. The gypsite is mostly white to grayish-orange, weakly resistant rock containing white gypsum crystals, generally less than 2 mm but in places as much as 15 cm across, with variable amounts of silt and clay. The unit locally includes an upper sequence that is light greenish gray with admixed clay to fine sand. At the PABCO Gypsum Mine on the east edge of the quadrangle, gypsum ore is more than 35 m thick and averages more than 80% gypsum (L. Ordway, 1997, personal commun.). According to Papke (1987), PABCO gypsum ore also contains montmorillonite, quartz, potash feldspar, and plagioclase. Southwest of the mine the gypsite is exposed along an erosional escarpment about 3 km long; here it is 3 to 10 m thick and overlies Tm.

Tmgg Gypsiferous gravel Gypsiferous gravel with some moderate-orange-pink to pale-red sandy and silty layers. Clasts are mainly gray Paleozoic carbonate and chert. The upper 2 to 5 m of Tmgg contains abundant gypsum and may be coeval with Tmg on the basis of topographic position. East of Gypsum Wash, this unit is interbedded with, and at least partly equivalent to, Tm.

Tm Sandstone, siltstone, and conglomerate Poorly to moderately sorted pale-reddish-brown and pale-red sandstone and siltstone with some interbedded pebble to boulder conglomerate. Locally, the unit is mostly coarse conglomerate. Fine-grained lithologies generally dominate in the east part of the quadrangle. Sandstone is generally fine- to medium-grained with subangular to subrounded grains, weakly indurated with calcite cement, and thinly bedded. Conglomerate generally contains subangular clasts and includes both matrix and clast-supported beds, but matrix-supported beds dominate. Bed thickness ranges from 2 to 30 cm. North of Sunrise Mountain in the Nellis Air Force Base, conglomerate gives way northward to limestone and gypsum (lacustrine facies) toward a depocenter near the north margin of the map area, here referred to as the Nellis basin. Near the Frenchman fault, Tm is dominated by thinly to moderately bedded, poorly to moderately sorted, matrix-supported, weakly indurated (calcite cement), pale-brown or reddish-brown to light-gray conglomerate containing subangular clasts of Paleozoic lithologies ranging up to 50 cm. Where composed of sandstone and siltstone, Tm is difficult to distinguish from other redbed units, such as Tht and Tr (see below) but generally has flat-lying or gently dipping (less than 20°) bedding and commonly contains some gypsum.

Volcanics of Callville Mesa

Basaltic flow rocks and associated cinders that crop out in the central east part of the Frenchman Mountain Quadrangle have been correlated with the 11.5- to 8.5-Ma volcanics of Callville Mesa (Anderson and others, 1972; Feuerbach and others, 1991) on the basis of stratigraphic position. The basalts are associated with unconsolidated tuffaceous beds (map unit Tvt) that seem to be interstratified with the Muddy Creek Formation. However, it is possible that these rocks are instead related to basaltic rocks in the southeast part of the quadrangle that are 13.16 Ma (see "igneous rocks coeval with the River Mountains Volcanics" below).

Tvt **Tuffaceous siltstone** Nonresistant pinkish-gray tuffaceous siltstone. Includes some beds with Tvc cinders near base. Underlies Tmgg and may be coeval with part of Tm.

Tvc **Mafic flows and cinders** Dark gray to dark greenish-gray or grayish-red basaltic or andesitic lava, agglomerate, and cinder accumulations. The lava has phenocrysts of plagioclase, ± olivine, and ± pyroxene up to 1 mm in diameter in a fine-grained pilotaxitic groundmass.

Red sandstone unit

The red sandstone is an informal unit of Bohannon (1984). It is generally difficult to distinguish from similar rock in other units such as the older Thumb Member of the Horse Spring Formation and the younger Muddy Creek Formation. In some areas, it was mainly distinguished from the Muddy Creek by the presence of relatively steeply dipping strata (20° or more). In a tributary of Las Vegas Wash at 36° 07' 50"N, 114° 53' 28"W an angular unconformity of about 20° between the red sandstone and the overlying Muddy Creek Formation is well exposed. The red sandstone unit crops out in two areas that may represent separate basins: (1) in the northwest part of the quadrangle, mostly on Nellis Air Force Base; and (2) in a much larger area in the southeast quarter of the quadrangle.

In the northwestern part of the quadrangle, the red sandstone unit consists of a thick (at least 600 m) sequence of mainly east-tilted sedimentary rocks that accumulated in an east-tilted half graben that forms a distinct subbasin of Las Vegas Valley, as evidenced by isostatic gravity data (Langenheim and others, 1997). In the southeast quarter of the quadrangle, the red sandstone unit is estimated to be about 700 m thick, and mainly occurs in a northeast-trending basin that is about 5 km long and 3 km wide and may extend eastward for as much as 10 km (Duebendorfer and Wallin, 1991).

Tr **Red sandstone undifferentiated** In the northwest part of the quadrangle, Tr is chiefly composed of interbedded, moderately sorted, weakly indurated (calcite cement) pale to dark reddish-brown to purplish-brown and locally yellowish-gray to yellowish-brown mudstone, siltstone, fine- to medium-grained sandstone, and pebble conglomerate. The conglomerate is generally matrix supported and contains subangular clasts of Paleozoic lithologies (carbonate, chert, and sandstone), Proterozoic gneiss and amphibolite, and large feldspar grains probably derived from Proterozoic granite and gneiss. Clasts are generally pebble size, but some are as much as 20 cm in diameter. The beds are locally gypsiferous and include stringers and small pods of gypsum. The sandstone and the matrix of the conglomerate consist of subangular to subrounded grains of quartz, K-spar, plagioclase, and accessory biotite, muscovite, epidote, and zircon. Beds typically range from 2 to 30 cm in thickness. Some mudstone and siltstone beds contain raindrop impressions. This unit locally includes thin beds of pale brown micritic limestone that contains pelloids, algal laminations, and ostracod fossils.

Waterlaid tuff beds are intercalated in Tr in the northwest part of the map area. They include a white tuff as much as 2 m thick that contains ~3% phenocrysts of sanidine, biotite, and plagioclase in a matrix of pumice fragments and glass shards. An $^{40}Ar/^{39}Ar$ date on sanidine and glass chemistry correlation both indicate an age of 11.6 Ma for this tuff (sample JF99-452, table 1). A silver-gray vitric shard tuff of similar thickness is slightly higher in the section.

In the southeast quarter of the quadrangle the red sandstone unit is mostly poorly to moderately indurated, partially calcite-cemented, moderate-orange-pink to pale-reddish-brown, fine-grained sandstone with minor gypsum. The unit includes several tuff layers in its lower part and a thick conglomerate sequence in its upper part. Near the base of the red sandstone unit is a 1.5-m-thick bed of silver-gray, glassy, rhyolite shard tuff (C95-4, table 2). About 100 m above this tuff is a 2-m-thick white to very pale-green tuffaceous sequence that mainly consists of tuffaceous sandstone with local soft sediment deformation folds. The basal 30 cm of this sequence consists of thinly bedded, fine-grained rhyolite tuff (C95-3, table 2) with small crystals of quartz, sanidine, plagioclase, biotite, pyroxene, and hornblende. The sanidine yielded a date of about 11.47 Ma (table 1), nearly indistinguishable from the age of the rhyolitic Ammonia Tanks Tuff, a regionally extensive high-silica rhyolite to alkali trachyte ash-flow sheet from the Timber Mountain caldera about 150 km northwest of the Frenchman Mountain Quadrangle (Sawyer and others, 1994).

Excellent outcrops of a thick sequence (at least 200 m) of well-bedded pebble to boulder conglomerate that is laterally equivalent to sandy beds in the red sandstone unit occur along the east bank of a large wash adjacent to Lake Mead Boulevard. Clasts consist of high-grade Proterozoic metamorphic rock, Tertiary basalt, white mudstone, and reddish sandstone. Bedding dips are as great as 60° to the southeast. About 75 m to the southeast in the wash is conglomerate with much gentler tilts (the maximum dip is 18° southeast) and clast lithologies similar to those noted above but additionally including abundant porphyry similar to Td (see below). The contact area in the wash, at 36° 11' 19"N, 114° 54' 00"W, is covered. R.E. Anderson (personal commun., 1999), who has noted similar relationships elsewhere suggested that this contact is gradational, and the bedding fans gradually due to tilting during deposition. We find the evidence for such a relationship to be equivocal in this area. Instead, we have mapped a contact between the red sandstone and the Muddy Creek Formation at this site and infer an angular unconformity here on the basis of clear evidence for such a relationship elsewhere. In addition, the change in clast lithology may reflect provenance in two different source areas. However, we concur that the presence of a thick conglomerate sequence in the red sandstone in this area is problematic (although Bohannon, 1984, noted local conglomerate in the unit in the Muddy Mountains) and suggests uplift during deposition.

Near the south edge of the quadrangle, the contact between the red sandstone and the underlying Horse Spring Formation is a fault that dips steeply east. In the vicinity of Lake Mead Boulevard no fault is obvious along this contact. Whether faulted or not, the contact between the red sandstone and Horse Spring Formation is commonly marked by mafic flows (Tb).

Trg **Gypsum** Yellowish-gray to yellowish-brown bedded gypsum intercalated in Tr. The only mappable sequence of Trg was found near the Frenchman fault in the northwest part of the quadrangle, where it is as much as 30 m thick.

Igneous rocks coeval with the River Mountains Volcanics

In the southeast part of the quadrangle, dacitic to basaltic rocks predate the red sandstone unit. Our dates on these rocks range from about 13.2 Ma to 13.5 Ma, indicating that they correlate with the River Mountains Volcanics (Smith, 1982), which have yielded $^{40}Ar/^{39}Ar$ dates ranging from 13.0 to 13.45 Ma (Faulds and others, 1999).

Tb **Basalt** Medium-light-gray to dark-greenish-gray flows ± dikes with some vesicular rock and minor glassy basalt. These rocks, which include basalt and andesite on the basis of whole rock chemistry (samples C95-9 and C95-20, table 2), commonly have vesiculated tops and locally consist of glassy rock. They occur in the Lovell Wash Member (Thl) of the Horse Spring

Formation or separate it from the overlying red sandstone unit (Tr). Along the Thl/Tr contact east of Lava Butte at least two flows lie above light-green to white gypsum and tuff and are separated by reddish-brown sandstone and gypsum. The rocks typically contain phenocrysts of olivine and plagioclase in a fine-grained pilotaxitic matrix. A groundmass concentrate from sample C95-20, which consists of holocrystalline, intergranular, seriate flow rock with crystals of olivine as much as 4 mm long, yielded an $^{40}Ar/^{39}Ar$ age of 13.16 ± 0.18 Ma (table 1).

Tvd Dacite flow rock Light-gray porphyry with phenocrysts of plagioclase, biotite, and hornblende. Very similar to intrusive porphyry (Td) described below.

Td Intrusive porphyry Porphyry with abundant phenocrysts of white plagioclase to 5 mm, and lesser amounts of smaller black hornblende and biotite phenocrysts, in an aphanitic light-gray to light-brownish-gray matrix. It is locally altered to light gray or yellowish gray; weathered surfaces are commonly brownish gray. Td shows no clear evidence of extrusion and is therefore considered to be entirely of intrusive origin. It contains sparse inclusions of more mafic volcanic rock (probably Tta) and some narrow very fine-grained dikes or xenoliths near the top of Lava Butte.

Td occurs in the upper part of the Thumb Member of the Horse Spring Formation, forming a large mass that comprises most of Lava Butte, a narrow exposure that extends along a ridge to the north, and a similar narrow body to the south that appears to be separated from the main Lava Butte mass by a fault. The narrow masses are clearly discordant dikes; exposed contacts between them and adjacent Thumb Member sedimentary rocks are nearly vertical, and the porphyry is commonly brecciated along them. However, the western boundary of the Lava Butte mass dips shallowly east and is parallel to anomalously shallow strata in the underlying Thumb Member. Here the porphyry is strongly foliated in a narrow zone (about 10 to 50 cm thick) along the contact. The eastern contact is clearly a high-angle feature and has provisionally been mapped as a fault. The eastern contact is exposed in two places; at one of these it is a fault dipping steeply west, but at the other exposure the porphyry includes a narrow strongly foliated border similar to that along the western boundary.

The shape of the Lava Butte porphyry mass at depth is problematic because of anomalously low dips in Tht to the west and below it. It has been suggested that the contact between Tht and Trl to the west is a reverse fault (R. Bohannon, written commun., 1999), but no evidence of such a fault was observed. We interpret the Lava Butte porphyry mass as an irregular intrusion, perhaps a “christmas tree laccolith” (see cross section B–B´) that deformed surrounding parts of the Horse Spring Formation.

Although phenocryst mineralogy (plagioclase, hornblende, and biotite, without potash feldspar or quartz) is suggestive of dacitic composition, rock chemistry on a single sample from Lava Butte is that of low-silica rhyolite with somewhat elevated potash (sample C95-29, table 2). Plagioclase phenocrysts have an estimated composition of An_{50}, suggesting intermediate composition.

Anderson and others (1972) reported K-Ar ages of 13.8±0.7 Ma and 12.0±2.0 Ma (recalculated to new constants) on biotite and hornblende, respectively, from this rock unit, although Bohannon (1984) suggested that these ages were reset by alteration. Our step-heating $^{40}Ar/^{39}Ar$ ages of 13.16±0.05 Ma and 13.50±0.16 Ma on biotite and hornblende, respectively, from sample C95-29 (table 1) confirm the biotite date of Anderson and others (1972). Both step-heating age spectra are plateaus except for the lowest and highest temperature steps; however, the hornblende and biotite separates provided somewhat different ages (table 1). Both minerals appear unaltered in thin section, but the biotite contains abundant inclusions in comparison to the hornblende, suggesting that the older hornblende date may be more accurate. Regardless of which age is used, the dacite porphyry is probably too young to have been extruded during Thumb Member deposition, and its age is virtually indistinguishable from ages obtained on tuffs in the overlying Bitter Ridge and Lovell Wash Members of the Horse Spring Formation (table 1). The ages that we obtained on Td are similar to K-Ar (Anderson and others, 1972; Weber and Smith, 1987) and $^{40}Ar/^{39}Ar$ ages (Faulds and others, 1999) reported for felsic volcanic and intrusive rocks in the River Mountains to the south, suggesting that intrusions of Td in the Lava Butte area were related to magmatism in the River Mountains.

Horse Spring Formation

The Horse Spring Formation, originally defined in the Muddy Mountains by Longwell (1928), was redefined and subdivided regionally by Bohannon (1984), who also described sections in the Lava Butte area. We have used Bohannon’s subdivision, but our descriptions of some units differ due to lateral variations. The Lovell Wash Member is typified by very pale to white colors and by tuffaceous rocks; it contains abundant carbonate and calcareous shale in the south part of the quadrangle but is dominated by tuff in the north part. We mapped the basal contact of the Bitter Ridge Member at the base of a thick sequence (as much as 120 m) of light-colored algal limestone at and south of the latitude of Lava Butte. This limestone is similar to that described by Bohannon (1984) as the dominant lithology in the member in the Lava Butte area. However, the unit contains progressively less limestone to the north, where it mostly consists of sandstone. To the south, this sandstone occurs between sequences that are dominantly composed of limestone. However, to the northeast of Lake Mead Boulevard the sandstone is too thin to map at 1:24,000, and thus shaly and tuffaceous strata of the Lovell Wash Member are shown lying directly on the Thumb Member. The Thumb Member, which includes significant amounts of basal conglomerate and gypsum in the south part of the quadrangle, is largely devoid of these rock types to the north. The Rainbow Garden Member, mainly limestone in the south part of the quadrangle, thins and is replaced by calcareous sandstone to the north. The only unit with consistent lithology throughout the quadrangle is the basal conglomerate of the Rainbow Gardens Member (Trc).

Thl Lovell Wash Member Mostly limy or dolomitic white, light-greenish-gray, very pale-orange, pale-pink or yellowish-gray tuff, mudstone, and siltstone with minor sandstone, gypsum, carbonate beds, and tufa. This member is dominated by carbonate, mudstone, and tuff in the south part of the Frenchman Mountain Quadrangle and by tuff in the eastern part of the quadrangle. Tuffs in the south part of the quadrangle range from pale-green, zeolitized rock with biotite ± hornblende to white, clay-altered material that is typified by “popcorn” weathering and is extremely slimy when wet. Lithium-rich clay (hectorite?) was noted in this unit in the Frenchman Mountain Quadrangle by Brenner-Tourtelot (1979) and Vine (1980). Clay-rich beds crop out locally along with minor amounts of finely laminated algal carbonate that resembles the “eggshell limestone” associated with borate mineralization in the Muddy Mountains (Castor, 1993). The mudstone and sandstone are locally ripple bedded. Carbonate beds, which include both dolomite and limestone, are typically finely laminated. A light-gray tufa bed with pods and layers of dark-weathering silica (shown as -o-o-o-o- on the map) occurs near the top of the unit and is overlain by light greenish-gray tuff and gypsum. The tufa occurrences were, in part, originally mapped by Brenner-Tourtelot (1979) as “spring pots.”

To the east of Lake Mead Boulevard, the Lovell Wash Member is composed mainly of very pale green to white tuff with minor dolomite. It is intruded and capped by Tb. Bohannon (1984) reported a zircon fission-track age of 13.0±0.8 Ma for tuff in the Lovell Wash Member. Samples collected during our mapping yielded a plagioclase $^{40}Ar/^{39}Ar$ isochron age of 13.12±0.24 Ma (sample C95-50, table 1), and $^{40}Ar/^{39}Ar$ step-heating ages of 13.40±0.05 Ma and 13.12±0.12 Ma on biotite and hornblende, respectively (sample C95-64, table 1).

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Thb Thbx Ths Bitter Ridge Limestone Member Resistant very light-gray to pale-orange limestone and dolomite that is commonly brecciated and locally contains tufa textures. The carbonate is generally massive to thin bedded, but locally contains white fissile beds. To the east and southeast of Lava Butte, the middle part of the member includes a unit (**Thbx**) as much as 30 m thick that consists of crudely to well-bedded volcanic breccias that Bohannon (1984) noted as intraformational breccia. Based on our examination, these rocks are lahars and bedded breccias, mostly light brown in color, that contain significant amounts of andesite lava (map unit Tta), cinders, silicified volcanic rock, and limestone in limy matrix. They also contain minor amounts of dacite porphyry (similar to map unit Td). In addition to the breccias, this part of the Bitter Ridge Member contains small possibly intrusive masses of dacite porphyry. Lapilli beds are interbedded with limestone indicating volcanic activity concurrent with lacustrine deposition. This member also contains at least one sequence of pinkish-gray to yellowish-gray sandstone with limy cement (**Ths**) that is up to 60 m thick and composed mostly of fine- to medium-grained sandstone with some coarse sand to pebbly beds. In addition, it includes a 6-m-thick light-greenish-gray tuff, mainly of air-fall or reworked origin, and locally it includes ash-flow tuff (sample C95-38). About 1 km northeast of Lava Butte, the limestone pinches out, and the Bitter Ridge Member is represented by less than 30 m of Ths that includes a 6-m-thick pale-green tuff. This member is present but included in Thl to the east of Lake Mead Boulevard, where it consists of only about 5 m of sandstone and fissile white limestone plus 3 m of light-greenish-gray tuff. Sanidine from sample C95-38 yielded a mean single crystal $^{40}Ar/^{39}Ar$ age of 13.07±0.08 Ma (C. Henry, personal commun., 1997). Thb is up to 240 m thick.

At sample site C95-38, a bed of pumiceous pale-green zeolitized ash-flow tuff about 1.5 m thick lies stratigraphically above the breccias from which it is separated by 23 m of light-colored shale and laminated limestone. The 13.1-Ma age of this sample is indistinguishable (within analytical uncertainties) from the age of the intrusive porphyry (Td) at Lava Butte and tuffs in the Lovell Wash Member (fig. 1). Above the dated tuff is about 30 m of white to light yellowish-gray ripple-marked, thin-bedded to laminated carbonate and calcareous mudstone that is overlain by strata of the Lovell Wash Member.

The laterally discontinuous units, presence of volcanic detritus in intraformational breccias, and presence of ash-flow tuff within the largely algal calcareous Bitter Ridge Member are evidence of volcanic activity during lacustrine deposition. The fact that the age of tuff in the upper part of the Bitter Ridge Member is equivalent to or only slightly younger than that of the intrusive porphyry on Lava Butte is consistent with this interpretation, as are the masses of possibly intrusive porphyry in the Bitter Ridge Member.

Thumb Member

Tht Sandstone, siltstone, and conglomerate Mostly pale-reddish-brown to light-brown limy fine-grained sandstone and siltstone, in places containing some light-greenish-gray beds. Sandstone and siltstone of the Thumb Member are difficult to distinguish from similar rocks in other units in the quadrangle; in some areas the unit can be distinguished by the presence of breccia composed of Proterozoic rocks (Ttb). The sandstone is locally cross-bedded. It also locally contains minor to abundant gypsum, whereas in other areas it includes beds of pebble conglomerate with clasts of Paleozoic and Mesozoic carbonate, chert, and sandstone, with few if any Proterozoic clasts. Tht locally exhibits soft-sediment deformation, particularly adjacent to Ttb (see below). Minor amounts of tuffaceous rock occur in the upper part of the Thumb Member on the west side of Lava Butte. In the northeast part of the quadrangle, a pale-green biotite-bearing tuff bed occurs in the vicinity of Gypsum Spring and near the intersection of Lake Mead Boulevard and the road to the PABCO Mine. The Thumb Member is more than 305 m thick.

According to R.E. Anderson (personal commun., 1998), Thumb Member rocks mapped above the upper andesite flow (Tta) near the south edge of the quadrangle should be included in the overlying Bitter Ridge Member. However, we put these rocks in the upper part of Thumb Member because they are mainly light-yellowish-gray sandstone and siltstone and contain only minor amounts of limestone.

The age of the Thumb Member in the Frenchman Mountain area is poorly constrained. Relatively young ages, 11.2 to 13.8 Ma (by K/Ar, recalculated to new constants) obtained by Anderson and others (1972) are on igneous rocks that are probably intrusive, and thus represent minimum ages. Older ages, 16.0 and 17.6 Ma (by K/Ar, recalculated to new constants), are on flows within the Thumb Member, but these ages are not very accurate (± 3 Ma). Bohannon (1984) reported a 13.2 ± 0.9 Ma age on tuff in the Thumb Member, but proposed that this was an anomalously young age. He suggested a regional age range for the unit of 17.2 to possibly 13.5 Ma. Beard (1996) reported eight $^{40}Ar/^{39}Ar$ ages ranging between 16.2 Ma and 14.2 Ma in the South Virgin Mountains. The porphyry that holds up Lava Butte (Td) is considered to be intrusive into rocks of the Thumb Member on the basis of age and contact relationships. Dates on this porphyry (sample C95-29, table 1) indicate a minimum age of about 13.2 Ma for the Thumb Member in the Frenchman Mountain area. We obtained a new date of about 13.9 Ma on biotite from a tuff sample 2 km northeast of the Frenchman Mountain Quadrangle (C99-14, table 1). This is a 1-m-thick air-fall tuff that lies above siltstone and sandstone of the Thumb Member and beneath resistant limestone of the Bitter Ridge Member.

Tta Intermediate or mafic volcanic rock Fine-grained, pale-brown intermediate or mafic volcanic rock that contains small phenocrysts of plagioclase and biotite ± pyroxene ± altered hornblende and very fine-grained, medium- to light-gray intermediate volcanic rock with tiny plagioclase laths that form pilotaxitic texture. These lithologies comprise at least two flows and may include some intrusive rock in the Thumb Member. Flows are 2 to 5 m or more thick with vesiculated tops.

Ttb Breccia with Proterozoic detritus Lenses and beds of breccia composed exclusively of clasts of Proterozoic rock, which is diagnostic of the Thumb Member (e.g., Rowland and others, 1990). In some areas this breccia is monolithologic, but in other areas the breccia contains a variety of metamorphic and igneous lithologies including granite, amphibolite, biotite-quartz-feldspar gneiss (± garnet), alaskite, and pegmatite. The breccia is relatively resistant and generally forms steep-sided hills. As an example, the Red Needle, a prominent landmark in the southern part of the quadrangle (formerly "The Thumb" and stratigraphic namesake), consists of soft-sediment-deformed Thumb Member beds surmounted by a mass of such breccia. The breccia ranges from poorly bedded heterolithic matrix-supported debris flow deposits to clast-supported monolithologic megabreccia. Some breccia clasts are large. For example, at 36° 10' 14"N, 114° 56' 09"W a slab of Proterozoic gneiss and pegmatite at least 15 m long was observed. Certain types of breccia predominate in specific parts of the quadrangle. In the area between Lake Mead Boulevard and the paved road to the PABCO Gypsum Mine, most breccia masses consist exclusively of coarse granite with large feldspar phenocrysts ("rapakivi granite" of some researchers). Clasts of Paleozoic rock are absent in the breccia.

Ttc Conglomerate Resistant to nonresistant, planar-bedded conglomerate with some sandstone interbeds; intertongues with sandstone and siltstone of Tht to the north and up section. Clasts in the conglomerate are well-rounded to subrounded pebbles to boulders and are mainly of Paleozoic and Mesozoic carbonate and sandstone, Paleozoic chert, and some quartzite (possibly Eureka Quartzite or Tapeats Sandstone). Clasts in some beds consist almost exclusively of Mesozoic sandstone boulders. No clasts of Proterozoic rock were found. The matrix is pale- to moderate-reddish-brown carbonate-cemented, medium to granule sand. Sandstone interbeds are as much as 1 m thick, pale reddish brown, medium grained to granule, carbonate cemented, and generally contain some pebbles. The conglomerate sequence reaches a thickness of about 270 m at the southern edge of the quadrangle but pinches out 1.5 km to the north. The dashed eastern contact of the conglomerate signifies interfingering with more typical Thumb Member sandstone.

Ttg Gypsum-rich sequence This unit is as thick as 120 m at the base of the Thumb Member in the south half of the quadrangle; it is likely that this sequence has been thickened in places by folding or faulting. The gypsum sequence thins or pinches out to the north. The sequence contains light-greenish-gray gypsum beds as much as 7 m thick interbedded with moderate orange-pink or greenish-gray fine-grained sandstone, siltstone, and claystone. The upper part of the unit consists of as much as 20 m of nonresistant pale- to moderate-reddish-brown sandstone and siltstone with minor beds of pale green tuffaceous(?) sandstone. The gypsum in this unit is well exposed locally where it has been mined in the past.

Rainbow Gardens Member

Trl Resistant limestone unit This unit is as much as 100 m thick but pinches out near Lake Mead Boulevard and appears to intertongue with the overlying Tht. Trl mainly consists of a lower sequence of interbedded pale-orange to grayish-orange-pink algal limestone and pale-red, abundantly burrowed sandy limestone along with minor limy siltstone and tuff. The upper part of the unit is well-bedded, pale-yellowish-orange to grayish-orange and dark-yellowish-orange, thin-bedded, sandy limestone and limy sandstone as much as 35 m thick. The yellowish sandy rock is locally capped by grayish-pink algal limestone about 1 m thick that contains dark-brown-weathering chert. It is particularly well exposed west of the gypsum mines east of Rainbow Gardens. This well-bedded limestone intertongues with the redbed and gypsum sequence at the base of the Thumb Member. Beard (1996) noted limestone at a similar stratigraphic level in the South Virgin Mountains in the Thumb Member and proposed an unconformity between the Rainbow Gardens and Thumb Members in that area. It is possible that some of the limestone that we have included in the upper part of the Rainbow Gardens Member actually resides in the Thumb Member, but we have not identified a significant unconformity in the limestone section. Trl thins northward in the Frenchman Mountain Quadrangle and is completely absent to the north of Lake Mead Boulevard.

Trr Sandstone, conglomerate, and limestone unit This unit is as much as 120 m thick. The basal part, which is as much as 50 m thick, consists mainly of nonresistant moderate orange-pink to pale-reddish-brown, fine- to medium-grained sandstone. Similar sandstone along with resistant interbeds of grayish-orange-pink to pale-red limestone and sandy to pebbly limestone make up the middle part of the unit. The upper part consists mostly of moderate-reddish-brown, medium to granule sandstone with some beds of conglomerate and minor thin limestone beds. The conglomerate contains subrounded to rounded pebble to cobble-sized clasts of Paleozoic carbonate, chert, and quartzite along with some fragments of Proterozoic gneiss and granite and dark, micaceous, Late Proterozoic(?) quartzite. Trr includes a sequence of limy reworked tuffs at least 20 m thick in its upper part. The best exposure of this tuff sequence is in a road cut at 36° 10' 14"N, 114° 56' 09"W. A sample of the least reworked-appearing tuff was collected at this site in hopes that it might be suitable for $^{40}Ar/^{39}Ar$ dating. On the basis of thin section examination, it contains small fragments of pumice and fine subrounded grains of plagioclase and quartz along with tiny biotite flakes but also appears to contain abundant non-tuffaceous detritus. Because of this abundant and presumably older detritus, dating was not attempted. Beard (1996) reported an $^{40}Ar/^{39}Ar$ age of 18.8 Ma on anorthoclase for tuffaceous rock from 175 m above the base of the member in the South Virgin Mountains, and the dated rock is probably roughly equivalent to the tuffaceous sequence described above in the Frenchman Mountain Quadrangle. Beard also obtained a 24 Ma $^{40}Ar/^{39}Ar$ age on sanidine from a tuff lower in the section in the same area. Bohannon (1984) reported a zircon fission track age of about 15 Ma for tuff from the Rainbow Gardens Member in the Horse Spring area, but this age is probably too young because the overlying Thumb Member has consistently yielded older dates.

Trc Resistant basal conglomerate Moderate to strongly resistant basal conglomerate of Rainbow Gardens Member that typically forms ridges. Clasts, mostly of Paleozoic and Mesozoic carbonate and chert with some sandstone, are generally subrounded and are pebble to cobble in size. Rare clasts of gray quartzite were also noted; these are clearly not Mesozoic sandstone and most closely resemble Lower Cambrian or Late Proterozoic quartzite such as the Johnnie Quartzite. We found no clasts of highly metamorphosed Proterozoic rock. Bohannon (1984) noted granite and gneiss clasts in this unit in southernmost Rainbow Gardens, but we did not observe these clast lithologies. The conglomerate matrix is pale-red to pale-reddish-brown, fine- to coarse-grained sand cemented by calcite. At a distance, the overall color is light brownish gray owing to the predominantly gray color of carbonate clasts. The basal Rainbow Gardens conglomerate overlies Mesozoic rocks with slight angular unconformity. It rests unconformably on Aztec Sandstone in the central part of the quadrangle and on progressively older Mesozoic units farther south. However, it lies on folded Chinle and Moenave-Kayenta rocks at 36° 12' 22"N, 114° 56' 7"W. Locally, the basal contact is marked by channels a few meters deep. In addition, the conglomerate is too thin to map at 1:24,000 in places. Bohannon (1984) reported that its upper contact shows evidence of erosion and proposed that it formed as a lag gravel on a widespread pediment surface.

MESOZOIC

Ja Aztec Sandstone Moderate-orange-pink to moderate-reddish-orange, fine- to medium-grained sandstone. Invariably cross-bedded in sets as much as 20 m thick. Weathers to distinctive fiery moderate orange pink to moderate reddish brown. The Aztec Sandstone, which has been correlated with the Navajo Sandstone in Utah and the Nugget Sandstone in Wyoming (Peterson and Pipiringos, 1979), is part of a regionally extensive eolian sandstone sequence that is considered to be one of the most voluminous pure quartz arenite formations in the geologic record (Blakey, 1989). Although it is generally very distinctive, forming relatively resistant outcrops with bright-orange to reddish-brown colors and large-scale cross-bedding, isolated small outcrops can be confused with other sandy redbed units. It is overlain with low angular unconformity by the basal Tertiary conglomerate of the Horse Spring Formation. The Aztec Sandstone is as much as 100 m thick in the Frenchman Mountain Quadrangle.

Jmk Moenave and Kayenta Formation equivalents Mostly nonresistant pale-reddish-brown to pale-brown fine sandstone, siltstone, and shale approximately 250 m thick. Characterized by abundant veiny gypsum and richly hematitic beds of grayish-red to dark-reddish-brown siltstone and shale. Minor amounts of pale-green sandstone and shale and trace amounts of gray limestone are locally present near the base, which is locally marked by resistant grayish-brown to grayish-purple chert-pebble conglomerate up to 7 m thick.

The Moenave and Kayenta Formations are combined on our map. Longwell (1966) included rocks in these units in the Chinle Formation, but Wilson and Stewart (1967) proposed that strata equivalent to the Moenave and Kayenta Formations were present in southern Nevada between the Chinle Formation and the Aztec Sandstone. Wilson and Stewart (1967) put the base of this unit beneath chert-pebble conglomerate. This conglomerate is well exposed at 36° 11' 15"N, 114° 55' 48"W in the Frenchman Mountain Quadrangle in the south wall of a prominent east-draining wash. The conglomerate is about 7 m thick and is underlain by interbedded brown shale and pale sandstone with minor conglomerate and thin pale-green tuff beds that are typical of the upper part of the Chinle Formation. In thin section, a sample of this rock contains about 65% of well-sorted, rounded to subrounded clasts that average about 2 mm in diameter and are composed of chert, carbonate, quartzite, and sandstone in relative order of abundance. Porphyritic to fine-grained panidiomorphic igneous clasts of intermediate composition comprise about 2% of this rock. Wilson and Stewart (1967) reported abundant volcanic clasts in this conglomerate in the Spring Mountains. Above the exposure of basal Moenave-Kayenta conglomerate in the Frenchman Mountain Quadrangle is about 30 m of reddish-brown fine-grained sandstone to shale and a few limestone beds. Here, as elsewhere, the Moenave-Kayenta equivalent may be distinguished from the underlying Chinle Formation by the absence of pale-green tuff beds.

The age of the Moenave and Kayenta Formations was originally considered to be Late Triassic on the basis of vertebrate fossils found in Arizona. However, more recent work has indicated an Early Jurassic age for the units (Peterson and Pipiringos, 1979). Marzolf (1991) placed these units above a regionally extensive basal Jurassic unconformity cut on the Chinle Formation and older rocks.

Ꞧc **Chinle Formation** The upper part of the Chinle Formation, which is probably correlative with the Petrified Forest Member of the Chinle as described by Wilson and Stewart (1967), consists of about 100 m of brown to light-reddish-brown thin-bedded shale to fine-grained sandstone with minor interbeds of light-greenish-gray sandstone. Some veiny to bedded gypsum is also present. The uppermost 50 m of the formation contains thin beds of pale-yellowish-green to greenish-gray tuff. The middle part of the formation is a unit as much as 37 m thick that contains brownish-gray to yellowish-gray bentonitic ash; beds of reddish-orange to yellowish-orange, fine-grained to granule sandstone with associated conglomerate that locally contains petrified wood; light-greenish-gray, flaggy, fine-grained sandstone; and minor dark, organic-rich shale or siltstone. The base of the formation consists of a 2-m-thick sequence of dark-yellowish-brown-weathering, grayish-red to olive-gray carbonate pebble conglomerate with associated sandy limestone and limy sandstone. These rocks are the informal Spring Mountain member of Riley (1987). Altogether Ꞧc is about 130 m thick.

We have not subdivided the Chinle Formation into the traditional Shinarump and Petrified Forest Members, although both units may be present on the basis of regional stratigraphic descriptions in Wilson and Stewart (1967). The Chinle has been proposed for group status by Lucas and Marzolf (1993), who placed five formations (including the above mentioned members upgraded to formation status) in it. At 36° 11' 19"N, 114° 55' 53"W, a smectite-rich bed about 5 m thick that was probably derived from tuff occurs in the Chinle just above a 12- to 32-m-thick sequence largely composed of light-colored sandstone and pebble beds (probable Shinarump Member). The smectitic bed may correlate with the Blue Mesa Member of the Petrified Forest Formation of Lucas and Marzolf (1993) who reported the unit to consist of a bentonitic bed 8.5 m thick in the Valley of Fire in Clark County, Nevada. Petrified wood in the Chinle Formation has been noted at several localities in the Frenchman Mountain Quadrangle, mostly as pebbles and cobbles in the lower part of the unit, although a log segment about 50 cm in diameter was noted in the most northerly exposure in the quadrangle. We consider the base of the Chinle Formation in the Frenchman Mountain Quadrangle to lie just below the informal Spring Mountain member of Riley (1987), although Larson (1965) put this sequence in the top of the underlying Moenkopi.

Moenkopi Formation

Four Moenkopi Formation units were mapped, largely following Larson (1965), who measured a detailed section through the unit in the Frenchman Mountain Quadrangle. The upper redbed unit ("upper red" unit of Larson, 1965) consists mainly of fine-grained clastic sediments. We mapped the gypsum-rich Schnabkaib Member directly on the Virgin Member. The middle redbed member of the Moenkopi does not appear to be present in the Frenchman Mountain Quadrangle (Larson, 1965). The Virgin Member, which is mostly marine limestone and locally fossil-rich, grades downward into the lower redbed unit. The Timpoweap Member, a conglomeratic unit that is less than 10 m thick in the quadrangle (Larson, 1965), is included in our lower redbed unit ("lower red" unit of Larson, 1965).

Ꞧmu **Upper redbed unit** Mainly varicolored shale, siltstone, and sandstone with locally abundant gypsum. Sandstone beds are commonly marked by small-scale ripples. The base is locally composed of as much as 8 m of very pale-orange to pale-red, medium-grained quartz sandstone. Most of the unit is nonresistant pale-reddish-brown to pale-brown fine-grained sandstone, siltstone, and shale with veiny gypsum. It is approximately 400 m thick.

Ꞧms **Schnabkaib Member** Mostly gray dolomite and interbedded grayish-yellow to pale-yellowish-orange fine-grained sandstone and siltstone with abundant gypsum. Minor amounts of limestone are present. The dolomite is thin bedded, generally ripple marked, and commonly oolitic. Identifiable fossils are rare or lacking. The thickness is about 170 m.

The contact between the Schnabkaib and Virgin Limestone Members is marked by a color change from resistant yellowish limestone beds of the Virgin Member, to less resistant pale-green to white gypsum and dolomite beds of the Schnabkaib. Both members contain some fine-grained clastic redbeds, but this lithology, which is generally gypsum-rich, is more common in the Schnabkaib.

Ꞧmv **Virgin Member** Mostly gray to grayish-brown micritic limestone with interbeds of grayish-yellow to pale-olive fine-grained sandstone and siltstone with gypsum. The limestone beds commonly contain microscopic algal filaments and about 1% subrounded silt grains of quartz, feldspar, and muscovite. As a whole, this member is more resistant than Ꞧms and contains less gypsum. The limestone is mostly yellowish gray to light gray and thin bedded. It includes beds of bioclastic limestone as much as 1 m thick, particularly near the base of the member. Minor amounts of dolomite are also present. Fossils are abundant in some beds. Although Larson (1965) reported a pectinoid mollusc and star-shape crinoid stem segments as the most widespread fossils in the unit, gastropods were the most prominent fossils noted by us. At 36° 12' 37"N, 114° 56' 44"W, a bed containing abundant mytiloid pelecypods was noted, and silicified gastropod and pelecypod fossils were found about 100 m to the southwest. Ꞧmv thickness is about 150 m.

Ꞧmr **Lower redbed unit** Mostly friable pale-red, pale-reddish-brown, and pale-brown shale to fine-grained sandstone with abundant gypsum. Thickness varies from about 100 m in the north part of the quadrangle to 250 m to the south. The base of the unit is locally marked by pebble to cobble conglomerate. The upper part of the unit, mainly gypsiferous redbeds, also contains beds of light-gray to white carbonate, mostly dolomite, that are less than 50 cm thick, commonly ripple marked, and locally contain rip-up clasts.

PALEOZOIC

Kaibab Formation

The Kaibab Formation consists mostly of a resistant cherty limestone sequence that strongly resembles the main part of the underlying Toroweap Formation. This resistant limestone is probably equivalent to the Fossil Mountain Member of Sorauf and Billingsley

(1991) in Arizona but does not appear to contain sandy limestone as it does there.

The upper part of the Kaibab Formation was mapped as the Harrisburg Member (Reeside and Bassler,1922; Sorauf and Billingsley, 1991). This unit has regional economic importance as an major source of gypsum and has been mined continuously since 1909 at Blue Diamond southwest of Las Vegas. It was described but not mapped in Clark County by Longwell and others (1965). The Harrisburg Member seems to have strong lateral variability. As a result of poor exposures, the Harrisburg Member was locally lumped with the underlying cherty limestone in the Frenchman Mountain Quadrangle. Where well exposed, it contains distinctive light-colored, sparsely fossiliferous carbonate underlain by gypsum and redbeds.

An extensive Mesozoic section overlies the Kaibab Formation and is separated from it by an unconformity that was first recognized in Utah by J.W. Powell in 1876. The unconformity is not marked by obvious angular discordance but may have been a surface of some relief because Triassic deposits fill valleys eroded as much as 20 m into the Kaibab Formation (Larson, 1965).

Pkh **Harrisburg Member** The upper part of the Kaibab Formation consists of 3 to 20 m of distinctive very pale-orange to light-gray, resistant, flaggy, generally fossil-poor dolomite and/or limestone with abundant chert in some beds. These carbonate beds are underlain by a gypsiferous sequence as much as 20 m thick that contains some pebble conglomerate and fine-grained clastic material.

Pk **Kaibab cherty limestone** Thick-bedded to massive, cliff-forming, light-gray to light-brownish-gray limestone with abundant chert nodules that weather to darker brown. Chert nodules are as much as 25 cm in diameter. The limestone is generally fine to medium crystalline and typically fossiliferous, with abundant crinoid stem chips and locally abundant brachiopods and rugose corals. However, the upper 20 m of the Kaibab is nonfossiliferous to poorly fossiliferous, finely crystalline to micritic, locally cross-bedded, and contains only minor chert. A pinkish tint locally distinguishes Pk cherty limestone from that in Pt. The Pk cherty limestone is generally about 100 m thick, but may be as much as 170 m thick in places; it has inordinately wide map widths where it forms extensive dip slopes.

Toroweap Formation

The Toroweap Formation is dominated by a thick sequence of fossiliferous resistant limestone that generally contains abundant chert and is similar to Pk. Above and below this are nonresistant, gypsum-rich, redbed sequences of which only the lower was mapped.

Pt **Toroweap upper unit** Thick-bedded, coarsely crystalline, cliff-forming cherty limestone similar to that in the Kaibab Formation but contains some intervals that lack chert; cherty intervals include both nodules and lenses of chert. Beds, which are typically 1 to 2 m thick, are commonly fossiliferous and contain abundant oncolites, crinoids, and brachiopod fragments, including productid brachiopods as much as 8 cm in length. In the upper part of the unit, chert-rich beds give way to about 10 m of chert-free, gray limestone. The uppermost Pt that caps this chert-free limestone typically consists of 10 to 30 m of gypsum capped by as much as 6 m of reddish- to yellowish-brown siltstone and mudstone. Overall Pt thickness ranges from 80 to 170 m. The resistant limestone and overlying gypsiferous redbed sequences are considered to be equivalent to the Brady Canyon and Woods Ranch Members, respectively, of Sorauf and Billingsley (1991).

Ptl **Toroweap lower unit** Nonresistant gypsum and gypsiferous mudstone to sandstone. The upper part consists of a few meters of pale-red and pale-reddish-brown to pale-yellowish-orange, flaggy, fine-grained sandstone. Above this redbed sequence, minor pale-orange dolomite is locally exposed. The basal part of the unit is mainly pale-reddish-brown siltstone and mudstone with gypsum in beds as much as 2 m thick. Ptl is typically about 40 m thick but locally thins to less than 2 m in the southwest and northwest parts of the quadrangle. It is probably equivalent to the Seligman Member of Sorauf and Billingsley (1991).

Pc **Coconino Sandstone** Nonresistant to cliff-forming, grayish-yellow to grayish-pink and locally pale-reddish-brown, cross-bedded, fine- to medium-grained quartz-rich sandstone with variable amounts of calcite cement; commonly coated with dark-brown rock varnish; subrounded to subangular grains; typically consists of 90 to 95% quartz, 5 to 10% feldspar, and accessory zircon, magnetite, and hematite. The Coconino Sandstone in the Frenchman Mountain Quadrangle is similar to its counterpart on the Colorado Plateau in that it is nearly pure quartz arenite; however, it is generally not white and is cross-bedded on a much finer scale as noted by Longwell (1966). It may be distinguished from the underlying pale-reddish-brown Hermit Formation by thicker cross-bed sets and generally lighter color. In the northeast part of the quadrangle it forms prominent cliffs and is as much as 70 m thick. Elsewhere in the quadrangle it is relatively nonresistant and thinner. In the vicinity of the abandoned Sunrise Landfill near the southwest edge of the quadrangle, it is too thin (~5 m) to map at 1:24,000 scale.

Ph **Hermit Formation** Weakly to moderately indurated, weakly calcareous, thinly bedded, well-sorted, locally cross-bedded, pale-reddish-brown to moderate-orange-pink fine- to medium-grained sandstone and siltstone; locally includes very pale-orange to grayish-yellow or white sandstone and brick-red siltstone and mudstone. The reddish-brown sandstone locally contains pale-orange to white reduction spots up to 2 cm in diameter. Grains are typically subangular and consist of quartz, feldspar, and accessory muscovite, biotite, hematite, and magnetite. Ph is commonly a poorly exposed slope- or bench-forming unit. Its thickness ranges from 250 to 330 m.

Pq **Queantoweap Sandstone** Friable to moderately well indurated, weakly calcareous, fine-grained, well-sorted, white to very pale-brown, orange, or grayish-yellow, cross-bedded sandstone; grains are typically subrounded and consist mainly of quartz with lesser amounts of K-spar (5 to 10%) and plagioclase, and accessory zircon and muscovite. Pq locally includes thin sequences of reddish-brown siltstone and fine-grained sandstone similar to Ph. This unit correlates with the Esplanade Sandstone of the Supai Group on the Colorado Plateau (Rowland, 1987). It ranges between 18 and 150 m thick.

PIPp **Pakoon Formation** Nonresistant gypsum and light-gray to gray flaggy dolomite with minor pale-red siltstone and mudstone; typically consists of a thin upper sequence of reddish-brown to purplish-red siltstone and mudstone, thick middle sequence of bedded gypsum, and lower sequence of thinly bedded dolomite and lesser pale-grayish-brown-weathering, reddish-brown to yellowish-brown siltstone and silty dolomite. On the southeast flank of Sunrise Mountain, PIPp includes a basal sequence of purplish-red mudstone and lesser gypsum beneath the lower dolomite. Dolomite layers commonly contain 5 to 10% fine-grained subangular to subrounded quartz, feldspar, and accessory muscovite and biotite. Siltstone is composed of subangular to subrounded grains of quartz, feldspar, and lesser muscovite and biotite. Dolomite beds are commonly shattered into pebble- and cobble-size fragments that are engulfed in a matrix of gypsum. Gypsum intervals typically weather into low rounded hills, whereas some of the more coherent dolomite beds form small ridges. PIPp is as much as 200 m thick but is considerably thinner in places, possibly due to tectonic attenuation. The basal contact of the unit is commonly gradational with the highest sequence of interbedded limestone and calcareous cross-bedded sandstone of the Callville Limestone.

IPc **Callville Limestone** Dark-gray-weathering, light-gray micritic limestone and pale-brown calcareous, locally cross-bedded, fine-grained sandstone or sandy dolomite. Some limestone and sandstone beds contain chert nodules and lenses. The upper part is about 50 m thick and is composed of light-gray micritic to finely crystalline dolomite with some cherty beds, including one bed with abundant dark-weathering chert nodules as much as 1 m in diameter. The middle part, which is lighter in color than the lower part, typically consists of alternating 1- to 3-m-thick beds of light-gray to medium- or pinkish-gray limestone, which commonly contains rounded oncolites, and thinly laminated, cross-bedded sandy dolomite and calcareous fine-grained sandstone. The lower part weathers to dark grayish brown and consists of about 50 m of light-gray to pale-red cross-bedded sandy limestone and dolomite with some dolomitic sandstone beds. ℙc commonly includes a thin (as much as 10 m thick) lower sequence of purplish-red to reddish-brown siltstone and mudstone, as best exposed on the north flank of Frenchman Mountain. Carbonate layers generally contain 1 to 10% subrounded to subangular grains of quartz and feldspar. Some carbonate layers are fossiliferous and include abundant oncolites and fragments of brachiopods, corals, and crinoids. Sandy layers typically consist of subrounded grains of quartz (>80%), lesser K-spar and plagioclase, and accessory zircon. Some of these sandy layers are probably eolian (Rowland and others, 1990). The upper contact with the Pakoon Formation is commonly gradational and typically marked by the uppermost occurrence of interbedded calcareous fine-grained, cross-bedded sandstone and light-gray limestone or dolomite. Total thickness is 200 to 275 m.

Mr **Redwall Limestone** Light-gray to gray and purplish-gray, pale-brown-weathering, massive to medium bedded (~1 m thick beds), medium- to coarse-grained dolomitized limestone with a fossiliferous (crinoids, brachiopods, rare nautiloids) base (Dawn Member) and a chert-rich interval (Anchor Member) about 50 m above the base. Mr locally contains crinoid-rich beds and corals. The lack of chert in the upper part contrasts with an abundance of chert in the overlying Callville Limestone. Mr is marked by a basal disconformity (Langenheim and Webster, 1979), and its pale-brown color contrasts with the underlying gray Dsc. Mr correlates with the Monte Cristo Limestone directly to the west in the Las Vegas NE Quadrangle. Average thickness is about 240 m.

Sultan Formation

Dsc **Crystal Pass Member** Light-gray, finely laminated to medium-bedded (1-cm- to 1-m-thick beds) dolomite and limestone. Some beds contain stromatolitic laminae, as well as peloids. Dsc locally has thin chert interbeds to 3 cm thick. The member typically forms a small bench between more resistant Dsvi and Mr, but the uppermost part locally forms a series of small cliffs and benches. The lower part is more massive and dolomitic than the upper part. Average thickness is about 60 m.

Dsvi **Valentine and Ironside Members** Medium-gray, brownish-gray-weathering, thinly laminated to thinly bedded cliff-forming sucrosic (or grainy), medium- to coarse-grained dolomite with local stromatoporids; commonly contains vugs filled with calcite or dolomite. A distinct 1- to 2-m-thick chert bed commonly caps the unit, especially in the Sunrise Mountain area. The middle part is cherty and forms a dark band on Frenchman Mountain. Lowermost beds are very pale-brown to locally greenish or purplish sucrosic dolomite; the base is a disconformity. Thickness is about 135 m.

Ꞓn **Nopah Formation** Upper part consists of 10 to 15 m of light-gray to pinkish-brown, thick-bedded, very fine- to medium-grained dolomite. Some dolomite beds contain abundant stromatolites, whereas others include 5 to 15% fine-grained, subrounded quartz, feldspar, and accessory muscovite. Lower part (Dunderberg Shale Member), which typically forms a series of small ledges, consists of a basal 2 m of green calcareous shale and siltstone, an ~10-m-thick middle interval of light-gray to pinkish-gray, weathering orange brown to brown, fine- to coarse-grained vuggy detrital dolomite that locally contains glauconite pellets and rip-up clasts, and an upper unit of nonresistant olive-green to grayish-green calcareous shale and siltstone with brown dolomite interbeds. Sundberg (1979) reported a thickness of 18 m for the Dunderberg Shale Member just west of the quadrangle on Frenchman Mountain. Ꞓn forms a distinct bench between more resistant Ꞓfu and Dsvi. Total thickness averages about 45 m.

Frenchman Mountain Dolomite

Within the Grand Canyon, McKee (1945) identified an interval of dolomites that overlies the Muav Limestone, but he did not name or study this unit in detail. He referred to this interval as “undifferentiated dolomites.” Due to an absence of age-diagnostic fossils, the precise age of these rocks has been unknown. Korolev (1997) showed that these undifferentiated dolomites of the Grand Canyon are correlative with a portion of the Banded Mountain Member of the Bonanza King Formation and that they embrace the *Bolaspidella*, *Cedaria*, and *Crepicephalus* trilobite zones, which collectively straddle the Middle-Upper Cambrian boundary. Korolev (1997) proposed the name Frenchman Mountain Dolomite for McKee’s “undifferentiated dolomites,” and we use that name here. In the Grand Canyon, the upper portion of these dolomites was removed by pre-Middle Devonian erosion. Thus, in Colorado Plateau sections the Frenchman Mountain Dolomite is almost certainly all Middle Cambrian. However, at Frenchman Mountain and Sunrise Mountain these dolomites are overlain by the Upper Cambrian Nopah Formation, and they probably include Upper Cambrian beds as well as Middle Cambrian. So within the quadrangle the Middle-Upper Cambrian boundary probably lies high within this interval. Directly west of the quadrangle, the Frenchman Mountain Dolomite is 371 m in thickness (Korolev, 1997). We have divided this interval into two map units.

Ꞓfu **Upper part of Frenchman Mountain Dolomite** Relatively resistant, cliff-forming, distinctive pale-orange-weathering, thickly bedded, skeletal dolomite grainstone. Fresh surfaces are light gray. Contains fossil eocrinoid columnals. Green glauconite pellets are common in the lower few meters. Some layers contain 1–2% quartz silt. Ꞓfu correlates with the uppermost Banded Mountain Member of the Bonanza King Formation (unit Ꞓbb-10 of Gans, 1974) in miogeoclinal sections, and with unit 24 of Rowland and others (1990). Average thickness is about 55 m.

Ꞓfl **Lower part of Frenchman Mountain Dolomite** Generally banded light- and dark-gray, moderately to thickly bedded dolomicrite. Dark bands are commonly intensely burrowed; light bands typically contain fine wavy laminations that are interpreted to be cryptomicrobial, locally developed into domal stromatolites (Korolev, 1997). The base of the unit is defined by a nonresistant, bench-forming, light-gray, finely laminated interval about 30 m thick (unit 14 of Rowland and others, 1990). Ꞓfl contains conspicuous orange- to dark-brown chert nodules and lenses, typically 0.2 to more than 1.0 m long and 2 to 10 cm thick; no such chert lenses occur in the underlying Muav Limestone. Correlative with middle part of Banded Mountain Member of Bonanza King Formation and with units 14–23 of Rowland and others (1990). Thickness averages about 340 m.

Muav Limestone

Historically, several names have been applied to the Middle Cambrian carbonates of the Frenchman Mountain Quadrangle. In the neighboring Las Vegas NE Quadrangle, Matti and others (1993) assigned these rocks to the Bonanza King Formation. However, as summarized by Rowland and others (1990), the Frenchman-Sunrise Mountain section is cratonal with greater similarities to the Colorado Plateau sections than to miogeoclinal sections to the west and northwest. For this reason we assign the Middle Cambrian carbonates in the quadrangle to the Muav Limestone and overlying, previously unnamed dolomites. Unlike the Grand Canyon region, most of the Muav Limestone within the quadrangle has been dolomitized. The thickness of the Muav directly west of the quadrangle is 238 m (units 1–13 of Rowland and others, 1990). We have divided the Muav into two map units.

Ꞓmu Upper part of Muav Limestone Cliff- and slope-forming, dark-gray and orange-buff, burrow-mottled dolomite. Top of the unit is a 32-m-thick, dark-gray, cliff-forming interval (unit 13 of Rowland and others, 1990) overlain by a very light-gray bench-forming interval at the base of Ꞓfl. Ꞓmu includes the Kanab Canyon, Gateway Canyon, and Havasu members, although individual members are difficult to distinguish. Ꞓmu correlates with the lower portion of the Banded Mountain Member of the Bonanza King Formation and with units 10–13 of Rowland and others (1990). Thickness is ~100 m.

Ꞓml Lower part of Muav Limestone Cliff- and slope-forming, light- and medium-gray limestone and dolomite; some intervals are orangish toward the top. The lower third is predominantly limestone and the upper two thirds are predominantly dolomite. The base of unit is oncolitic. Burrow mottling is common and conspicuous; burrows are preferentially dolomitized and more resistant to weathering than the surrounding matrix. Cliff-forming intervals are separated by thin intervals of thinly bedded gray shale and siltstone composed of 25–50% quartz, feldspar, muscovite, and glauconite within a carbonate matrix. The top of the unit is defined by the top of a 9-m-thick, slope-forming interval of distinctive orange-buff, cross-bedded, dolomite grainstone (Ꞓbb-1 of Gans, 1974; unit 9 of Rowland and others, 1990). Ꞓml includes the Rampart Cave, Sanup Plateau, Spencer Canyon, and Peach Springs members of McKee (1945), although individual members are difficult to distinguish. Ꞓml is approximately correlative with the Papoose Lake Member of the Bonanza King Formation and equivalent to units 1–9 of Rowland and others (1990). Thickness is ~135 m.

Ꞓc Chisholm Shale Nonresistant, greenish-gray, finely laminated friable shale and siltstone; contains fossils of the Middle Cambrian trilobite genus *Glossopleura* (Palmer, 1989). The siltstone contains subangular grains of mainly quartz and lesser feldspar and muscovite. Ꞓc correlates with the Flour Sack Member of McKee (1945) of the Bright Angel Shale in the Grand Canyon region and with the Desert Member of the Carrara Formation in the Spring Mountains-Death Valley region (Palmer and Rowland, 1989). Ꞓc crops out only on the northwest flank of Sunrise Mountain. Thickness is ~25 m.

UNEXPOSED UNITS

The units described below appear only in cross sections but crop out directly west of the Frenchman Mountain Quadrangle. Because they do not crop out in the Frenchman Mountain Quadrangle, descriptions of the Lyndon Limestone and all older units were partly adapted from Matti and others (1993).

Ꞓl Lyndon Limestone Resistant, cliff-forming, dark-gray and orange-buff limestone. Burrow mottling is common, as are large thrombolite heads with internally clotted fabrics. Ꞓl correlates with the Meriwitica and Tincanebits dolomite tongues of McKee (1945), intervening shales of the Bright Angel Shale in the Grand Canyon region, and the Jangle Limestone Member of the Carrara Formation in the Spring Mountains-Death Valley region (Palmer and Rowland, 1989). Thickness directly west of the quadrangle is 30 m (Rowland and others, 1990).

Ꞓp Pioche Shale Mostly nonresistant olive-green to brown phyllitic shale (Matti and others, 1993). Dark-reddish-brown, hematitic, fine- to coarse-grained sandstone beds occur in the lower ~70 m, and an interval ~20 m thick of flaggy, fine-grained purple sandstone occurs in the upper part of the unit (see Palmer, 1989). Lower Cambrian olenellid trilobites are locally abundant in the lower 50 m of the unit (Pack and Gayle, 1971). Middle Cambrian trilobites of the genus Albertella first occur about 12 m below the top of the unit (Palmer, 1989), marking the approximate position of the Lower-Middle Cambrian boundary. Ꞓp correlates with the lower portion of the Bright Angel Shale in the Grand Canyon and with the lower portion of the Carrara Formation in the Spring Mountains-Death Valley region. The Lower-Middle Cambrian boundary is near the top of unit (Palmer and Rowland, 1989). The thickness is 128 m directly west of the quadrangle (Rowland and others, 1990).

Ꞓt Tapeats Sandstone Highly indurated white to brown, thin- to thick-bedded, locally cross-bedded, fine- to coarse-grained quartzitic sandstone with beds of pebble conglomerate near the base; includes both silica and calcite cement, and is locally hematitic near the base (Matti and others, 1993); correlative with the Zabriskie Quartzite in the Spring Mountains-Death Valley region and with the Saline Valley Formation in the White-Inyo Mountains region (Palmer and Rowland, 1989). The thickness varies but is about 48 m directly west of the quadrangle.

Xg Early Proterozoic gneiss Gray, medium- to coarse-grained microcline-quartz-biotite-garnet gneiss interlayered with pink to white coarse-grained leucocratic or pegmatitic gneiss (Matti and others, 1993); locally includes complexly folded layers and small boudins of hornblende-plagioclase-quartz±biotite±hypersphene gneiss. Discordant masses of fine- to coarse-grained biotite±garnet granite cut the gneiss. Mineralogy suggests granulite facies metamorphism. This unit may correlate with the Vishnu Group in the Grand Canyon (Rowland, 1987).

See accompanying text for figures, tables, references, and a discussion of the geology of the Frenchman Mountain Quadrangle

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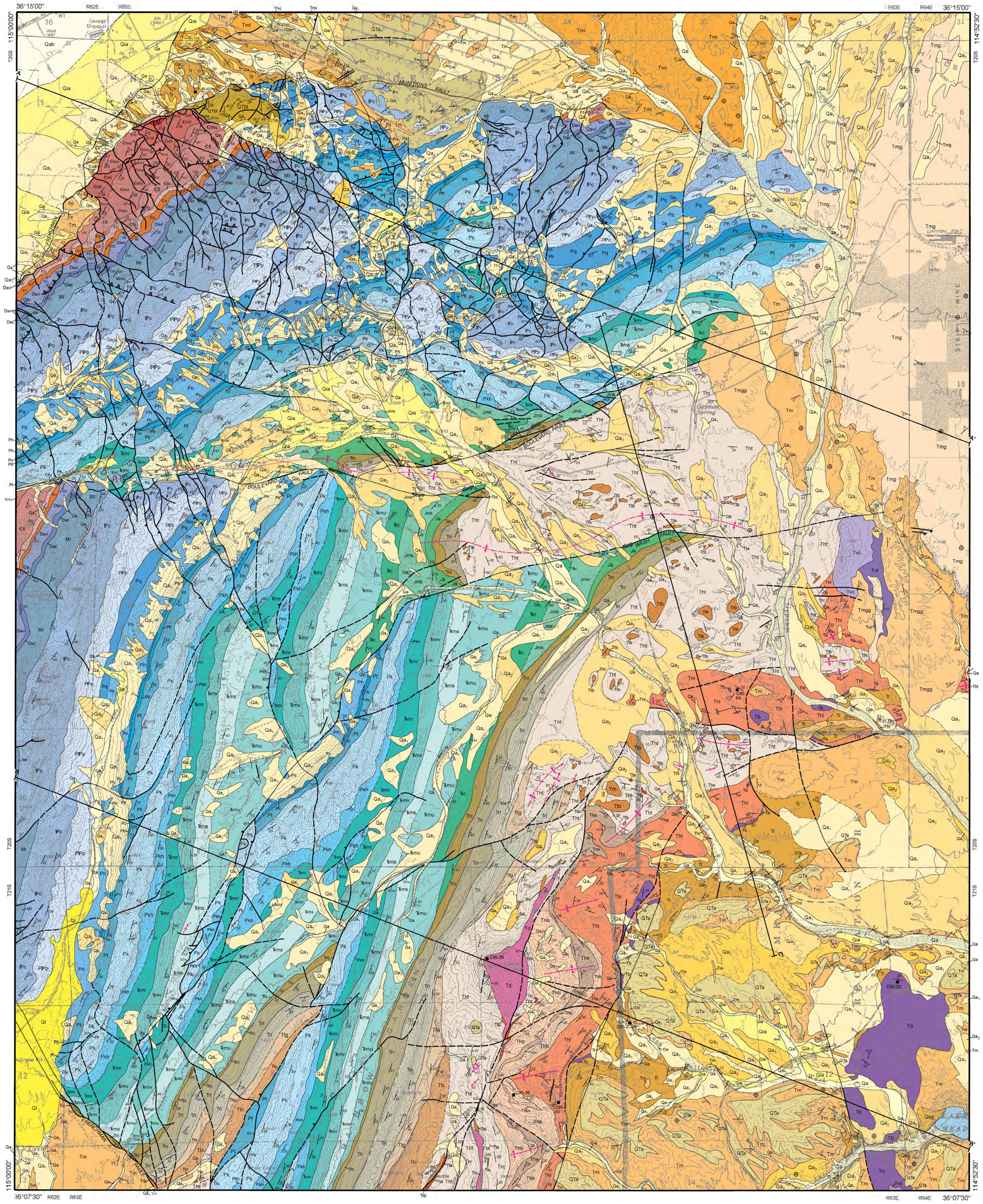
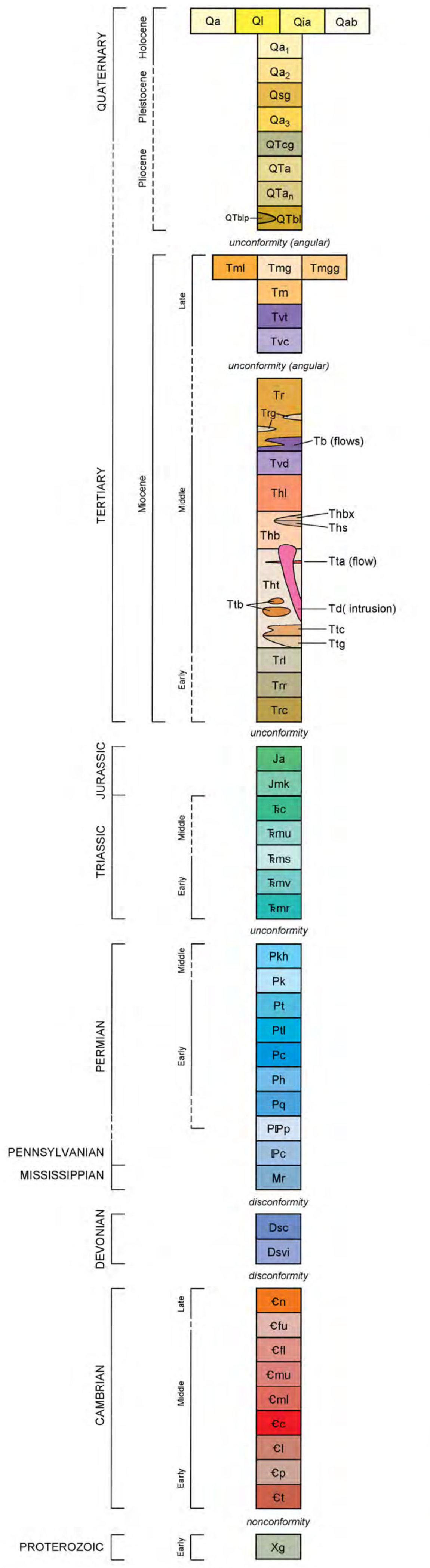




Qa	Active alluvium
Ql	Landfill
Qia	Intermittently active alluvium
Qab	Basin alluvium of Las Vegas Valley
Qa_1	Young stream-terrace and fan-terrace alluvium
Qa_2	Intermediate stream-terrace and fan-terrace alluvium
Qsg	Intermediate alluvium of Las Vegas Wash
Qa_3	Older stream-terrace and fan-terrace alluvium
QTcg	Older cemented conglomerate of Las Vegas Wash
QTa	Older alluvium and lag gravels
QTa_n	Older alluvium of Nellis basin
QTbl (QTblp)	Limestone megabreccia, Dc and Mr clasts; PDp clasts (QTblp)

Muddy Creek Formation

Tml	Limestone
Tmg	Gypsum
Tmgg	Gypsiferous gravel
Tm	Sandstone, siltstone, and conglomerate

Volcanics of Callville Mesa

Tvt	Tuffaceous siltstone
Tvc	Mafic flows and cinders

Tr (Trg)	Red sandstone; gypsum (Trg)
Tb	Basalt
Tvd	Dacite flow rock
Td	Intrusive porphyry

Horse Spring Formation

Thl	Lovell Wash Member
Thb (Thbx, Ths)	Bitter Ridge Limestone Member; volcanic breccia (Thbx); sandstone (Ths)

Thumb Member

Tht	Sandstone, siltstone, and conglomerate
Tta	Intermediate or mafic volcanic rock
Ttb	Breccia with Proterozoic detritus
Ttc	Conglomerate
Ttg	Gypsum-rich sequence

Rainbow Gardens Member

Trl	Resistant limestone unit
Trr	Sandstone, conglomerate, and limestone unit
Trc	Resistant basal conglomerate

Ja	Aztec Sandstone
Jmk	Moenave and Kayenta Formation equivalents
Ꞧc	Chinle Formation

Moenkopi Formation

Ꞧmu	Upper redbed unit
Ꞧms	Schnabkaib Member
Ꞧmv	Virgin Member
Ꞧmr	Lower redbed unit

Kaibab Formation

Pkh	Harrisburg Member
Pk	Kaibab cherty limestone

Toroweap Formation

Pt	Upper unit
Ptl	Lower unit

Pc	Coconino Sandstone
Ph	Hermit Formation
Pq	Queantoweap Sandstone
PIPp	Pakoon Formation
IPc	Callville Limestone
Mr	Redwall Limestone

Sultan Formation

Dsc	Crystal Pass Member
Dsvi	Valentine and Ironside Members

Ꞓn	Nopah Formation

Frenchman Mountain Dolomite

Ꞓfu	Upper part
Ꞓfl	Lower part

Muav Limestone

Ꞓmu	Upper part
Ꞓml	Lower part

Ꞓc	Chisholm Shale
Ꞓl	Lyndon Limestone
Ꞓp	Pioche Shale
Ꞓt	Tapeats Sandstone
Xg	Early Proterozoic gneiss

Lithologic contact Dashed where inferred or approximately located due to poor exposures.

Moderately to steeply dipping normal fault showing dip Ball on downthrown side; arrow near dip symbol shows trend of striae on fault surface; dashed where inferred or approximately located due to poor exposures; dotted where concealed; queried where uncertain.

Gently dipping normal fault showing dip Hachures on downthrown side; arrow near dip symbol shows trend of striae on fault surface; dashed where inferred or approximately located due to poor exposures; dotted where concealed.

Reverse fault showing dip Teeth on hanging wall; arrow near dip symbol shows trend of striae on fault surface; dashed where inferred or approximately located due to poor exposures; dotted where concealed.

Mainly strike-slip fault Arrows on either side of fault indicate sense of strike separation; arrow near dip symbol shows trend of striae on fault surface; dashed where inferred or approximately located due to poor exposures; dotted where concealed. In cross section, T indicates movement toward profile; A indicates movement away from profile.

Syncline Dashed where inferred or approximately located due to poor exposures, dotted where concealed.

Anticline Dashed where inferred or approximately located due to poor exposures, dotted where concealed.

Tufa with silica in the Lovell Wash Member of the Horse Spring Formation.

Strike and dip of inclined bedding

Horizontal bedding

Minor anticline showing bearing and plunge of hingeline

Overturned syncline

C95-38 **Sample locality for $^{40}Ar/^{39}Ar$ geochronologic age determination**

See accompanying text for explanation of units, figures, references, and a discussion of the geology of the Frenchman Mountain Quadrangle.

Scale 1:24,000

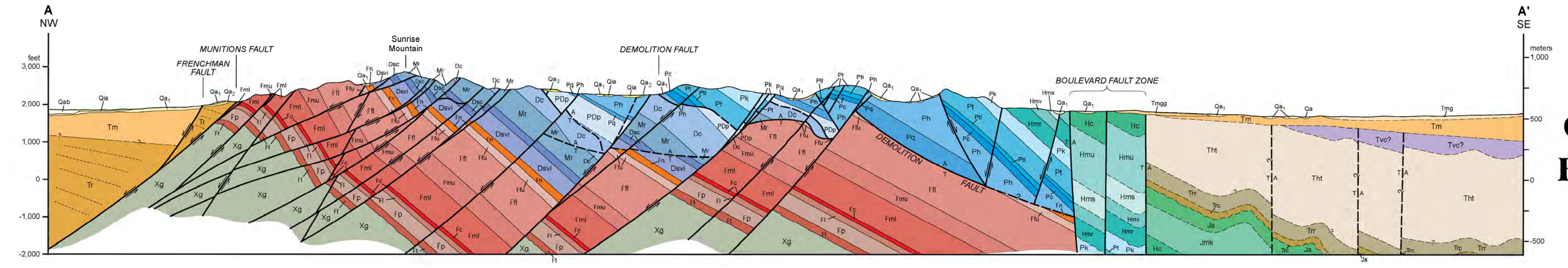
0 0.5 1 kilometer

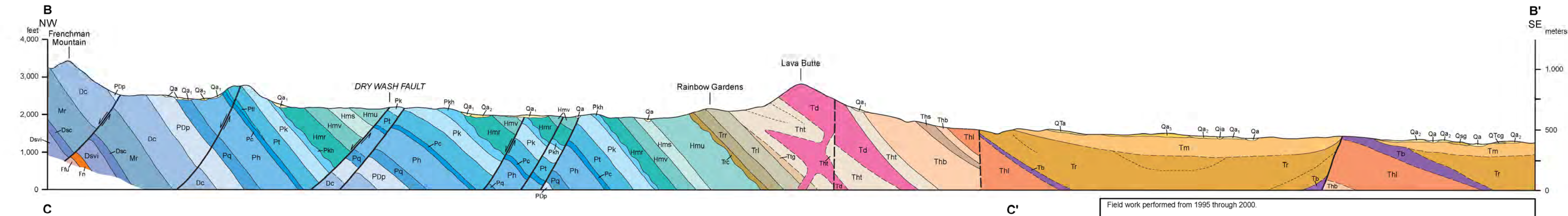
0 0.5 1 mile

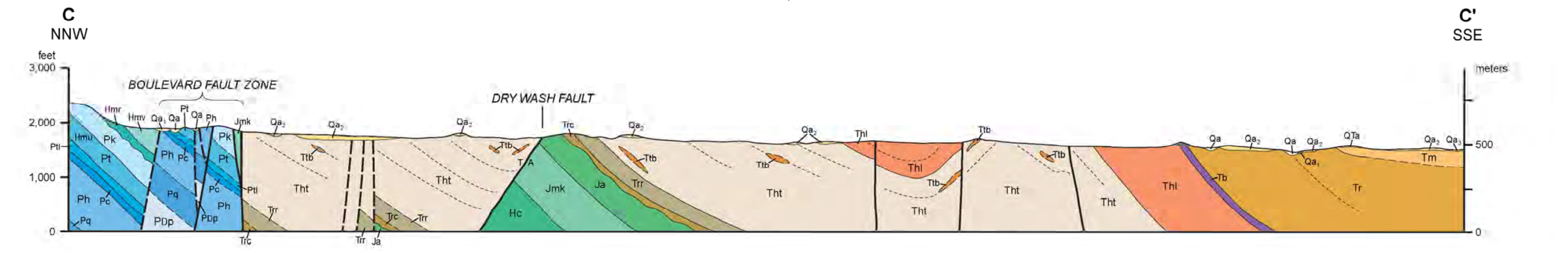
0 1000 2000 3000 4000 5000 feet

CONTOUR INTERVAL 40 FEET

Base map: U.S. Geological Survey Frenchman Mountain 7.5' Quadrangle, 1983







GEOLOGIC MAP OF THE FRENCHMAN MOUNTAIN QUADRANGLE, CLARK COUNTY, NEVADA

Stephen B. Castor,
James E. Faulds,
Stephen M. Rowland,
and Craig M. dePolo

2000

Field work performed from 1995 through 2000.

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Text and references for Nevada Bureau of Mines and Geology Map 127

GEOLOGY OF THE FRENCHMAN MOUNTAIN QUADRANGLE

CLARK COUNTY, NEVADA

by

S.B. Castor, J.E. Faulds, S.M. Rowland, and C.M. dePolo

GEOCHRONOLOGY

Nine new $^{40}Ar/^{39}Ar$ ages were determined on seven samples from the Horse Spring Formation and overlying informal red sandstone of Bohannon (1984) (table 1). Two ages were determined by M. Perkins (written commun., 1999) on glass shards from red sandstone and Muddy Creek Formation ash beds using geochemical correlation techniques (Perkins and others, 1998). Additionally, we compiled published $^{40}Ar/^{39}Ar$, K-Ar, and fission-track ages to constrain the timing of magmatism and sedimentation in the area.

For $^{40}Ar/^{39}Ar$ dating, mineral separates were obtained from our samples by crushing, sieving, and magnetic and density separation. Sanidine and plagioclase were leached with dilute HF to remove adhering matrix. Biotite and hornblende concentrates were handpicked to obtain primarily monomineralic grains free of alteration. Samples were irradiated at Texas A&M University and analyzed at the New Mexico Geochronological Research Laboratory (New Mexico Institute of Technology; methodology discussed in McIntosh and Chamberlin, 1994) and the Nevada Isotope Geochronology Laboratory (University of Nevada, Las Vegas; methodology in Justet and Spell, in review). In both labs, single grains of sanidine were quantitatively fused using a CO_2 laser. Other samples were heated in a low-blank, resistance furnace, generally in eight to ten 10-minute increments between about 700°C and 1450°C. Fish Canyon sanidine (27.84 Ma, relative to an age of 520.4 Ma on hornblende MMhb-1; Cebula and others, 1986; Samson and Alexander, 1987) was used to monitor neutron fluence. Calculated ages and $\pm 1\sigma$ uncertainties are listed in table 1. $^{40}Ar/^{39}Ar$ ages reported by Beard (1996) and Harlan and others (1998) use the same monitor ages. However, Sawyer and others (1994) used an age of 513.9 Ma for MMhb-1. We therefore recalculated their ages for direct comparison.

Most ages were readily interpretable as either means (sanidine) or plateaus (biotite and hornblende) (table 1, fig. 1). Eleven sanidine grains from C95-38 gave a tight mean with no indication of inherited grains. Sanidine from sample C95-3 included several probable xenocrysts, which were excluded from the final age calculation. Hornblende and biotite pairs from samples C95-64 and C95-29 differ by more than 1σ but are indistinguishable at 2σ. The spectrum for plagioclase from sample C95-50 was slightly disturbed; an inverse isochron plot gives an age of 13.12±0.24 Ma with an MSWD of 2.11. We consider this a reliable age, because it agrees well with stratigraphic relations and ages of other samples (fig. 1).

Our $^{40}Ar/^{39}Ar$ ages from all samples except C95-3 and JF99-455 (red sandstone) range narrowly between 13.12 and 13.94 Ma. Along with published data (fig. 1), these indicate that the upper part of the Horse Spring Formation was deposited rapidly, with no discernible age difference between rocks of the Bitter Ridge and Lovell Wash Members. Moreover, ages are indistinguishable from those of the "igneous rocks of Lava Butte" (e.g., the dacite intrusion that makes up Lava Butte; sample C95-29) and K-Ar ages on igneous rocks from the River Mountains volcanics (Anderson and others, 1972; Faulds and others, 1999). In contrast, our new age (13.94±0.03 Ma; C99-14) and published ages on the Thumb Member are distinctly older, ranging from about 14 to 16 Ma. The Rainbow Gardens Member is still older; the youngest age reported by Beard (1996) is 18.8 Ma, and ages range back to 26 Ma.

The red sandstone (Bohannon, 1984) is noticeably younger. Our sanidine ages agree closely with $^{40}Ar/^{39}Ar$ ages on a tuff in the red sandstone reported by Harlan and others (1998) and, within their large uncertainties, with fission-track ages on zircon reported by Bohannon (1984). Additionally, the age for sample C95-3, at 11.47 Ma (table 1), is indistinguishable from the reported age of the Ammonia Tanks Tuff, a regionally extensive high-silica rhyolite to alkali trachyte ash-flow sheet from the Timber Mountain caldera about 150 km northwest of the Frenchman Mountain Quadrangle (Sawyer and others, 1994). Sample C95-3 is mineralogically similar to the Ammonia Tanks Tuff (with phenocrysts of quartz, sanidine, plagioclase, biotite, pyroxene, and hornblende) and is likely a distal fall from that tuff.

The two ages determined using geochemical correlation include one for a tuff bed from the red sandstone unit that was also dated by $^{40}Ar/^{39}Ar$, giving identical dates (JF99-452, table 1). This tuff, which is correlative with the CPT IX ash bed of Perkins and others (1998), lies beneath a white

SE ROA 39850

Table 1. $^{40}Ar/^{39}Ar$, K/Ar, fission track, and chemical correlation ages, Lake Mead area.

Reference	Sample No.	Location N. Lat.	Location W. Long.	Stratigraphic unit	Rock type	Mineral	Age Method	n* or %^{39}Ar	Age (Ma)	±1σ
Spencer and others, 1998		35°58'29"	114°24'47"	Hualapai Limestone	tuff	biotite	Step heating plateau		5.97	0.07
this study	JF99-455	36°15'12"	114°56'37"	Muddy Creek Fm	air-fall tuff	glass	Geochemical correlation		6.0	
Feuerbach and others, 1991		36°09'51"	114°43'57"	Volcanics of Callville Mesa	basaltic andesite lava	plagioclase	K/Ar		8.49	0.20
”		36°10'37"	114°44'39"	”	basaltic andesite lava	plagioclase	K/Ar		10.21	0.23
”		36°10'19"	114°42'30"	”	basalt lava	plagioclase	K/Ar		10.46	0.23
Harlan and others, 1998		36°10'28"	114°48'45"	”	basalt lava	whole rock	Step heating plateau		11.41	0.07
Sawyer and others, 1994		Yucca Mtn. area		Ammonia Tanks Tuff	ash-flow tuff	sanidine	Single crystal mean		11.59	0.03
Bohannon, 1984		Frenchman Mtn. quad		”	air-fall tuff	zircon	Fission track		10.6	0.90
”		White Basin		”	”	”	”		11	0.90
this study	C95-3	36°08'34"	114°55'11"	”	”	sanidine	Single crystal mean	20	11.47	0.05
”	JF99-452	36°14'30"	114°58'35"	red sandstone	”	sanidine	Single crystal mean	8	11.59	0.06
”	”	”	”	”	”	glass	Geochemical correlation		11.60	
Bohannon, 1984		White Basin			”	zircon	Fission track		11.9	0.90
Harlan and others, 1998		36°14'01"	114°48'20"		crystal vitric tuff	sanidine	Step heating plateau		11.70	0.04
Harlan and others, 1998		”	”		crystal vitric tuff	biotite	Step heating plateau		11.86	0.05
Bohannon, 1984		Lovell Wash		Horse Spring Fm. Lovell Wash Mbr.	air-fall tuff	zircon	Fission track	13	0.80	
this study	C95-50	36°08'03"	114°55'43"	” ”	plagioclase	Step heating	isochron	7	13.12	0.24
”	C95-64	36°10'42"	114°54'19"	” ”	”	hornblende	” plateau	51.9	13.12	0.12
”	C95-64	”	”	” ”	”	biotite	” plateau	88.8	13.40	0.05
Harlan and others, 1998		36°09'10"	114°51'31"	” ”	basalt lava	whole rock	” isochron		13.28	0.05
Harlan and others, 1998		36°10'39"	114°48'52"	” ”	basalt lava	whole rock	” plateau		13.17	0.05
this study	C95-38	36°08'06"	114°56'18"	” Bitter Ridge Mbr.	ash-flow tuff	sanidine	Single crystal mean	11	13.07	0.08
this study	C95-20	36°08'49"	114°53'04"	River Mountains Volcanics equiv.	basalt lava	whole rock	Step heating plateau	100	13.16	0.18
Anderson and others, 1972		River Mtns.		River Mountains Volcanics	silicic lava	biotite	K/Ar		13.2	0.40
”		”		”	”	”	”		13.2	0.30
Weber and Smith, 1987		”		”	lamprophyre dike	”	K/Ar		13.4	0.30
Harlan and others, 1998		36°10'46"	114°50'14"	Intrusion in Thumb Member	diorite sill	hornblende	Step heating plateau		13.19	0.06
this study	C95-29	36°08'58"	114°56'18"	Dacite porphyry (Lava Butte)	dacite intrusive rock	biotite	Step heating plateau	93.3	13.16	0.05
”	C95-29	”	”	”	”	hornblende	” plateau	95.3	13.50	0.16
Anderson and others, 1972		Frenchman Mtn. quad		Igneous rocks of Lava Butte	biot.-hornbl. rhyodacite	biotite	K/Ar		13.7	0.70
Bohannon, 1984		”		Horse Spring Fm. Thumb Mbr.	air-fall tuff	zircon	Fission track		13.2	0.90
this study	C99-14	36°15'24"	114°51'15"	” ”	air-fall tuff	biotite	Ar/Ar plateau	94.2	13.94	0.03
Beard, 1996		Lime Ridge		” ”	tuff	biotite	Ar/Ar		14.2	0.50
”		Gold Butte		” ”	”	”	”		14.4	0.30
”		Wilson Ridge		” ”	”	sanidine	”		15.1	0.10
”		Pakoon Ridge		” ”	”	”	”		15.4	0.04
Anderson and others, 1972		SE of Muddy Mtns.		” ”	”	biotite	K/Ar		15.6	0.70
Beard, 1996		Pakoon Ridge		” ”	air-fall tuff	sanidine	Ar/Ar		15.7	0.20
Bohannon, 1984		Frenchman Mtn. quad		” ”	”	zircon	Fission track		16.2	0.80
Beard, 1996		Horse Spring		” Rainbow Gardens Mbr.	”	anorthoclase	Ar/Ar		18.8	0.20

This study * n = number of single crystals analyzed; %^{39}Ar = percentage of ^{39}Ar that defines plateau.
Decay constants after Steiger and Jager (1977) and $^{40}Ar/^{39}Ar$ ages normalized to a monitor age of 520.4 Ma on MMhb-1 hornblende (27.84 Ma on Fish Canyon sanidine).
Step heating and single crystal ages are by $^{40}Ar/^{39}Ar$ method.

tuff that may be the Ammonia Tanks Tuff (Perkins, written commun., 1999). In addition, a geochemical correlation age was determined for a fine-grained vitric tuff in the Muddy Creek Formation just to the north of the Frenchman Mountain Quadrangle (JF99-455, table 1). This age (6.0 Ma) was critical to the determination of the age of the enclosing rocks and the overlying limestone in the Muddy Creek Formation, which was previously assigned to the older (ca. 13.5 Ma) Bitter Ridge Member of the Horse Spring Formation by Bohannon (unpublished mapping, Apex Quadrangle).

CHEMICAL ANALYSES

Whole-rock major oxide analyses were performed at Washington State University and at the Nevada Bureau of Mines and Geology Analytical Laboratory using XRF analysis of fused lithium borate disks. Data are presented in table 2.

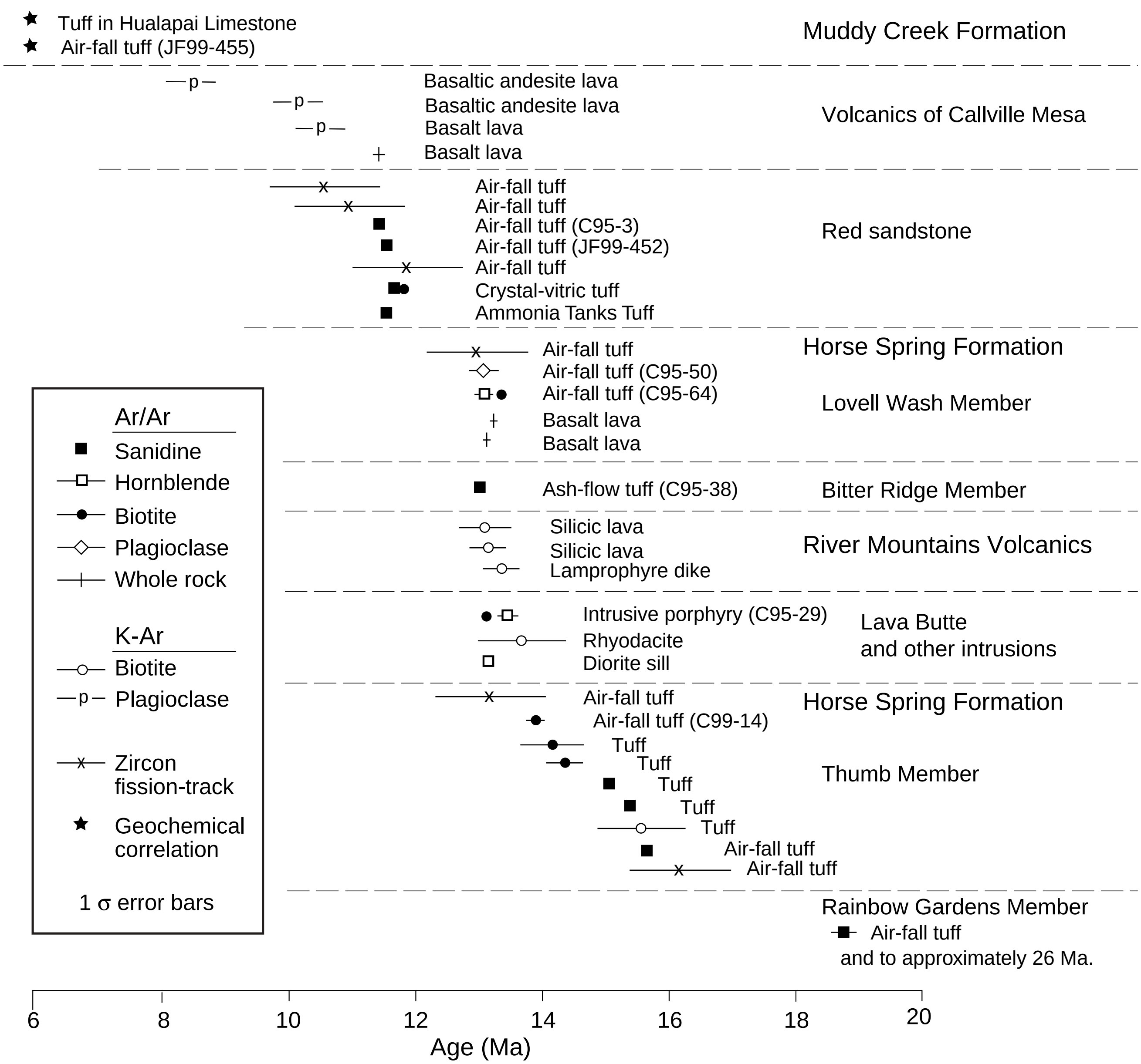

Figure 1. Isotopic and geochemical correlation ages, Frenchman Mountain Quadrangle and vicinity. Data are from this study (numbered samples), and from Anderson and others (1972), Sawyer and others (1984), Weber and Smith (1987), Feuerbach and others (1991), Bohannon (1994), Beard (1996), Harlan and others (1998), and Spencer and others (1998); see table 1. Samples from individual sources are arranged in stratigraphic order.

Table 2. Whole-rock major oxide contents of samples from the Frenchman Mountain Quadrangle. All analyses were conducted at Washington State University, except for samples C95-9 and C95-29, which were analyzed by the Nevada Bureau of Mines and Geology.

Sample	C95-3	C95-4	C95-9	C95-20	C95-29	C95-38	C95-50	C95-64
Map unit	Tr	Tr	Tb	Tb	Td	Thb	Thl	Thl
Latitude	36°08'34"	36°08'39"	36°09'01"	36°08'50"	36°08'58"	36°08'06"	36°08'03"	36°10'42"
Longitude	114°55'11"	114°55'18"	114°55'11"	114°53'04"	114°56'18"	114°56'18"	114°55'43"	114°54'19"
SiO_2	72.36	74.45	52.86	47.89	68.59	73.22	63.47	62.30
TiO_2	0.22	0.21	1.58	1.58	0.39	0.15	0.46	0.58
Al_2O_3	13.86	12.65	15.57	15.19	14.50	13.17	14.46	18.31
Fe as Fe_2O_3	1.49	2.04	8.81	10.40	2.21	0.92	2.87	4.72
MnO	0.08	0.04	0.12	0.16	0.05	0.02	0.07	0.08
MgO	1.80	0.96	6.37	9.25	0.99	0.81	4.39	2.11
CaO	1.13	1.11	7.97	9.12	2.74	0.56	4.67	4.98
Na_2O	2.25	2.11	3.72	3.02	3.53	2.20	2.56	2.90
K_2O	5.07	4.64	1.96	1.13	5.29	6.73	2.72	2.53
P_2O_5	0.04	0.01	0.49	0.37	0.16	0.03	0.20	0.22
Total	98.30	98.22	99.45	98.12	8.45	97.81	95.87	98.73

STRUCTURE

The Frenchman Mountain Quadrangle occupies a position critical to understanding the structural and tectonic framework of southern Nevada (fig. 2). It contains beautifully exposed Paleozoic, Mesozoic, and Tertiary stratigraphic sections that have strong affinities to sections far to the east near the western margin of the Colorado Plateau, portions of large middle to late Miocene basins, part of a major range-bounding normal fault that has accommodated Quaternary displacement and poses a potential seismic hazard to the city of Las Vegas, and several strike-slip fault zones. Much of the rock in the Frenchman Mountain Quadrangle may have originated 60 km or more to the east, having been transported to its present position by systems of strike-slip and normal faults (Anderson, 1973; Bohannon, 1984; Rowland and others, 1990; Duebendorfer and others, 1998). The discussion below addresses the geometry and kinematics of the most prominent structural features within the quadrangle.

The Frenchman Mountain Quadrangle contains at least five major structural elements, here referred to as the Frenchman Mountain block, Boulder basin, Sunrise Mountain block, Nellis basin, and Las Vegas Valley (fig. 3). The Frenchman Mountain block is bounded by the Frenchman fault and Las Vegas Valley on the west, Boulevard fault zone and Sunrise Mountain block on the north, and the Boulder basin on the east. The Frenchman Mountain block is dominated by north-northeast striking, moderately to gently east-tilted Paleozoic, Mesozoic, and Miocene strata (fig. 4a). Directly west of the Quadrangle on the west flank of Frenchman Mountain, the Cambrian Tapeats Sandstone rests directly on Early Proterozoic gneiss (e.g., Rowland and others, 1990; Matti and others, 1993). The boundary between the Frenchman Mountain block and Boulder basin was placed at the contact between the Rainbow Gardens and Thumb Members of the Horse Spring Formation, because this marks the approximate stratigraphic level where tilts begin to decrease up-section (i.e., tilt fanning). Tilt magnitudes within the Rainbow Gardens Member are similar to those of Paleozoic and Mesozoic strata, despite the minor angular unconformity at the base of the Tertiary. Several widely spaced north-northeast to north-northwest striking, generally west-dipping normal faults cut the Frenchman Mountain block. Some of these faults cut the Boulevard fault zone. In the northeast part of the block, several of these faults curve northeastward and become parallel with the left-lateral Boulevard fault zone (fig. 3). The eastern part of the boundary between the Frenchman and Sunrise Mountain blocks steps southward from the Boulevard fault zone to follow the eastern portion of one of these curved faults, here referred to as the Dry Wash fault. The eastern part of this fault accommodated about 2.7 km of left-lateral separation. The area between the eastern part of the Dry Wash fault and Boulevard fault zone was included in the Sunrise Mountain block because the attitude of strata within that area is significantly oblique to that within most of the Frenchman Mountain block but subparallels that within the Sunrise Mountain block.

The Boulder basin lies directly east of the Frenchman Mountain block and consists primarily of middle to late Miocene sedimentary strata. It occupies the eastern part of the quadrangle and covers much of the western Lake Mead area (fig. 2). On a broad scale, Miocene strata within the western part of the basin (i.e., within the quadrangle) are tilted gently to moderately eastward, with the magnitude of tilting progressively decreasing up-section. Thus, the basin may correspond, at least in part, to an east-tilted half graben that developed in the hanging wall of the Saddle Island detachment (Duebendorfer and Wallin, 1991). However, the northern extent of the Saddle Island detachment is poorly defined. Moreover, the northern part of the Boulder basin is complicated by an east- to northeast-trending fold belt. This

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fold belt extends from the eastern part of the Frenchman Mountain Quadrangle (fig. 4c) eastward through the Government Wash (Duebendorfer, in review) and Callville Bay Quadrangles (Anderson, in review). If once a half graben or series of half grabens, the Boulder basin has since been significantly modified by north-south shortening, possibly associated with the intersection of the left-lateral Lake Mead fault system and right-lateral Las Vegas Valley shear zone (Çakir and others, 1998). Anderson (in review) has suggested that sedimentation patterns in the red sandstone and Muddy Creek units were controlled by east-trending folds rather than by northerly striking faults. The late Miocene Muddy Creek Formation is commonly mildly deformed throughout this area. The tilted and folded strata are onlapped by latest Miocene(?) to Quaternary fan deposits. To the south of the quadrangle, the Boulder basin appears to join with the River Mountains structural block (fig. 2), which is dominated by middle Miocene intermediate to felsic lavas (Anderson and others, 1972; Bell and Smith, 1980; Smith, 1982, 1984).

The Sunrise Mountain block is bounded by the Frenchman fault and Las Vegas Valley on the west and northwest, the Nellis basin and Munitions fault on the northwest and north, the Boulder basin and Dry Wash fault on the southeast, and the Frenchman Mountain block and Boulevard fault zone on the southwest (fig. 3). In contrast

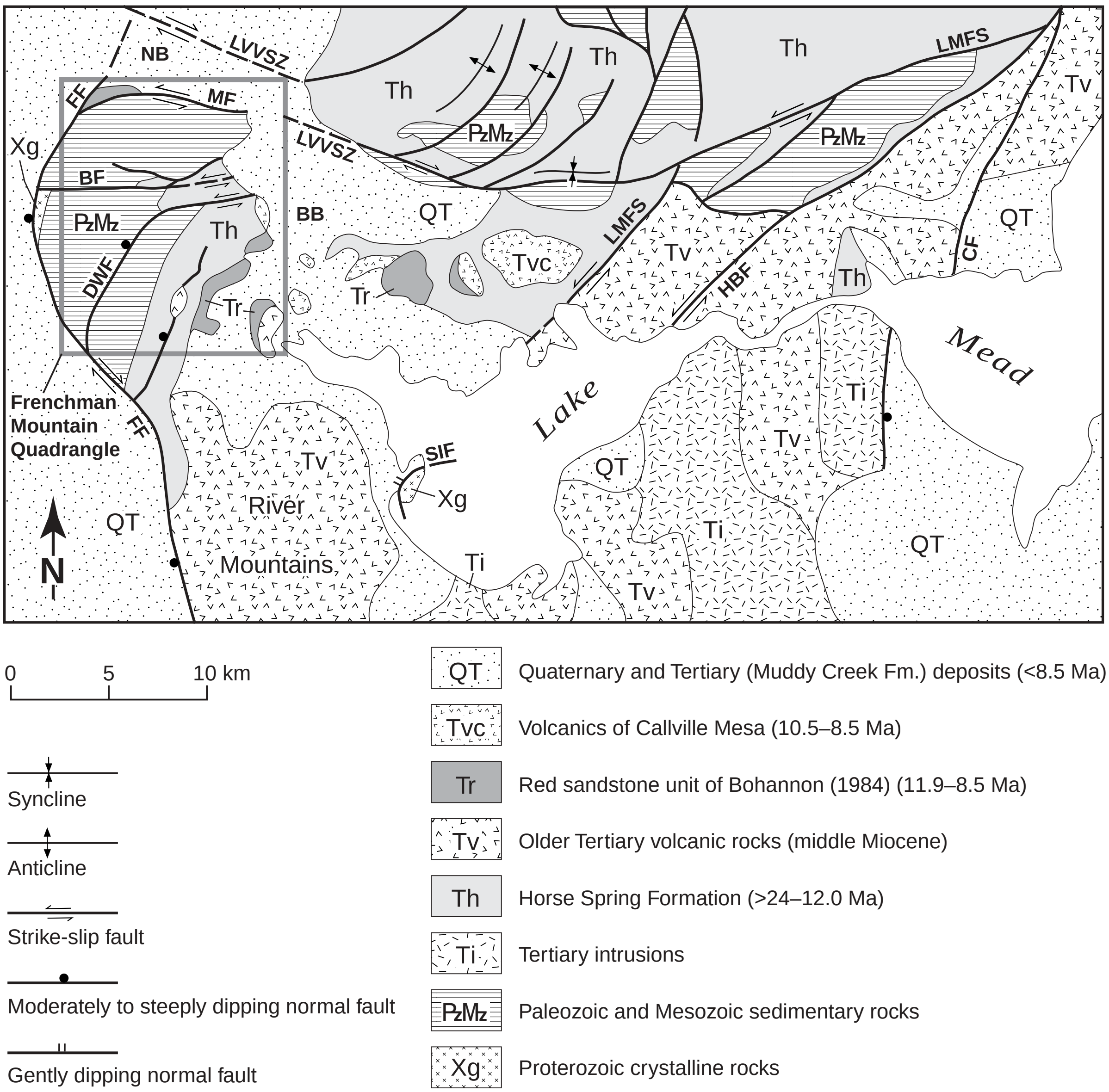


Figure 2. Generalized geology of the western Lake Mead area. Faults or fault zones labelled are: BF - Boulevard fault zone; CF - Cleopatra fault; DWF - Dry Wash fault; FF - Frenchman fault; HBF - Hamblin Bay fault of Lake Mead fault system; LMFS - Lake Mead fault system; LVVSZ - Las Vegas Valley shear zone; MF - Munitions fault; SIF - Saddle Island fault. Basins labelled are: BB - Boulder basin; NB - Nellis basin.

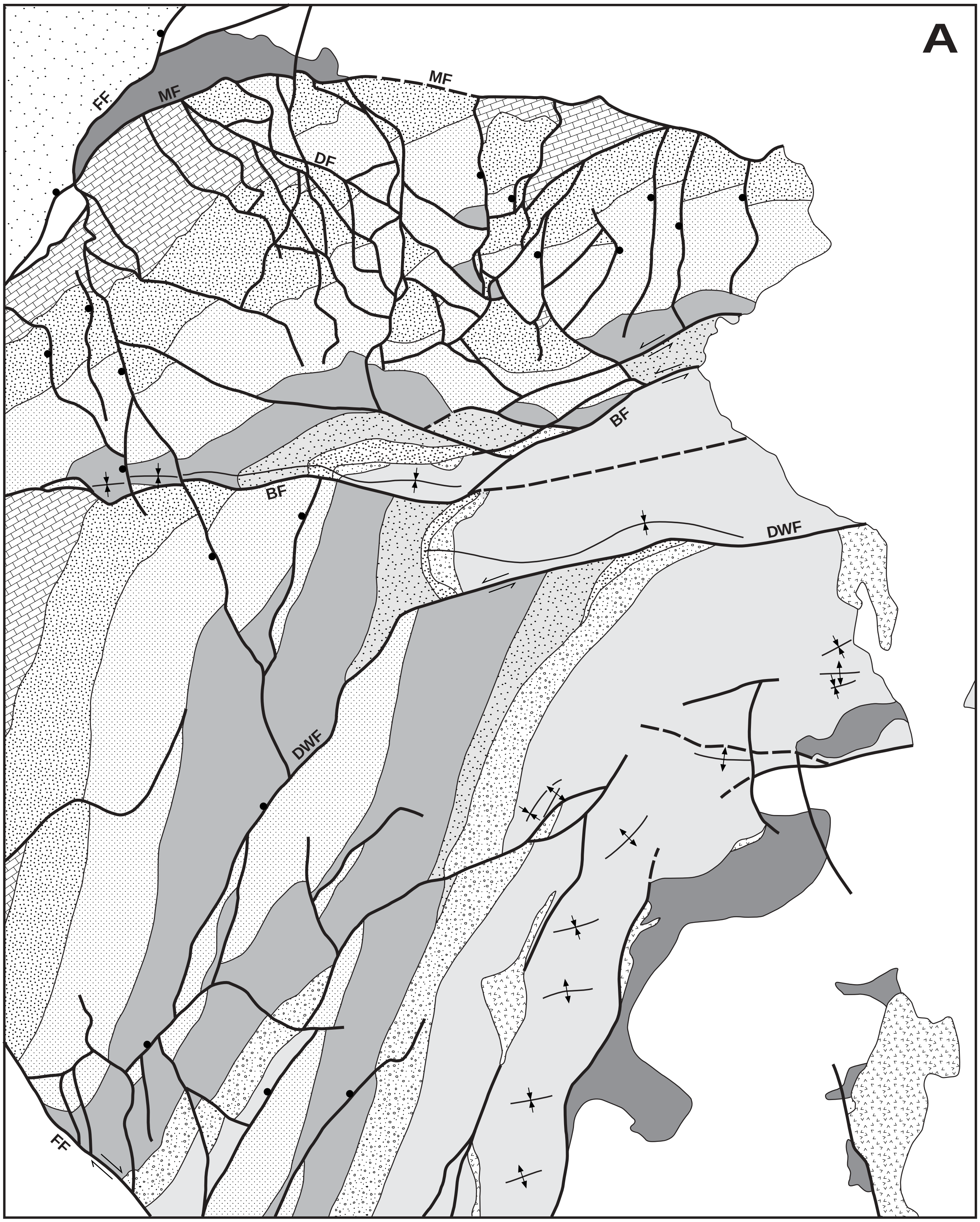
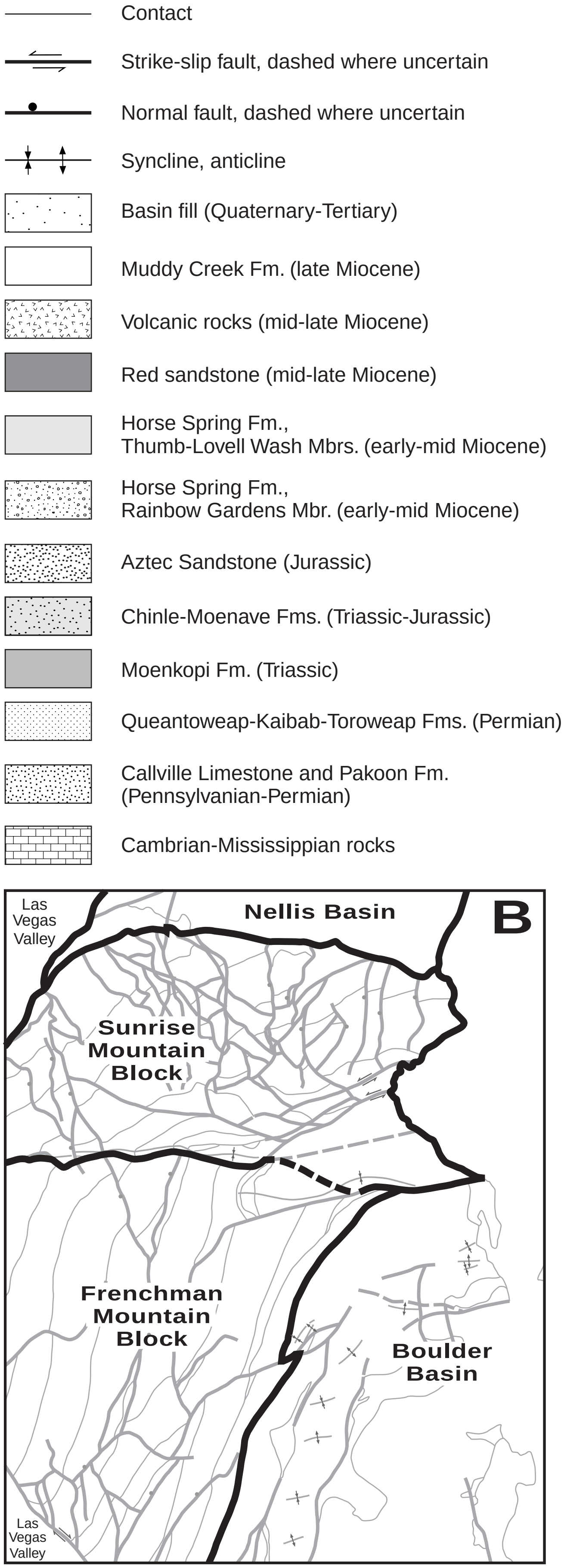


Figure 3A. Simplified geology of the Frenchman Mountain Quadrangle. Faults or fault zones labelled are: BF - Boulevard fault zone; DF - Demolition fault; DWF - Dry Wash fault; FF - Frenchman fault; MF - Munitions fault.

Figure 3B. Map showing major structural elements discussed in text.



to the Frenchman Mountain block, the Sunrise Mountain block is dominated by east-northeast striking, moderately southeast-dipping Paleozoic and Mesozoic strata (fig. 4b) that are cut by a complex array of closely spaced normal, oblique, and strike-slip faults. The multiple fault sets fragment the Sunrise Mountain block into a myriad of small blocks. The most prominent fault sets in the Sunrise Mountain block are: 1) north-northwest to north-northeast striking, moderately to steeply dipping normal faults that generally dip west; 2) east-northeast-striking, steeply dipping, mainly sinistral faults, some of which can be considered splays of the Boulevard fault zone; and 3) west-northwest-striking, moderately to steeply dipping dextral and sinistral faults, although the dextral faults predominate. In addition, a few minor northeast- and west-northwest-striking reverse separation faults were observed. Although normal faults of the first set commonly truncate and offset the east-northeast- and west-northwest-striking fault sets, important exceptions can be found. For example, near the northern margin of the quadrangle, several normal faults swing northwestward and appear to merge with a major west-northwest-striking sinistral-normal fault, here referred to as the Demolition fault (fig. 3a) because it bisects a demolition range on Nellis Air Force Base.

The structural complexity in the Sunrise Mountain block increases northward toward a major east-striking fault zone that dips gently to moderately (29° to 39°) northward. This fault zone bounds the Sunrise Mountain block on the north and is referred to as the Munitions fault, because it extends through the munitions storage area of the Nellis Air Force Base. The Munitions fault cuts the post-6-Ma limestone member of the Muddy Creek Formation but does not cut Quaternary fan deposits. The N80°E strike of much of the Munitions fault suggests that it may be a splay of the right-lateral Las Vegas Valley shear zone. However, the Munitions fault accommodated a large component of normal separation and curves to a northeasterly strike as it merges westward with the largely normal Frenchman fault. The northeast-striking portion of the Munitions fault accommodated sinistral-normal oblique slip. These relations imply that the Munitions fault has experienced a complex kinematic history and cannot be directly related to the Las Vegas Valley shear zone.

Relatively thick sections of middle to late Miocene sedimentary rocks and isostatic gravity data (Langenheim and others, 1998; in press) indicate that a small, 2- to 3-km-deep, late Tertiary basin lies directly north of the Munitions fault, straddling the northern margin of the Frenchman Mountain Quadrangle. This basin is referred to as the Nellis basin, because it contains the eastern part of Nellis Air Force Base. The limestone member of the Muddy Creek Formation (Tml) is essentially confined to this basin. A 6.0-Ma air-fall tuff lies beneath the limestone. This limestone is typically gently tilted and cut by widely spaced faults in the Frenchman Mountain Quadrangle. However, to the north in the Apex Quadrangle it is warped into several north-northwest- to east-trending folds (R.G. Bohannon,

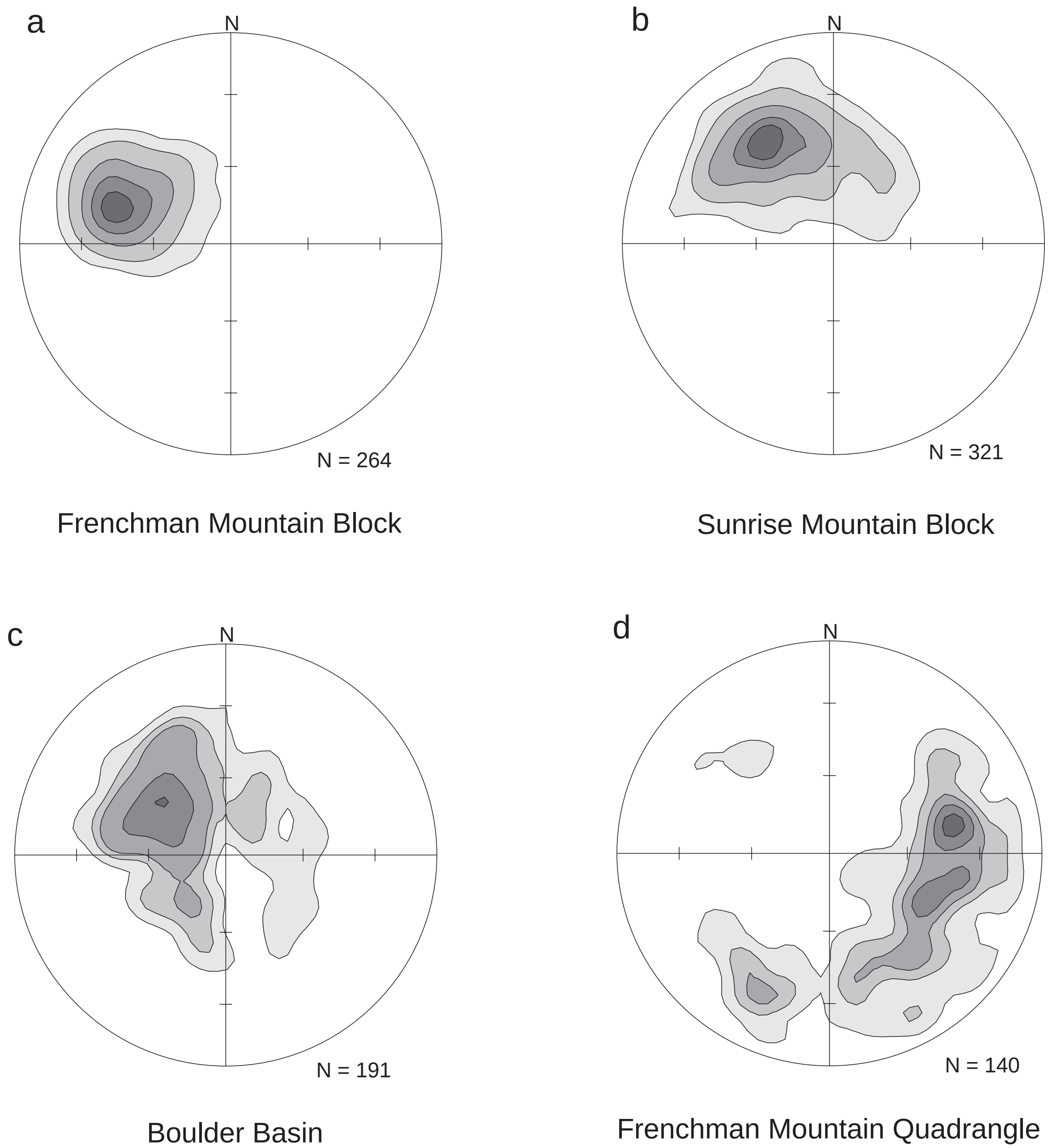


Figure 4. Equal-area density contour stereograms. Density contours were calculated utilizing Gaussian counting. N - number of measurements. (a) Poles to bedding of Cambrian strata through the early Miocene Rainbow Gardens Member in the Frenchman Mountain block; density contours at 0, 4, 16, 32, and 48% per 1% area; bedding attitude averages N17°E, 47°SE; (b) Poles to bedding of Cambrian through early Miocene strata in the Sunrise Mountain block; contours at 0, 4, 12, 20, and 24% per 1% area; bedding attitude averages N54°E, 47°SE; (c) Poles to bedding of middle to late Miocene strata (Thumb Member of the Horse Spring Formation through Muddy Creek Formation) in the Boulder basin; contours at 0, 2, 4, 12, and 20% per 1% area; bedding attitude averages N41°E, 31°SE. (d) Poles to fault planes in the entire Frenchman Mountain Quadrangle; contours at 0, 2, 4, 6, and 8% per 1% area; faults generally strike north-northeast to north-northwest and dip to the west, but a significant subset strikes west-northwest and dips to the north.

unpublished mapping). Within the Frenchman Mountain Quadrangle, nearly flat-lying beds beneath the limestone rest in angular unconformity on the moderately east-tilted red sandstone unit, which contains an 11.6 Ma air-fall tuff. This suggests that most of the tilting in this area occurred between 11.6 and 6.0 Ma.

It is noteworthy that the red sandstone unit in this area contains abundant clasts of Proterozoic gneiss and granite. Possible sources of this detritus include the Proterozoic exposures on the west flank of Frenchman Mountain, Proterozoic detritus in the Thumb Member of the Horse Spring Formation south of the Sunrise Mountain block, and Proterozoic exposures far to the east in the Gold Butte area. Considering the present position of the Nellis basin, it would be difficult to derive detritus from any of these sources. However, much of the tilting of the Nellis basin and Frenchman Mountain block clearly postdates deposition of the red sandstone unit. Thus, the paleogeography during deposition of the red sandstone unit probably differed significantly from the present physiography. It is also important to note that the strike of strata within the Nellis basin (e.g., north-northwest strike of red sandstone unit beds) is highly discordant to that in the Sunrise Mountain block (e.g., east-northeast strikes of Paleozoic through middle Miocene strata). This suggests that the Nellis basin and Sunrise Mountain block were essentially decoupled and followed somewhat different evolutionary paths.

The Las Vegas Valley shear zone is a major west-northwest-striking right-lateral fault zone that extends across much of southern Nevada (fig. 2). It has accommodated as much as 65 km of dextral displacement to the west of the Frenchman Mountain Quadrangle (Longwell, 1974; Wernicke and others, 1988; Duebendorfer and Black, 1992), and is associated with large-magnitude clockwise rotations as reflected in a major oroclinal flexure and documented by paleomagnetic data from Paleozoic and Tertiary rocks (Nelson and Jones, 1987; Sonder and others, 1994). The Las Vegas Valley shear zone essentially bounds both the Boulder and Las Vegas basins on the north. On the basis of gravity data, Campagna and Aydin (1994) and Langenheim and others (1998; in press) have suggested that parts of the Las Vegas Valley originated as pull-aparts in right steps of the Las Vegas Valley shear zone. The shear zone may have also served as a major transfer zone (cf., Faulds and Varga, 1998) that linked en echelon domains of extension (Liggett and Childs, 1977; Duebendorfer and Black, 1992). Dextral motion on the shear zone has been kinematically linked to normal displacement on the Saddle Island detachment fault (Weber and Smith, 1987; Duebendorfer and Black, 1992). However, a direct linkage between the Saddle Island detachment and Las Vegas Valley shear zone is not supported by the distribution of rock units or structural relations in the Frenchman Mountain and adjacent quadrangles. Furthermore, gravity and seismic reflection data showed no evidence for a major detachment fault in the Frenchman Mountain area (Langenheim and others, in press).

The west-northwest elongated Nellis basin may have developed in a right step or pull-apart near the eastern end of the Las Vegas Valley shear zone. Isostatic gravity data define a 7-km-long basin that trends approximately N70°W, parallel to the eastern part of the shear zone (fig. 5). Although the Munitions fault on the southern margin of the western part of the basin did not accommodate dextral motion, it may intersect the western end of a southern strand of a right-stepping dextral shear zone to the east. The main strand of the Las Vegas Valley shear zone may bound the Nellis basin on the north. Opening of the Nellis basin may have been accommodated along its northern margin by dextral motion on a northern strand of the Las Vegas Valley shear zone and along its southern margin by sinistral-normal movement on the Munitions fault (fig. 5).

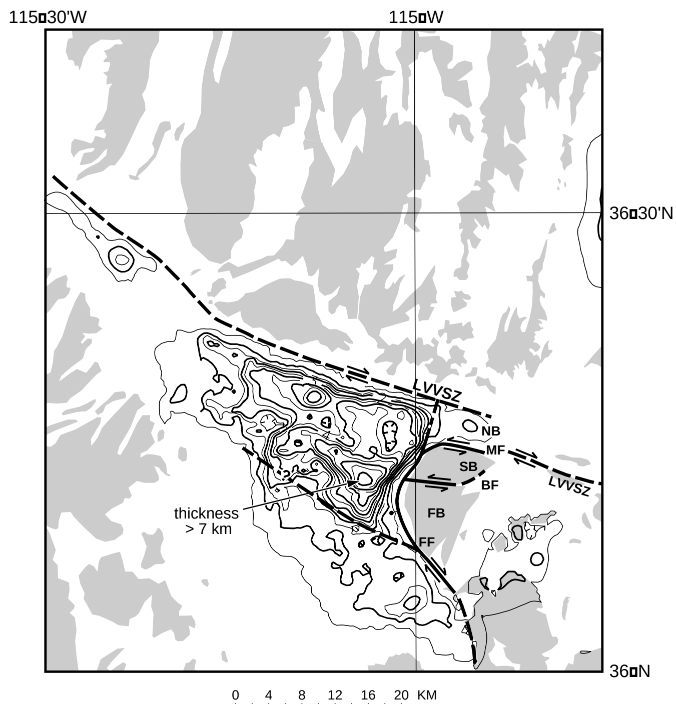


Figure 5. Thickness of Cenozoic basin fill and inferred location of major faults in the Frenchman Mountain area, based on isostatic residual gravity data (modified from Langenheim and others, 1997). Contour intervals at 0.5 and 1.0 km. Basin model utilized the seismically derived density-depth function, as discussed in Langenheim and others (1997). Faults designated as in figure 2; FB = Frenchman Mountain block, NB = Nellis basin, SB = Sunrise Mountain block.

The swing from northerly striking strata in the Frenchman Mountain block to east-northeast-striking strata in the Sunrise Mountain block is interpreted to reflect oroflexural deformation associated with right-lateral displacement and/or north-south shortening accommodated by the Las Vegas Valley shear zone. Sonder and others (1994) documented more than 75° of clockwise rotation within the Thumb Member of the Horse Spring Formation near the Boulevard fault zone. The magnitude of clockwise rotation decreases appreciably to both the north and south of the Las Vegas Valley shear zone (Sonder and others, 1994). On the basis of the average strike of strata (figs. 4a, b), clockwise rotation of the Sunrise Mountain block, relative to the Frenchman Mountain block, probably averages about 45°. In general, stratal rotations in the Sunrise Mountain block increase to the east, with maximum rotations occurring in the southeast part of the block near the Boulevard fault zone.

The Boulevard fault zone separates the Frenchman and Sunrise Mountain blocks in the western part of the quadrangle and cuts through the southern part of the Sunrise Mountain block in the east. This fault was formerly termed the Frenchman fault by Longwell (1966) but was renamed due to the proximity of much of the fault zone to Lake Mead Boulevard. The western part of this fault zone dips moderately northward (~35° to 65°) and accommodated normal-sinistral separation, whereas the eastern part of the fault zone dips steeply and accommodated both normal-sinistral and reverse-sinistral separation. Riedel shears and striae indicate that the eastern part of the fault zone accommodated mostly left-slip. Sinistral separation across the zone ranges from about 3.5 to 5.0 km. The Boulevard fault zone may represent a segment of the left-lateral Lake Mead fault zone that has been offset by the Las Vegas Valley shear zone. Alternatively and perhaps more likely, the Boulevard fault zone may have simply accommodated the northward increase in clockwise rotation toward the Las Vegas Valley shear zone, particularly the differential rotation between the Sunrise and Frenchman Mountain blocks. Sinistral-normal movement on the subparallel Munitions fault to the north may have also accommodated clockwise rotation of the Sunrise Mountain block. Thus, the Munitions and Boulevard fault zones may be kinematically related to one another, both having accommodated clockwise rotation associated with oroflexural folding along the Las Vegas Valley shear zone. A possible problem with this model is the apparent lack of clockwise rotation in the Nellis basin, which presumably lies astride the Las Vegas Valley shear zone.

The large-magnitude clockwise rotation may have significant implications for interpreting the origin of some of the fault sets and folds within the Sunrise Mountain block and Boulder basin, respectively. For example, removal of 45° to 75° of clockwise rotation restores many of the west-northwest striking left-lateral faults in the Sunrise Mountain block to east-northeast strikes, subparallel to other major left-lateral faults in the region. In addition, the clockwise rotation of the Sunrise Mountain block would likely generate some north-south shortening to the southeast of the block, and thus may have induced some of the folding in the Boulder basin as well as the greater stratal rotations in the southeast part of the block. The reverse-sinistral motion on some splays of the eastern part of the Boulevard fault zone is compatible with this model. East-northeast-striking faults in this area do not consistently display a reverse component of motion, however, as evidenced by the eastern part of the Dry Wash fault, which accommodated normal-sinistral separation directly north of many of the folds in the Boulder basin. Reverse and normal components of motion on similarly oriented faults implies that the rotating fault blocks experienced a complex kinematic history involving both local and regional forces. The eastward continuation of this fold belt through the western Lake Mead region further suggests that regional forces were at least partly responsible for the folding. Possible regional forces include broad north-south shortening accommodated by the left-lateral Lake Mead fault zone and right-lateral Las Vegas Valley shear zone (Anderson and Barnhard, 1993), north-south shortening resulting from opposing senses of motion on the left-lateral Lake Mead fault zone and right-lateral Las Vegas Valley shear zone (Çakir and others, 1998) and localized near their intersection, and wrench-style tectonics near the strike-slip faults (e.g., Wilcox and others, 1973). In the latter case, dextral motion on the west-northwest-striking Las Vegas Valley shear zone could induce northwest-southeast to north-south shortening in the local strain field. This may account for at least some of the northeast- to east-trending folds within the region. Furthermore, such folding could be episodic and coincide with major periods of movement on the Las Vegas Valley shear zone, alternating perhaps with intervals in which regional extension dominated. The east-trending synclines directly adjacent and parallel to the Boulevard and Dry Wash fault zones may exemplify the complex three-dimensional strain field, as the eastern parts of the folds may reflect north-south shortening associated with movement on the Las Vegas Valley shear zone and clockwise rotation of the Sunrise Mountain block, whereas the western parts of the folds may have resulted from normal drag along the Boulevard and Dry Wash fault zones induced by the clockwise rotation of the Sunrise Mountain block.

Intense deformation with multiple intersecting fault sets similar to that in the Sunrise Mountain block probably characterizes much of the Las Vegas Valley shear zone within the northern part of Las Vegas Valley and may greatly influence groundwater flow. Possible strands of the shear zone are covered by sediments in Las Vegas Valley but may follow strong gravity gradients (Langenheim and others, 1998; in press). Although the uplifted Sunrise Mountain area contains relatively little groundwater, it is noteworthy that most of the faults are not sealed. The central Nevada carbonate aquifer empties into the northern part of Las Vegas Valley, flows laterally along the Las Vegas Valley shear zone, and discharges near the shear zone in several springs, many of which are marked by Quaternary carbonate mounds (G.L. Dixon, personal commun., 1998). Multiple intersecting fault sets along the shear zone probably provide abundant channelways for the groundwater. Major strike-slip transfer zones play a major role in controlling groundwater flow patterns elsewhere within the Basin and Range province (e.g., Rowley, 1998; Faulds and Varga, 1998).

The Frenchman fault bounds both the Frenchman and Sunrise Mountain blocks on the west and consists of at least two distinct strands (fig. 2). The southern strand strikes northwest, dips steeply to both the northeast and southwest, and accommodated normal dextral (our mapping) and reverse dextral motion (R.E. Anderson, personal commun., 1998). The trace of this strand cuts the southwest corner of the quadrangle. The southern strand of the Frenchman fault may bifurcate directly west of the quadrangle. One strand appears to continue to the northwest into the Las Vegas basin, as indicated by northwest-trending isostatic gravity and aeromagnetic discontinuities, and may ultimately link northwestward with the Las Vegas Valley shear zone (Langenheim and others, 1998; in press). A second branch merges northward with the central strand of the Frenchman fault. This central strand surfaces directly west of the quadrangle (Matti and others, 1993) and extends northward into the northwest corner of the quadrangle. It strikes north-northwest to north-northeast, dips 35° to 50° westward, and primarily accommodated normal slip, as evidenced by Riedel shears and other kinematic indicators. This strand is best exposed in road cuts on the eastern fringe of Las Vegas (figs. 2 and 3) and along the northwest flank of Sunrise Mountain. It is important to note that the trace of the central strand of the Frenchman fault and the major basin-bounding fault imaged by gravity data may not be the same. For example, the trace of the central strand of the fault lies about 2 km east of the steeply dipping fault that forms the east margin of the Las Vegas basin (Langenheim, written commun., 1999).

Both the Munitions and Boulevard fault zones may also be related to the Frenchman fault. The Munitions fault clearly splays from the Frenchman fault (figs. 2 and 3). The Frenchman fault has much less displacement north of its juncture with the Munitions fault, suggesting that much of its displacement is transferred to the Munitions fault. Prior to >45° clockwise rotation of the Sunrise Mountain block, the Munitions fault presumably had a more northerly strike, implying that much of the fault initially accommodated primarily normal slip similar to the central strand of the Frenchman fault. Interestingly, the Las Vegas basin deepens significantly southward (fig. 5) near the intersection of the Frenchman and Boulevard fault zones, suggesting that some slip on the Frenchman fault may also be transferred to the Boulevard fault zone. It may also be noteworthy that the Munitions fault and the southern and central strands of the Frenchman fault collectively form a surface that is convex to the west, mimicking the pattern of the Dry Wash fault to the east (fig. 2). In the case of the Frenchman and Munitions faults, the apex of the footwall corresponds to the topographically and structurally elevated summit of Frenchman Mountain.

Moreover, the apparent kinematic linkages between northerly striking normal, northwest-striking dextral, and east-northeast-striking sinistral faults suggest that all such faults were active pene-contemporaneously in a complex three-dimensional strain field that accommodated both north-south shortening and northwest-southeast extension (e.g., Anderson and Barnhard, 1993). For example, if the Frenchman fault is kinematically linked to the Munitions and Boulevard faults, which accommodated clockwise rotation of the Sunrise Mountain block induced by dextral motion on the Las Vegas Valley shear zone, it seems likely that movement on the Las Vegas Valley shear zone, Frenchman fault, and Munitions and Boulevard faults occurred more or less simultaneously.

The Frenchman fault cuts late Pleistocene stream-terrace and fan-terrace alluvium as well as intermittently active alluvium of probable Holocene age. Although scarps in alluvium of modern washes were not observed along the Frenchman fault, it does pose a potential seismic hazard to the Las Vegas Valley. More detailed studies are necessary to determine the age of most recent movement, frequency of major earthquakes, and magnitude of past events on the fault. Studies of seismic hazards in this region must consider the possibility of coeval normal, strike-slip, and possibly reverse motion on individual faults or closely related groups of faults.

Deformational History

As noted by others (e.g., Anderson and Barnhard, 1993; Duebendorfer and Simpson, 1994), a complex three-dimensional strain field has characterized the Cenozoic evolution of the Lake Mead region. Reviewing all models and timing relations within the region is beyond the scope of this report. We therefore focus on what can be gleaned from critical structural relations within the Frenchman Mountain Quadrangle.

As discussed above, the apparent continuity of several individual faults or groups of faults suggests that normal slip on north- to north-northeast-striking faults, sinistral movement on east-northeast-striking faults, and dextral motion on northwest-striking faults were all roughly contemporaneous. Clockwise rotation of the Sunrise Mountain block probably coincided with activity on these three sets of faults, as some of the east-northeast-striking faults (e.g., Boulevard fault zone) appear to have accommodated differential rotation between the Sunrise and Frenchman Mountain blocks. These relations further suggest that northwest-southeast extension accommodated by the normal faulting and strike-slip faulting overlapped in time with north-south shortening accommodated by the east-trending fold belt, clockwise rotation of the Sunrise Mountain block, and strike-slip faulting. A major question is when did such deformation occur.

The slightly greater tilt magnitudes in the Rainbow Gardens Member of the Horse Spring Formation compared to that within the younger Tertiary units (compare fig. 4a to 4c) suggest that minor east-tilting and presumably east-west extension began during deposition of the Thumb Member of the Horse Spring Formation. Age constraints on the Thumb Member as well as relations to the east in the Lake Mead region (e.g., Beard, 1996) indicate an onset of extension at about 16 Ma.

However, the most significant episode of deformation in the Frenchman Mountain area probably postdated deposition of at least the 11.9- to 11.5-Ma lower part of the red sandstone unit, which clearly experienced the bulk of tilting within both the Boulder and Nellis basins, as well as significant folding within the east-trending fold belt in the western Lake Mead region. For example, the 11.6-Ma tuff intercalated within the red sandstone unit in the Nellis basin is tilted about 60°. In contrast, the Muddy Creek Formation is generally gently tilted (<10°). General similarities in the red sandstone unit sections in the northwest and eastern parts of the quadrangle suggest that a continuous basin may have extended across the Frenchman and Sunrise Mountain blocks at least until about 11 Ma (i.e., the Nellis and Boulder basins were originally part of the same basin). The 6.0 Ma age from an essentially flat-lying tuff directly below the limestone member of the Muddy Creek Formation indicates that most of the tilting had ceased by 6.0 Ma.

The kinematic linkages between the normal and strike-slip faults suggest that northwest-southeast extension and north-south shortening also occurred between 11.6 and 6.0 Ma. Thus, most of the east-tilting of the Boulder and Nellis basins, east-trending folding within the western Lake Mead region, rotation of the Sunrise Mountain block, and movement on the Frenchman Mountain fault and Las Vegas Valley shear zone may have been contemporaneous. It is possible that northwest-southeast extension and north-south shortening may have been somewhat episodic, perhaps induced by perturbations in the regional stress field (e.g., Angelier and others, 1985). For example, north-south shortening associated with pulses of movement on the Las Vegas Valley shear zone may have alternated with episodes dominated by northwest-southeast extension. Thus, rotation of the Sunrise Mountain block may have been accompanied by periodic extension, which generated new sets of northerly striking normal faults as older sets were rotated into positions unfavorable for accommodating regional extension. This may explain the complex multiple fault sets in the Sunrise Mountain block. Alternatively, some of the northwest-southeast extension may have been driven by north-south shortening, as blocks such as Frenchman and Sunrise Mountain were extruded laterally in the wake of a southward advancing block on the north side of the Las Vegas Valley shear zone and Lake Mead fault system (e.g., Anderson and others, 1994), similar in some respects to grand-scale extrusion or indentor tectonics (e.g., Molnar and Tapponier, 1975; Tapponier and others, 1982).

ECONOMIC GEOLOGY

Gypsum

The PABCO Gypsum Mine, which has also been called the Apex Mine, is located in the northeast part of the Frenchman Mountain Quadrangle and extends to the east into the Government Wash Quadrangle. It is one of four active gypsum mines in Nevada and has been the site of continuous mining since 1959 and sporadic earlier activity. It is owned and operated by Pacific Coast Building Products, Inc., which operates a wallboard plant near the mine site. Production from the mine has ranged between 400,000 and 600,000 tons annually since 1989; however, the ore contains about 80% gypsum, and production figures for beneficiated gypsum (92% or more gypsum by weight) must be adjusted downward to account for this factor. Exploratory drilling indicates that the thickness of the gypsum exceeds 35 m in the vicinity of the mine (L. Ordway, PABCO Mine Manager, personal commun., 1997). The gypsum is generally covered by less than 2 m (6 feet) of sandy overburden and occurs in an area of 13 km^2 (5 square miles) (Papke, 1987). On this basis, mineable reserves are quite large, probably more than 400 million tons.

The ore mined by PABCO is generally friable and porous, mostly consisting of fine intergrown gypsum crystals with various amounts of admixed clay and sand. In the open pit, it is white to grayish orange, depending on the gypsum content, but some light-greenish-gray sandy material was noted high on the eastern pit wall. Locally it contains layers of fine-grained, sugary, compact gypsum and in places relatively large selenite crystals or masses of crystals are present (Papke, 1987). Selenite crystals as much as 20 cm long were noted during our examination of the deposit. Steeply dipping northwest-striking faults that probably have only minor amounts of offset are exposed in the pit. Outcrops are commonly efflorescent gypsite. The PABCO Mine has been excavated into a gently south-dipping plateau capped by the gypsum, which is slightly more resistant than the underlying characteristic redbeds of the Muddy Creek Formation (unit Tm).

Gypsum has been mined and prospected for at several other sites in the Frenchman Mountain Quadrangle in the past, and gypsum prospect pits are common. The Pennsylvanian-Permian Pakoon Formation is the oldest unit that has been prospected for gypsum. Other units that contain beds of relatively pure gypsum are the Toroweap, Kaibab, Moenkopi, and Horse Spring Formations. At the White Eagle Mine near the southern edge of the quadrangle, gypsum was mined from a series of narrow pits between 1938 and 1956 by PABCO (Papke, 1987). Here, the gypsum is white to pale greenish yellow, may be as much as 35 m thick, contains some silty interbeds, and is in the lower redbed unit of the Moenkopi Formation. Gypsum was mined by PABCO from the Thumb Member of the Horse Spring Formation about 1 km east of and 5 km northeast of the White Eagle Mine in the 1950s at the Rainbow Gardens and Rainbow Gardens North properties, respectively (Papke, 1987). The latter property was also the site of small-scale mining by Nevada Gypsum and Mining in the late 1980s (Castor, 1989). In the Rainbow Gardens North pit, the gypsum sequence is about 150 m wide and is thought to be repeated by faulting or folding.

Limestone

Relatively pure limestone suitable for use in portland cement and possibly high-calcium lime occurs in the Frenchman Mountain Quadrangle but has not been mined. At Apex, about 12 km north of the quadrangle, large amounts of high-calcium lime are produced annually from pure micritic limestone in the upper part of the Crystal Pass Member of the Sultan Formation. Similar rock is present in the unit in the Frenchman Mountain Quadrangle, but access is poor and economic exploitation is unlikely. Lacustrine algal limestone that we map in the Muddy Creek Formation in the northeast part of the quadrangle (unit Tml) may have more potential because of its location and easily mined geometry. This limestone unit is as much as 50 m thick in places, has nearly flat-lying bedding, and is exposed over a large area (about 25 km^2) in the Frenchman Mountain Quadrangle and in the Apex Quadrangle to the north. However, the chemistry of this limestone has not been characterized and its suitability for commercial use is unknown.

Lithium clay

During the 1970s, relatively high growth in lithium consumption, driven by new uses and coupled with apprehension about future availability for the production of deuterium, prompted significant lithium exploration by the U.S. Geological Survey. Exploration mainly focused on modern playa deposits in Nevada and California, but deposits of older lithium-rich lacustrine sedimentary rocks were also studied. The upper part of the Lovell Wash Member of the Horse Spring Formation in the Frenchman Mountain Quadrangle was found to contain a 40-m-thick section with average lithium content of 1,000 ppm (Brenner-Tourtelot, 1979), and the presence of hectorite, a trioctahedral lithium-rich clay mineral, was suspected.

Samples collected from the Lovell Wash Member in both the Frenchman Mountain and Henderson Quadrangles were found to have Li contents as high as 900 ppm on the basis of atomic absorption analyses at the Nevada Bureau of Mines and Geology Analytical Laboratory. In addition, XRD analysis indicates that clay separates from one of these samples contains trioctahedral clay. On this basis, hectorite is considered to have been positively identified in the area.

Silica

According to Longwell and others (1965), the Sunrise Mountain silica deposit, which is probably in the Aztec Sandstone, lies in the Frenchman Mountain Quadrangle. No production has been recorded from this deposit and its location is poorly constrained. In addition, we found no evidence of mining in the Aztec Sandstone exposures in the quadrangle. Analyses given in Hewett and others (1936) for Aztec Sandstone from a silica prospect in the Muddy Mountains indicate that SiO_2 content, at about 94%, is too low to meet specifications for glass sand. On this basis, potential for silica production in the Frenchman Mountain Quadrangle is thought to be low.

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Issues Related to Conjunctive Management of the Lower White River Flow System

Presentation to the Office of the Nevada State Engineer

in Response to Order 1303

U.S. Fish and Wildlife Service

July 3, 2019

Overview

The U.S. Fish and Wildlife Service (USFWS) respectfully submits this report in response to the State Engineer's request for information regarding conjunctive management of water resources of the Lower White River Flow System (LWRFS), including but not limited to the following questions posed in Order 1303 (NSE 2019):

a. The geographic boundary of the hydrologically connected groundwater and surface water systems comprising the LWRFS;

b. Information obtained from the Order 1169 aquifer test and subsequent to the aquifer test, including changes in Muddy River headwater spring flows, as it relates to aquifer recovery since completion of the aquifer test;

c. The long-term annual quantity of groundwater that may be pumped from the LWRFS, including relationships between the location of pumping and capture of the Muddy River Springs and Muddy River;

d. Effects of the 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.

Section 1 of this report presents our current assessment of hydrologic issues and considerations related to the development of an effective conjunctive water management program for the LWRFS, including the five questions posed in Order 1303. Section 2 summarizes the current status of the Moapa dace and our understanding of habitat conditions required within the Muddy River Springs Area for its continued protection and recovery.

Summary of Conclusions

What is the geographic boundary of the hydrologically connected groundwater and surface water systems comprising the LWRFS?

Based on information developed in Sections 1.1 and 1.3.1, revisions to the areal extent of the LWRFS should be considered as shown in Figure 1 to include the following basins and parts of basins:

- the MRSA;
- most of Coyote Spring Valley;
- Hidden Valley;
- Garnet Valley;
- most of California Wash;
- northwest Black Mountains Area;
- Kane Springs Valley; and
- most of LMVW

We acknowledge the National Park Service's (NPS's) concern that there may be impacts from future pumping, particularly from wells located further south and east in the LWRFS. Based on our evaluation of the available geologic and hydrologic information, we believe that, to the extent that outflow occurs across any portion(s) of the Glendale and Muddy Mountain thrusts (or the northern strand of the Las Vegas shear zone), differences in head in carbonate and other rocks on either side of the thrusts mean that any outflow is fairly constant and unlikely to change with water management in the LWRFS. See Section 1.3.1, Lateral Outflow. However, we are open to any new evidence that would counter this view.

What information has been obtained from the Order 1169 aquifer test and subsequent to the aquifer test, including changes in Muddy River headwater spring flows, as it relates to aquifer recovery since completion of the aquifer test?

The high-elevation springs on the Moapa Valley National Wildlife Refuge continue to respond to fluctuations in carbonate water levels as expected and described in the Department of the Interior (DOI) 2013 interpretation of the Order 1169 pumping test. In contrast, the flow of the Big Muddy Spring, a major contributor to the Muddy River, appears to be unrelated to carbonate water levels in basins currently recognized as the LWRFS, including the MRSA, and may be responding primarily to a climate signal that has yet to be characterized. Moreover, a time lag was observed in the recovery of carbonate water levels and spring flows following the cessation of Order 1169 aquifer test which is consistent with basic hydrologic principles, but based on those same principles, is not a constant and depends on a great many things affecting conditions in the carbonate aquifer at the time, in addition to the location of the pumping and resource(s) in question (See Section 1.3.5).

What is the long-term annual quantity of groundwater that may be pumped from the LWRFS, including relationships between the location of pumping and capture of the Muddy River Springs and Muddy River?

An initial threshold of combined carbonate and alluvial pumping within the LWRFS of 9,318 afy appears to be the best initial estimate of the sustainable yield of the system, based on the optimum method currently available for arriving at an estimate of the maximum allowable rate of pumping in the LWRFS, i.e., the average annual rate of pumping from 2015-2017. See Section 1.4, Sustainable Levels of Pumping in the LWRFS for more discussion.

What are the effects of movement of water rights between alluvial wells and carbonate wells on deliveries of senior decreed rights to the Muddy River?

Since the Muddy River Springs (at least the refuge springs) are derived almost entirely from the carbonate aquifer, total carbonate pumping should not be increased (e.g., in exchange for reductions in alluvial pumping), even if total carbonate and alluvial pumping is maintained at a "sustainable" overall level. Additionally, existing carbonate pumping should not be moved closer to any springs (or the river), which could reduce the time lag in the development of impacts possibly before the impacts are detected based on periodic data collection and processing.

Since (in addition to the contributions of the springs) the remainder of water in the river comes from alluvium adjacent to the river in the MRSA and California Wash, alluvial pumping should not be increased (e.g., in exchange for reductions in carbonate pumping elsewhere), even if total alluvial and carbonate pumping is maintained at a "sustainable" overall level. Beyond that, existing alluvial pumping in the vicinity of the river should not be moved closer to the river, reducing the time lag in the development of impacts possibly before the impacts are detected based on periodic data collection and processing (Section 1.5).

Additional issues, considerations, and conclusions regarding the development of an effective conjunctive water management program for the LWRFS.

See Sections 1.1 through 1.6, Hydrologic Considerations Related to Conjunctive Management of the LWRFS, and Section 2, Status and Recovery of Moapa Dace. The results from our Section 1.6 on groundwater/spring relationships demonstrate that the system continues to behave as hypothesized, with the highest elevation springs being the most sensitive to changes in carbonate water levels. This implies that the triggers for flows measured at the Warm Springs West gage established in the 2006 Memorandum of Agreement between the Southern Nevada Water Authority, the USFWS, Coyote Springs Investment LLC, the Moapa Band of Paiute Indians, and the Moapa Valley Water District (2006 MOA, USFWS 2006a) are still valid and important for protecting the springs on the refuge. Protecting the most sensitive springs in the system should protect springflow, and habitat of the endangered Moapa dace as well. Recovery of Moapa dace is dependent on maintaining stream flows within the Moapa Valley National Wildlife Refuge and in the Muddy River Springs Area generally, and available information indicates that any reduction in current flow levels would result in reduced habitat for the species.

Table of Contents

Section 1 – Hydrologic Considerations Related to Conjunctive Management of the LWRFS

1.1 Groundwater-Surface Water Interactions in the LWRFS

1.1.1 *Sources of the Muddy River Springs and Muddy River*

The Muddy River Springs

It is well established that the source of the Muddy River Springs is the regional carbonate-rock aquifer (NSE 2014a-f, NSE 2002, and Eakin 1964 and 1966); specifically, that portion of the "central corridor" of the carbonate-rock province of southern and eastern Nevada identified by Dettinger et al. (1995) as effectively terminating in the area of the Muddy River Springs, including the whole of the roughly 240-mile long White River Groundwater Flow System which includes Kane Springs Valley (Eakin 1966), as well as possibly Lower Meadow Valley Wash (Page et al. 2006, NSE 2002, Dettinger et al., 1995, and Eakin 1964)[1], and additionally Hidden and Garnet valleys, California Wash, and the northwest part of the Black Mountains Area identified in the DOI (2013) analysis of the Order 1169 pumping test[2].

The Muddy River

It is also clear that the springs and intermittent runoff of local precipitation are not the only sources of water in the Muddy River (as proposed by Eakin 1964 and 1966). Synoptic discharge measurements made in February 2001 by Beck and Wilson 2006 on the Muddy River and a large number of Muddy River Spring tributaries show that the river was gaining from the confluence of its North and South Forks to below its confluence with the last spring tributary in the Muddy River Springs Area (MRSA), absent the contributions of the spring tributaries. Since the study was conducted during a period of "steady baseflow" on February 7, 2001 (presumably, no local precipitation or runoff and minimal irrigation return flows), this gain must have largely, if not entirely, occurred as natural seepage from alluvial aquifer adjacent to the river (in this case within the MRSA); which on the day of the study represented at least 17.6 cubic feet per second (cfs) or 42 percent of the 41.8 cfs measured in the river just below the last spring tributary[3]; the other roughly 24.2 cfs or 58 percent attributable to surface discharges from Muddy River Spring

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[1] Deuterium calibrated mixing-cell modeling by Thomas et al. 1996 suggests that Lower Meadow Valley Wash is a source of the Muddy River Springs (about 22 percent); although the authors were unclear regarding the extent to which their findings were influenced by deuterium samples collected in Lower Meadow Valley Wash where carbonate wells appear to be unavailable, or by samples collected from the Big Muddy Spring in the MRSA which may be uniquely influenced by Lower Meadow Valley Wash based on hydrogeologic considerations. The same can be said of the deuterium-calibrated mixing-cell modeling of Kirk and Campana 1990 which suggests broadly that Lower Meadow Valley Wash contributes underflow to the MRSA.

[2] In addition to the regional carbonate-rock aquifer, streams issuing from the Muddy River Springs are known to include at least some cold water inputs (e.g., along lower elevation portions of Pederson stream) which are attributable to gains from the local alluvial aquifer based on distributed water temperature measurements made in 2011 and 2012 for U.S. Fish and Wildlife Service (USFWS) by the University of Nevada-Reno and U.S. Geological Survey Biological Resources Division (USFWS 2012); the latter supporting an earlier observation by NSE 2002 that the alluvial aquifer may have some influence on the discharge of the Muddy River Springs.

[3] This temporary station located about one mile above the Moapa gage; the contributions of the alluvial aquifer to discharge at this location likely somewhat greater than 17.6 cfs or 42 percent given the documented occurrence of cold water seeps along low elevation portions of at least some spring tributaries in the MRSA (USFWS 2012).

tributaries.[4] The river was also gaining over about 11 of the next 15 river miles from the Moapa gage in the MRSA, through California Wash, to the vicinity of Anderson Wash above Bowman Reservoir in Lower Moapa Valley[5] through an area where a lack of permitted spring rights (NDWR 2018d) suggests no significant spring tributaries exist. The Muddy River Springs, seepage from alluvial aquifers adjacent to the river, and to a much lesser extent intermittent runoff of local precipitation, are the immediate sources of water in the Muddy River from its headwaters in the MRSA to the vicinity of Bowman Reservoir in Lower Moapa Valley. Maxey et al. 1966 proposed these same sources in the MRSA, although no supporting data were provided.

Sources of Water in Alluvial Aquifers Adjacent to the River – the MRSA

Within the MRSA, sources of water in the alluvial aquifer were originally thought to be limited to infiltration of Muddy River Spring flows, subsurface seepage from the springs, and to a lesser degree recharge of local precipitation[6] (Eakin 1964). Based on early mapping, Maxey et al. (1966) believed that Quaternary sediments in the MRSA (the alluvial aquifer) were bound from beneath and on most sides by low permeability Muddy Creek Formation, precluding significant upward movement of groundwater from the carbonate-rock aquifer into the overlying alluvium (consistent with known good water quality in the alluvial aquifer, better than in Muddy Creek Formation). Consequently, Maxey et al. (1966), in contrast to Eakin (1964), concluded that two washes in the northwest part of the basin (i.e., Arrow Canyon and a north-trending wash) were the primary sources of water in the alluvial aquifer of the MRSA, the bulk of inflows occurring during storm events. Some 30 years later (based on this limited review of the literature), Dettinger et al. (1995) was the first to acknowledge the potential for significant upward leakage from the regional carbonate-rock aquifer into local alluvial aquifers, generally. In 2014, the Nevada State Engineer (NSE 2014a-f) similarly concluded that "the alluvial aquifer surrounding the Muddy River ultimately derives virtually all of its water supply from the carbonates, either through spring discharge that infiltrates into the alluvium or through subsurface hydraulic connectivity between the carbonate rocks and the alluvium"; this presumably based on the occurrence of minimal precipitation recharge in the combined MRSA, Coyote Spring Valley, and California Wash area, any amount of which is significantly exceeded by local groundwater evapotranspiration (SNWA 2009a, Table I-7).

Since the release of the Eakin (1964) report, four (surficial) geologic maps have been constructed covering the MRSA: Longwell et al. 1965 (1:250,000), Stewart and Carlson 1978 (1:500,000), Page et al. 2005 (1:250,000), and Crafford 2007 (1:250,000). All show that alluvium is in lateral contact with outcrop of Permian to upper Mississippian Bird Spring Formation (typically

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[4] Note: The Cardy Lamb Springs were the only major spring group or spring tributary not included in Beck and Wilson's 2006 seepage study.

[5] Of the approximate 15 river miles between the Moapa gage in the MRSA and Anderson Wash in Lower Moapa Valley, the Muddy River was losing for 3 miles across the Moapa Indian Reservation and a one mile reach one to two miles below the Glendale gate during the February 2001 seepage run (Beck and Wilson 2006).

[6] Precipitation recharge in the MRSA is an estimated 41 afy (SNWA 2009a).

associated with the "upper" carbonate-rock aquifer) at the land surface about one mile west of the river[7]. However, given the depth to water in the basin's alluvial wells (10 to 25 feet minimum, NDWR 2018a), all located in "channel alluvium" near the center of the basin (Page et al. 2005) and roughly aligned with the Muddy River, the water table may be located in Muddy Creek Formation, rather than alluvium, at the contact with Bird Spring Formation carbonates[8].

What is clear is that groundwater level data collected over the last two decades (NDWR 2018a) show that water levels in alluvial and carbonate monitoring wells in the MRSA respond more or less in sync to significant increases / decreases in carbonate pumping in an area that includes, but is not limited to, the MRSA: i.e., the four-fold increase in pumping at the Arrow Canyon wells in the MRSA in May 1988; the start of pumping by Coyote Spring Investments (CSI) in Coyote Spring Valley in May 2005; and start and stop of pumping at MX-5 by the Southern Nevada Water Authority (SNWA) in southern Coyote Spring Valley for the Order 1169 pumping test in September 2010 and April 2013, respectively. Whereas groundwater level fluctuations due to local alluvial pumping dominate water levels in the alluvial wells, as expected, responses to the major changes in carbonate pumping listed above are also discernable in nearly all of the basin's alluvial wells based on simple inspection of water level hydrographs (e.g., Lewis 1 Old, Lewis 2, Lewis North, Lewis South, LDS West, Perkins Old, Behmer MW, and Abbott); although carbonate pumping signals are more clear where alluvial pumping signals are less pronounced in Lewis North, Perkins Old, Behmer Monitoring, and Abbott (Figure 2). Water levels in carbonate wells (i.e., EH-5b and EH-4[9],[10]) are also tens to more than 100 feet (ft) higher than in alluvial wells in the MRSA (NDWR 2018a). Given the existence of a clear hydraulic connection between the carbonate-rock and basin-fill aquifers in the MRSA (their roughly synchronized response to carbonate pumping), and higher hydraulic head in the underlying carbonate aquifer, leakage (whether at contacts between Bird Spring Formation carbonates and saturated alluvium, upward through the Muddy Creek Formation, or by way of fault damage zones) must occur from the carbonates into the alluvial aquifer in some volume within the basin.

Available geologic maps (Longwell et al. 1965, Tschanz and Pampeyan 1970, Stewart and Carlson 1978, Page et al. 2005, and Crafford 2007) show that in western MRSA, as well as elsewhere in the vicinity of the Order 1169 study area, Permian Bird Spring Formation carbonates are in contact with Mississippian to Cambrian carbonate rocks composing the

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[7] Page et al. 2005 depicts considerably more Muddy Creek Formation in eastern MRSA than the other three geologic maps (at the land surface), but still interprets that alluvium and Bird Spring Formation carbonates are juxtaposed from the area of Lewis South well or Cardy Lamb Springs south about 1.5 miles to Battleship Wash.

[8] The Muddy Creek Formation has been variously mapped in eastern MRSA (Longwell et al. 1965, Stewart and Carlson 1978, Page et al. 2005, and Crafford 2007). No consensus exists regarding its surficial expression, but a significant amount of Muddy Creek Formation has been mapped by all investigators in western MRSA.

[9] Both EH-5b and EH-5 appear to be completed in Bird Spring Formation carbonates based on their depths of completion (NDWR 2018a) and geologic cross-section D of Page et al. 2006.

[10] Water levels in carbonate monitoring wells EH-5b and EH-4, which vary only a fraction of a foot across the MRSA (~1,813 feet amsl), have been historically more than 10, and as much as about 110 feet higher, than water levels in alluvial monitoring wells from northwest to southeast across the basin (NDWR 2018a).

regional ("lower") carbonate-rock aquifer (cross-sections C – F, Page et al. 2006, 1:250,000). Moreover, there is limited to no evidence of confining units (common elsewhere in the carbonate-rock province of Nevada and western Utah) in the study area.

Specifically, in the study area west of the Meadow Valley Wash Fault and Muddy Mountain thrust, no outcrop of Mississippian Scotty Wash Quartzite or Cambrian Dunberberg or Pioche shale has been mapped (Page et al. 2005 and Crafford 2007). Only outcrop of strata that may contain Chainman Shale (Mississippian), Pilot Shale (Mississippian to Devonian), Eureka Quartzite (Ordovician), and undifferentiated Ely Spring Dolomite, Eureka Quartzite, and / or Pogonip Group (Ordovician) (Crafford 2007) have been identified, and then only in the Arrow Canyon Range and south part of the Meadow Valley Mountains in the area of Arrow Canyon in the MRSA. The geologic maps of Crafford (2007) and Page et al. (2005) are inconsistent with respect to mapping of Eureka Quartzite (or strata that may include it), but the presence of Eureka Quartzite, a potential confining unit, is possible in the vicinity of Arrow Canyon. Nonetheless, southeasterly groundwater flow is known to occur in the carbonates through Arrow Canyon from central Coyote Spring Valley into the MRSA based on trends in measured groundwater levels (NDWR 2018a)[11]. Given the depths of completion of the carbonate wells involved (NDWR 2018a) and information contained in geologic cross-section D of Page et al. 2006 (passing through the area of the wells), southeasterly flow appears to pass through any Eureka Quartzite that is present unimpeded[12]. Eureka Quartzite is either absent through Arrow Canyon (i.e., between the Arrow Canyon Range and Meadow Valley Mountains) or not sufficiently continuous in the regional carbonates to be an impediment to flow. If based only on geologic considerations, the lack of significant confining units in the MRSA, as well as the remainder of the Order 1169 study area, suggests that the Paleozoic carbonates, Permian through Cambrian, function as one aquifer. As such, a hydraulic connection between the alluvial aquifer of the MRSA (or other basins within the study area) and any of the Paleozoic carbonates is a hydraulic connection with the regional carbonate aquifer as a whole. In particular, the portion of the regional carbonate aquifer underlying the MRSA is in hydraulic connection with the basin's alluvial aquifer and a source of water in alluvium adjacent to the river, notwithstanding that the exact nature of the connection between the alluvial and carbonate aquifers is unknown.

Alluvial inflow from Lower Meadow Valley Wash (LMVW) also appears to be a source of water in the alluvial aquifer of the MRSA based on the continuity of alluvium between the two basins ("QTs" in Figure 3, interpreted from Crafford 2007) and trends in alluvial groundwater levels (Heilweil and Brooks 2011, SNWA 2012, and NDWR 2018a) which decrease in a southerly direction through LMVW and into the MRSA. Although limited as evidence goes, carbonate

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[11] Measured water levels decrease gradually in a southeasterly direction from carbonate monitoring wells MX-4, CVS-RW2, and CSVM-1 in southern Coyote Spring Valley, to UMVM-1, MX-6, EH-5b, and finally EH-4 in the MRSA (NDWR 2018a).

[12] Due to the truncation of south-trending folds and vertical offsets at one or more north-striking faults (seen in cross-section "D", Page et al. 2006), southeasterly flow from MX-4, CSV-RW2, and CSVM-1 in southern Coyote Spring Valley (likely completed in Devonian to Silurian carbonates) to UMVM-1 (likely completed in Cambrian carbonates), and then on to MX-6 (likely completed in Devonian to Silurian carbonates), of necessity involves flow through the Ordovician Pogonip Group mapped in outcrop (Crafford 2007, Page et al. 2005), including any Eureka Quartzite.

pumping signals, identifiable in all other alluvial wells in the MRSA, appear to be "swamped out" in LDS Central and LDS East by alluvial inflows from LMVW (based on simple inspection of the hydrographs); the two wells located immediately downgradient of the alluvial channel connecting LMVW and the MRSA, most clearly depicted in Crafford (2007) and Stewart and Carlson (1978). Less clear is the continuity of (saturated) alluvium between the MRSA and Coyote Spring Valley where shallow groundwater flow may be impeded at the mouth of Arrow Canyon by outcrop of Muddy Creek Formation (shown in all available geologic maps).

Notwithstanding the above, the extent to which groundwater in the alluvial aquifer of the MRSA is derived from the alluvial aquifers of LMVW and possibly Coyote Spring Valley versus the underlying regional carbonate-rock aquifer cannot be determined using available groundwater level data, or water budget estimates prepared at the scale of whole basins wherein no distinction is made between carbonate, alluvial, and surface flows.

Sources of Water in Alluvial Aquifers Adjacent to the River – California Wash

No or minimal precipitation recharge is believed to occur in California Wash, any amount of which is significantly exceeded by local groundwater evapotranspiration (SNWA 2009a, Table I-7). As such, the source of water in alluvium adjacent to the river in California Wash, including that documented seeping into the river during the February 2001 seepage study (a net gain of 2.0 cfs or 1,448 acre-feet per year, Beck and Wilson 2006), can only be alluvial inflows from adjacent basins, local leakage from the carbonate-rock aquifer, or both.

California Wash is bordered by four basins: Coyote Spring Valley, Garnet Valley, the MRSA, and LMVW. Alluvial inflow from Coyote Spring Valley is precluded by carbonate outcrop (Page et al. 2005 and Crafford 2007). Available water level measurements (SNWA 2012, and Heilweil and Brooks 2011) are insufficient to determine if alluvial inflow occurs from eastern Garnet Valley (the area of a dry playa) into California Wash. However, the continuity of mapped "alluvium" (Page et al. 2005 and Crafford 2007) and trends in alluvial groundwater levels (Heilweil and Brooks 2011, SNWA 2012, and NDWR 2018a) suggest that alluvial inflow does occur from both LMVW and the MRSA into California Wash, proximal to the river. In fact, two-thirds of total gains documented to the river in California Wash during the February 2001 seepage run (Beck and Wilson 2006), 3.10 of 4.70 cfs, occurred in a reach of the Muddy River intersected by the axis of LMVW.

The regional carbonate-rock aquifer is also a local source of water to the alluvial aquifer of California Wash. Indirect evidence of this leakage is available today in the form of basin-fill groundwater level measurements that decrease roughly 200 feet (ft) from south to north through the basin toward the river (SNWA 2012 and USGS 2019b), indicative of south to north groundwater flow through the fill. Since no net precipitation recharge is believed to occur in the basin (SNWA 2009a, Table I-7), including its southern part where basin fill water levels are at a maximum, the regional carbonate-rock aquifer must be the source of this south to north alluvial flow. While all available geologic maps (Longwell et al. 1965, Stewart and Carlson 1978, Page et al. 2005, and Crafford 2007) show that basin fill is in lateral contact with outcrop of Bird

Spring Formation carbonates at the land surface over most of western California Wash, the depth to water in the fill at the south end of the basin is about 800 ft (218 S18 E65 18CC 1 USBLM; SNWA 2012 and USGS 2019b); about 300 ft in the central part of the basin (218 S16 E65 31AA 1 and 218 S16 E65 32AB 1, SNWA 2012; and 218 S16 E65 33ACAA1 USBLM, USGS 2019b); and 10 ft or less in alluvium adjacent to the river in the northernmost part of the basin (218 S14 E65 36BADA1, 218 S15 E66 06 1, 218 S15 E66 09BADB1, and 218 S15 E66 04AA 1, USGS 2019b; and 218 S15 E66 02CA 1 MV-4, SNWA 2012). Any leakage that occurs from the regional carbonate-rock aquifer into basin fill, on the west side of California Wash or elsewhere in the basin, must occur at significant depths[13,14].

The regional carbonate-rock aquifer extends from south to north beneath the basin fill all the way to the Muddy River, and as far east as the Muddy Mountain thrust (cross-sections E – G, Page et al. 2006)[15]; the depth of burial of the carbonates generally increasing from south to north and at a maximum on the east side and north end of the basin, 2,000 ft or more (cross-sections E, F, G, and H, Page et al. 2006). Despite these depths of burial, this portion of the regional carbonate aquifer, like other parts of this fractured rock aquifer, is transected by a not insignificant number of normal, reverse, and strike-slip faults (Page et al. 2005, Page et al. 2006), which may provide conduit(s) for the movement of groundwater from the underlying carbonate aquifer into the alluvium and other basin fill in California Wash. Although limited, there is direct evidence of leakage from the regional carbonate-rock aquifer into overlying basin fill in the southernmost part of the basin where the depth of burial of the carbonates is at a minimum (cross-section G, Page et al. 2006). Water levels in two wells, both reportedly 860 ft deep, one completed in carbonates (218 S18 E64 25AACC1) and one in basin fill about one mile north (218 S18 E65 18CC 1 BLM), were identical at one time (i.e., 1,772 ft amsl, 1949, USGS 2019b); the two wells in apparent equilibrium, indicative of a direct hydraulic connection between the regional carbonate-rock aquifer and basin fill in southern California Wash.

Additionally, although lateral hydraulic gradients are anomalously flat in the carbonate-rock aquifer through Garnet and Hidden valleys and California Wash, and even flatter from the area of MX-5 in southern Coyote Spring Valley through the MRSA based on recent, as well as historical, groundwater level measurements[16], water levels in the regional carbonate-rock aquifer

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[13] Note: No or little outcrop of Permian redbeds, a potential confining unit between the alluvium and carbonates, has been mapped in the vicinity of the Order 1169 study area west of the Meadow Valley Wash fault and Glendale and Muddy Mountain thrusts on the east side of California Wash (Page et al. 2005).

[14] Whereas the depth to the water table is minimal in northernmost California Wash, the depth of the contact between fill and the carbonates is great in this area (Page et al. 2006, cross-section D).

[15] In California Wash, no Mississippian Chainman Shale, Scotty Wash Quartzite, or other siliciclastic rocks, which may act as a local confining unit between Permian to Mississippian carbonate rocks and Mississippian to Cambrian carbonate rocks, are present based on detailed geologic mapping by Page et al. (2005) and Crafford (2007) at locations where (less detailed) geologic cross-sections by Page et al. 2006 (D and E) indicate Mississippian siliciclastic rock outcrop should occur if present.

[16] This first observed over 20 years ago by Thomas et al. 1996 and Dettinger et al. 1995 based on groundwater level measurements collected largely in the 1960's to 1980's (as well as some older measurements). More contemporary measurements suggest a possible shift in equipotentials defining the potentiometric surface of the carbonate aquifer northward

are as much as 150 ft higher than in overlying basin fill in central California Wash and about 240 ft higher than in the alluvium close to the river (SNWA 2012, NDWR 2018a, and USGS 2019b). Given these significant differences in head, the potential exists for upward leakage from the regional carbonate-rock aquifer into overlying basin fill and / or alluvium in northern and central California Wash, if only by way of fault damage zones (in addition to direct leakage from the carbonates in the southern part of the basin).

Whereas the majority of gains documented to the Muddy River in California Wash during the February 2001 seepage study occurred in a reach intersected by the axis of LMVW (from which alluvial inflows from LMVW can safely be inferred), this same reach is also traversed by two south-southwest trending faults: a regional-scale strike-slip fault and at least one fault associated with the Glendale thrust (Page et al. 2006, cross-section D), either or both of which may provide conduit(s) for groundwater flow from the underlying carbonate-rock aquifer into the alluvium.

Notwithstanding the above, as in the MRSA, the extent to which groundwater in the alluvial aquifer of California Wash is derived from the alluvial aquifers of LMVW and the MRSA versus the underlying regional carbonate-rock aquifer cannot be determined using currently available groundwater level data, or water budget estimates prepared at the scale of whole basins wherein no distinction is made between carbonate, alluvial, and surface flows.

Summary – Sources of the Muddy River Springs and Muddy River

The source of the Muddy River Springs is the regional carbonate-rock aquifer, which in this area includes some Permian to upper Mississippian carbonate rocks of the Bird Spring Formation. Immediate sources of water in the Muddy River, from its headwaters in the MRSA through California Wash to uppermost Lower Moapa Valley, are the Muddy River Springs (surface discharges), seepage from alluvial aquifers adjacent to the river (in the MRSA, California Wash, and likely uppermost Lower Moapa Valley), and to a much lesser extent intermittent runoff of local precipitation. Sources of water in alluvium adjacent to the river, in turn, are: infiltration of surface discharges of the Muddy River Springs and subsurface seepage from the springs (within the MRSA); the regional carbonate-rock aquifer, specifically those portions underlying the MRSA and California Wash; and alluvial inflows from basins bordering the MRSA and California Wash (LMVW and perhaps Coyote Spring Valley). Recent estimates of precipitation recharge and groundwater evapotranspiration (SNWA 2009a, Table I-7) suggest that net recharge of precipitation to alluvium adjacent to the river in the MRSA, California Wash, or Lower Moapa Valley is unlikely. Consequently, the sources of water in the river, from the MRSA to uppermost Lower Moapa Valley, are the Muddy River Springs (derived nearly entirely from the regional carbonate-rock aquifer), leakage from the regional carbonate-rock aquifer into alluvium of the MRSA and California Wash, alluvial inflows from basins bordering the MRSA and California Wash (LMVW and maybe Coyote Spring Valley), and to a much lesser degree runoff of local precipitation.

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within Garnet, Hidden, and Coyote Spring valleys (based on an inspection of carbonate water levels compiled by NDWR 2018a and SNWA 2012 by this author).

1.1.2 *Basins Known to Act as One Basin as of Today*

DOI 2013 interpreted changes in groundwater levels and pumping rates documented during and prior to the two-year Order 1169 pumping test (NSE 2002 and NSE 2014a-f) using SeriesSEE (Halford et al. 2012) with the goal of characterizing the extent of drawdown created by test pumping in carbonate well MX-5 in southern Coyote Spring Valley within the regional carbonate-rock aquifer, as well as other geologic / hydrogeologic units, in the overall Order 1169 study area; a basic question that yielded surprising results.

SeriesSEE Analysis

SeriesSEE is a U.S. Geological Survey Microsoft® Excel add-in (Halford et al. 2012) curve-fitting tool that "models" changes in the level of water in a well by jointly optimizing analytical approximations of the effects of various stresses judged to be contributing to changes in water level. The authors have described the purpose of SeriesSEE curve-fitting a number of ways (Halford et al. 2012 and Garcia et al. 2013), including "analytically simulating all pumping and non-pumping water-level stresses simultaneously with the aim of differentiating pumping signals from changes in groundwater levels due to "environmental" stresses (e.g., long-term trends in area groundwater levels, barometric pressure fluctuations, tides, earth tides, groundwater recharge, or changes in the stage of connected surface-water bodies). More generally, SeriesSEE curve-fitting can be used to differentiate (isolate) the effects of individual pumping and / or non-pumping (environmental) stresses on the level of water in a well. In DOI (2013), SeriesSEE curve fitting was used to differentiate the effects of ongoing water supply pumping from that induced by the MX-5 test pumping during the Order 1169 pumping test in monitoring wells located across the study area.

Put another way, curve-fitting using SeriesSEE begins with the premise that changes in water level in a well are generally due to a combination of stresses, pumping and / or non-pumping, each of which can be approximated by an analytical expression that is a function of independent input (e.g., the rate of pumping in a nearby well or measurements of barometric pressure) and coefficients that are "fitted" to the expression during an optimization process. In the case of pumping, the analytical expression takes the form of a "Theis transform" (the Theis solution used as a transfer function), which is then used to transform recorded rates of pumping (approximated stepwise for efficiency) into "simulated" drawdown; the Theis solution (Theis 1935) serving only to approximate the nature of the relationship between pumping and the creation of drawdown during the curve fitting process. The parameters of "Theis transforms", as applied in SeriesSEE analysis, are neither intended to represent or serve as estimates of aquifer parameters, but merely as empirical fitting coefficients with the aim of isolating changes in groundwater level due to pumping. Firstly, because the underlying assumptions of the Theis solution are rarely (if ever) met (Garcia et al. 2013); but more important because the coefficients are not intended to be "predictive", but rather facilitate *a posteriori* identification of pumping effects during curve fitting.

Having assembled a collection of analytical expressions (a "water level model") judged to adequately approximate the effects of potential pumping and non-pumping (environmental) stresses on the level of water in a well, the coefficients of the analytical expressions are jointly optimized using singular value decomposition and Tikhonov regularization to minimize a sum-of-squared residuals objective function, where the residuals are calculated as the difference between observed changes in water level and those approximated (simulated) using the SeriesSEE water level model (Halford et al. 2012). Once the "water level model" as a whole has been optimized (the residuals judged to be sufficiently minimized), its component analytical expressions are likewise presumed to be reasonably optimized inasmuch as taken together they reproduce measured water levels with minimal residuals.

That SeriesSEE serves well in this capacity, despite the use of transfer functions in the form of the Theis solution, even in highly heterogeneous (and anisotropic) aquifers, is supported by examples provided by Garcia et al. (2013), as well as the results of the DOI (2013) application of SeriesSEE to the interpretation of the Order 1169 pumping test in which measured changes in water levels in a large number of monitoring wells known to be completed in the regional carbonate-rock aquifer were successfully reproduced across the study area. One of many possible examples is presented in Figure 4, which shows good agreement between measured water level changes in carbonate monitoring well EH-4 in the MRSA prior to and during the pumping test and those approximated using SeriesSEE (the latter exceeding the goodness of numerical model simulations to date).

Test Data Analyzed

Prior to and during the two-year Order 1169 test, pumping occurred in 31 major wells within the study area (a minor correction from DOI 2013): carbonate test well MX-5 in southern Coyote Spring Valley, introduced specifically for the test; and 30 additional wells (carbonate and alluvial) for ongoing water supply, primarily in Coyote Spring Valley, the MRSA, Garnet Valley, and Black Mountains Area. SeriesSEE curve-fitting was employed to differentiate (isolate) drawdown created by the 31 pumped wells aggregated into 13 "pumping centers" (based on the proximity of many of the water supply wells to each other[17]).

SeriesSEE curve-fitting was performed to water level records for 14 monitoring wells across the Order 1169 study area:

- (8) wells judged *a prori* to be completed in the regional carbonate-rock aquifer based on geologic mapping (Page et al. 2005, Page et al. 2006, and Crafford 2007) and groundwater level trends during and prior to the test (NDWR 2018a): CSVM-4, CSVM-6, and CSVM-2 in Coyote Spring Valley (as well as CE-VF-2 in Coyote Spring Valley,

[17] For the purposes of the curve-fitting analysis, the effects of pumping at 31 production wells were "simulated" at the following wells and "pumping centers": "CSI-12" (CSI-1 and CSI-2), CSI-3, CSI-4, and MX-5 in Coyote Spring Valley; MX-6, "ArrowCanyon1+2" (Arrow Canyon wells 1 and 2), "Lewis+LdsW" (the Lewis wells and LDS West), "LdsCE" (LDS Central and LDS East), and "Beh+Perk" (Behmer and Perkins Production wells) in the MRSA; and "GV_M1+PW" (GV-Migrant1 and GV-PW-WS-1), GV-RW-1, "Apex" (Republic Wells 1, 2, 5, and 6, Chem Lime Old and New, and GV_Duke-WS-1 and GV_Duke-WS-2), and "NV_Cogen" (NV Cogen EGV-3 and NV Cogen EBP-2) in Garnet Valley.

later discarded since breached in November 2011 during the test); GV-1 and M-2 in Garnet Valley; M-1 in California Wash; and EH-4 and CSV-2 in the MRSA;

- (2) wells judged *a priori* to be completed in carbonate rocks isolated from the regional carbonate-rock aquifer based on geologic mapping and groundwater level trends during and prior to the test: Byron-1 in eastern California Wash and EH-7 in Lower Moapa Valley;
- (2) wells judged *a priori* to be completed in carbonate rocks isolated from the regional carbonate-rock aquifer based only on groundwater level trends during and prior to the test (NDWR 2018a): CSVM-3 and CSVM-5 in Coyote Spring Valley;
- (1) well completed in siliciclastic rocks outside the mapped extent of the regional carbonate-rock aquifer (Page et al. 2005, and Crafford 2007): BM-ONCO-1 in the Black Mountains Area; and
- (1) well completed in basin fill: MW-1A in LMVW about 18 miles north of the Muddy River.

Because changes in groundwater levels during the test (September 2010 to December 2012, the official end of the test) were in part due to pumping that preceded the test, the curve fitting was performed from January 2008 to December 2012, beginning 21 months prior to the test.

Given that the purpose of the curve-fitting was to isolate (approximate) drawdown induced by the MX-5 test pumping apart from the effects of ongoing water supply pumping, the relatively minor effects of earth tides, changes in barometric pressure, and long-term trends in area groundwater levels were not accounted for during the analysis. Additionally, no-flow boundaries cannot be "simulated" (accounted for) during SeriesSEE curve fitting; SeriesSEE not a distributed groundwater flow model. Consequently, although a number of no-flow boundaries are known or likely to exist in the vicinity of the portion of the regional carbonate-rock aquifer stressed during the test[18], they were not accounted for during the estimation of MX-5 induced drawdowns. Despite this, or particularly because of this, MX-5 induced drawdowns were, if anything, underestimated by the 2013 analysis (due to the compounding effects of no-flow boundaries on pumping-induced drawdowns). Had it been possible to account for the effects of no-flow boundaries during the 2013 analysis, estimates of MX-5 induced drawdowns would likely have been no less (roughly) uniform than presented in DOI 2013; carbonate monitoring well EH-4 was the only location at which MX-5 induced drawdown may have been underestimated (originally an estimated 1.2 ft[19]).

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[18] No-flow boundaries identified and discussed in detail in Section 1.3.1.

[19] Carbonate monitoring well EH-4 may be located just upgradient of one or more unmapped west-dipping normal faults of the East Arrow Canyon Range fault zone (Page et al. 2006); fault gouge in the footwall of the fault(s) forcing groundwater flowing southeast through the regional carbonate-rock aquifer to the surface in the form of springs, while damaged zones (zone of enhanced fracturing) on the hanging wall sides of the faults act as conduits for spring discharge. These same gouge zones may have compounded MX-5 induced drawdown in EH-4 during the Order 1169 pumping test beyond that isolated using SeriesSEE.

Findings and Limitations

The DOI 2013 SeriesSEE estimates of MX-5 induced drawdown as of December 2012, the official end of the test, are shown in Figure 5 (as reported in 2013 with the exception of CE-VF-2).

Several of the analyzed water level records (i.e., locations) were chosen because the wells were anticipated, based on geologic considerations and trends in measured groundwater levels, to be completed in carbonates or other geologic / hydrogeologic units located outside the area in which groundwater levels are responsive to carbonate pumping in southern Coyote Spring Valley; confirmed by the results of these analyses. Specifically, no MX-5 induced drawdown could be isolated in the water level records for carbonate wells EH-7 or Byron-1, or clastic well BM-ONCO-1; suggesting that locations east of faults and offsets associated with the Glendale and Muddy Mountain thrusts in Lower Moapa Valley and California Wash, and east of the Muddy Mountain thrust and south of the northern strand of the Las Vegas Shear Zone in the Black Mountains Area, are outside the area responsive to carbonate pumping in Coyote Spring Valley[20]. Likewise, no MX-5 induced drawdown could be isolated in the water level record for carbonate well CSVM-5 in Coyote Spring Valley, located just upgradient of an overturned anticline, one of a series, on the east side of the northern part of the Las Vegas Range (Page et al. 2005), which appears to act as a local barrier to flow and the propagation of drawdown in southern Coyote Spring Valley[21]. SeriesSEE estimates of MX-5 induced drawdown in carbonate monitoring wells CSVM-3 and CSVM-4 in northern Coyote Spring Valley are discussed in Section 1.1.3.

To the west, north, and east of the above no-flow boundaries, the test pumping clearly resulted in the development of a drawdown cone in the regional carbonate-rock aquifer (as shown in distance drawdown hydrographs presented in DOI 2013, Figures 1.11 and 1.12). Nevertheless, a remarkably uniform 1.5 to 1.6 ft of drawdown was induced by the MX-5 pumping during the Order 1169 test across multiple basins in the regional carbonate aquifer, irrespective of distance from MX-5: in CSVM-6, three miles north in Coyote Spring Valley; CSVM-2, nine miles south in Coyote Spring Valley; GV-1, twenty-seven miles south in Garnet Valley; M-1, fifteen miles southeast in California Wash; and CSV-2, nine miles east in the MRSA. This can only occur if the field-scale transmissivity of the regional carbonate aquifer is exceptionally high in an area that at a minimum includes the above wells[22, 23]. Moreover, there is no evidence that wells

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[20] This result also consistent with the known areal extent of the regional carbonates (Page et al. 2005, Page et al. 2006, and Crafford 2007). Note, the northern strand of the Las Vegas Shear Zone and Muddy Mountain thrust also delineate the extent of the regional carbonates in the Black Mountains Area; limited to the northwest part of the basin.

[21] CSVM-5 is also located at the mouth of a drainage that may be contributing to steadily rising water levels observed in the well since 2003.

[22] This conclusion consistent with anomalously flat hydraulic gradients long observed in this portion of the aquifer Thomas et al. (1996) and Dettinger et al. (1995) and the lack of mapped confining units noted earlier.

[23] Although exceptionally high based on the response to the MX-5 test pumping, the field-scale transmissivity of this portion of the regional carbonate-rock aquifer cannot, and consequently was not, estimated as part of this SeriesSEE analysis. To date, estimates of the transmissivity of this portion of the carbonate-rock aquifer are limited to model-calibrated values (SNWA 2009b,

CSVM-6, CSVM-2, GV-1, M-1, and / or CSV-2 are located in or connected by a few high permeability structures within the carbonates (Page et al. 2005 and Crafford 2007). This pattern of near uniform drawdown in response to the test pumping, and the high transmissivity inferred by it, must be the result of permeable secondary structures that are pervasive throughout this portion of the carbonate aquifer.

This is not to say that local low transmissivity zones and structures are not present within the regional carbonate aquifer. The estimation of relatively low transmissivities based on the interpretation of small-scale pumping tests at carbonate well CE-VF-2 in Coyote Spring Valley (3,100 ft^2/d, USGS 2019a), carbonate well CSV-2 in the MRSA (1,000 ft^2/d, USGS 2019a), and reportedly carbonate production well CSI-3 (also Coyote Spring Valley), are good examples. Lesser amounts of MX-5 induced drawdown in carbonate monitoring well M-2 (western California Wash), 1.1 ft (Figure 5), is likely another example of the effects of local low transmissivity zones within the regional carbonate aquifer, in this case at the scale of the screened or gravel-packed interval of the well. Despite the inevitable presence of localized low permeability zones and structures within this fracture-rock aquifer, the response to the MX-5 test pumping could not have occurred if not for exceptionally high field-scale transmissivity in the portion of the aquifer which includes CSVM-6, CSVM-2, GV-1, M-1, and CSV-2.

What is more, considering that the drawdown cone created by the MX-5 test pumping was as “flat” as it was, but nonetheless a drawdown “cone”, drawdown created by the test pumping must have extended some distance east of M-1 and CSV-2, south of GV-1, and west of CSVM-6, CSVM-2, and GV-1 in the regional carbonate-rock aquifer; at least to nearby no-flow boundaries (given that drawdown generally decreases logarithmically with distance). Those no-flow boundaries include[24]:

- the Muddy Mountain thrust on the east side of California Wash;
- Muddy Mountain thrust on the east side of northernmost Black Mountains Area;
- northern strand of the Las Vegas Shear Zone within northeastern Las Vegas Valley and northern Black Mountains Area;
- Gass Peak thrust from the northern strand of the Las Vegas Shear Zone through northeast Las Vegas Valley, along the western boundary of Garnet and Hidden valleys, and along the southernmost portion of the western boundary of Coyote Spring Valley;
- a series of anticlines on the east side of the northern part of the Las Vegas Range in southern Coyote Spring Valley, particularly where overturned (vicinity of CSVM-5); and

Tetra Tech 2012, and Brooks et al. 2014) which vary considerably from model to model, but are anomalously high based on the calibration of all models to present (e.g., up to 1,000,000 ft^2/day per SNWA 2009b).

[24] Known and likely no-flow boundaries identified based on geologic considerations; confirmed by differences in groundwater levels where available (see Section 1.3.1).

- Gass Peak thrust through the northern half of Coyote Spring Valley (beyond the series of anticlines in the northern part of the Las Vegas Range) to the Pahranagat Shear Zone or, if not, the groundwater divide along the crest of the Sheep Range.

Based on the 2013 interpretation of the Order 1169 pumping test, the following “five-plus” basins (or parts of basins) are known to be underlain by a portion of the regional carbonate-rock aquifer possessing exceptionally high field-scale transmissivity (DOI 2013 and NSE 2014a-f):

- the MRSA;
- most of Coyote Spring Valley;
- Hidden Valley;
- Garnet Valley;
- most of California Wash; and
- northwest Black Mountains Area.

The latter encompasses an area of about 1,050 square miles, as much as 24 miles from west to east and 60 miles from north to south; most of which is underlain by the full or nearly full sequence of Paleozoic carbonates (Page et al. 2006, cross-sections B through G).

In conclusion, inasmuch as the alluvial aquifers of the MRSA and California Wash have been demonstrated to be in hydraulic connection with this portion of the carbonate-rock aquifer (Section 1.1.1), and a similar connection likely exists in Coyote Spring Valley and possibly in Garnet Valley[25], and the basin-fill aquifers in some of the above basins are themselves connected: the alluvial aquifers of the “five-plus” basins listed above, as well as the underlying carbonate-rock aquifer, function for all practical purposes as one groundwater basin that is connected to and the source of the Muddy River Springs and Muddy River. The alluvial and carbonate aquifers of this collection of basins are currently known as the Lower White River Flow System (LWRFS).

1.1.3 *Kane Springs Valley and Lower Meadow Valley Wash as Likely Parts of the LWRFS*

Kane Springs Valley and LMVW are not currently recognized as part of the Lower White River Flow System (LWRFS) based on the results or lack thereof of the Order 1169 pumping test. Kane Springs Valley was excluded from the pumping study in 2007 (NSE 2007) prior to the 2010 to 2012 test. Groundwater level monitoring was conducted in LMVW as part of the test, but limited to basin-fill wells MW-1a, b, and c. No carbonate wells were monitored in either basin as part of the Order 1169 test.

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[25] Based on the roughly synchronized response of water levels in basin-fill monitoring well CE-VF-1 and carbonate monitoring well CE-VF-2 to significant increases / decreases in carbonate pumping (prior to November 2011 when CE-VF-2 was breached, NDWR 2018a), a hydraulic connection likely exists between the alluvial aquifer of Coyote Spring Valley and the underlying carbonate aquifer. Basin-fill groundwater level data (NDWR 2018a and SNWA 2012) are insufficient to determine if a similar hydraulic connection exists in Garnet Valley.

Kane Springs Valley

Kane Springs Valley was excluded from the Order 1169 pumping test following a February 2007 finding that a low permeability structure or change in lithology likely exists between Kane Springs Valley and central Coyote Spring Valley[26] which should allow for limited pumping in Kane Springs Valley without "any measurable impact on the Muddy River Springs" (NSE 2007). The 2007 finding was based on an interpretation of groundwater levels at two generalized locations within the carbonate aquifer between which water levels drop about 50 to 75 ft. However, upon reexamination of carbonate water level measurements available as of the time of the finding (late 2006), the data suggest a different set of conclusions or at least a high degree of uncertainty.

The 2007 Finding

The 2007 finding (NSE 2007) was based on an interpretation of groundwater levels at two generalized locations within the carbonate aquifer: "near" the boundary between Kane Springs Valley and Coyote Spring Valley (water level approximately 1,875 ft in elevation) and an unspecified location (or locations) further south in Coyote Spring Valley and / or other basins of the Order 1169 study area (water levels about 1,800 to 1,825 ft in elevation).

As of late 2006, carbonate water level measurements were available in two monitoring wells "near" the boundary between Kane Springs Valley and Coyote Spring Valley: KMW-1 in southern Kane Springs Valley located about 1,000 ft from the boundary with Coyote Spring Valley, water level 1,880 to 1,881 ft above mean sea level (amsl)[27]; and CSVM-4 in northern Coyote Spring Valley, water level 1,875 ft amsl (NDWR 2018a). During this same period, carbonate water levels in the range of 1,800 to 1,825 ft amsl were first encountered in central Coyote Spring Valley (the most northerly location with carbonate water levels in this range); specifically, the area of CSVM-6 (1,819 ft amsl), MX-4 (1,821.5 ft amsl), MX-5 (1,822 ft amsl), and CSVM-1 (1,821.5 ft amsl) (NDWR 2018a).

Separated by a distance of roughly two miles, the hydraulic gradient between KMW-1 in southern Kane Springs Valley and CSVM-4 in northern Coyote Spring Valley was about 2.75 ft/mile, while the gradient between CSVM-4 and CSVM-6 in Coyote Spring Valley (distance approximately 11 miles) was about 5.1 ft/mile; both gradients considerably steeper than at more southerly locations in the Order 1169 study area where the transmissivity of the carbonate aquifer has been determined to be exceptionally high (Section 1.1.2). Steeper gradients in the area of CSVM-4 to CSVM-6, and KMW-1 to CSVM-4, could be due to significant changes in lithology within the carbonate sequence (e.g., confining units) or discrete low permeability structures (fault gouge) as suggested in 2007; or alternatively, simply a relative scarcity of the

[26] Described in NSE 2007 as southern Coyote Spring Valley, but presumably in reference to the vicinity of CSVM-6, MX-5 and CSVM-1 in central Coyote Spring Valley where carbonate water levels drop to 1,819 to about 1,821.5 in elevation (late 2006), or more recently (2017) 1,817.4 to about 1,819.7 ft in elevation (NDWR 2018a).

[27] Estimated from monitoring data collected beginning in early 2007 (NDWR 2018c).

types and numbers of permeable secondary structures giving rise to exceptionally high transmissivity in the carbonate aquifer to the south and east.

Eureka Quartzite, Pilot Shale, strata that may contain Chainman Shale, and undifferentiated Ely Spring Dolomite, Eureka Quartzite, and / or Pogonip Group have been mapped in carbonate outcrop in the Arrow Canyon Range and Meadow Valley Mountains (Crafford 2007). Likewise, two faults are mapped between KMW-1 and central Coyote Spring Valley (the area of CSVM-6, MX-4, MX-5, and CSVM-1): the Kane Springs Wash Fault near the boundary of Kane Springs and Coyote Spring valleys, and a north-northwest striking normal fault located just east of CSVM-6, MX-4, MX-5, and CSVM-1 (Figure 6). Nonetheless, prior to the 2007 finding, water level trends in CSVM-4 mirrored those in the central Coyote Spring Valley wells, and trends in KMW-1 mirrored those in CSVM-4; the similarity of carbonate water level responses continuing post-2007 through the Order 1169 pumping test (Figures 7, 8a and 8b). Based on the continuity of water level responses across this portion of the carbonate aquifer, any changes in lithology or discrete low permeability structures present in the carbonate aquifer between KMW-1 and central Coyote Spring Valley are not sufficiently impermeable to preclude or significantly minimize the impacts of carbonate pumping in KPW-1 (or KMW-1) on carbonate water levels in Coyote Spring Valley (or the other basins currently recognized as the LWRFS), consequently the Muddy River Springs or Muddy River.

Moreover, to the extent that the completion of KMW-1 (the only carbonate well in Kane Springs Valley) relative to the Kane Spring Wash Fault is unclear, broad conclusions should not be drawn concerning the effects of pumping in Kane Springs Valley based on water level responses, or the response to pumping, in KMW-1 alone. Well KMW-1 is located about 150 to 200 ft northwest of the mapped location of the Kane Springs Wash Fault (Page et al. 2005), but is completed from 955 to 2,013 ft bgs (NDWR 2018b) in an area where the dip of the fault is unknown[28].

Beyond the 2007 Finding

What is known with certainty is that the carbonate aquifer (the full or nearly full sequence of Paleozoic carbonates) extends north to south through Coyote Spring Valley from the Pahranagat Shear Zone to Hidden Valley (and beyond), and west to east from the Gass Peak thrust (if not the crest of the Sheep Range) into LMVW, the MRSA, and California Wash (SNWA 2009b, hydrogeologic framework model; and cross-section B, C, D, and F, Page et al. 2006); and that large amounts of groundwater flow into the north end of Coyote Spring Valley through the carbonates at the Pahranagat Shear Zone (Eakin 1964, Dettinger et al. 1995, and SNWA 2009a), the majority likely between the Gass Peak thrust and a north-striking normal fault that passes through the areas of CE-VF-2 and CSVM-3[29] (Figure 6). Additionally, much of the groundwater

[28] Well KMW-1 located intermediate between cross-sections B and C, Page et al. 2006.

[29] The full sequence of Paleozoic carbonate units preserved over this section of northernmost Coyote Spring Valley, but not east of the north-striking normal fault passing near CE-VF-2 and CSVM-3 and not west of the Gass Peak thrust (cross-section B, Page et al. 2006).

flowing into northern Coyote Springs Valley at the Pahranagat Shear Zone is known to discharge at the Muddy River Springs (Eakin 1964 and Dettinger et al. 1995). Consequently, large volumes of groundwater must flow through the carbonate aquifer across the Kane Springs Wash Fault from northern into central Coyote Spring Valley (before flowing into the MRSA). The Kane Springs Wash Fault must be permeable over much of central Coyote Spring Valley.

What is also known with reasonable certainty is that the full or nearly full sequence of Paleozoic carbonates is continuous on the southeast / east side of the Kane Springs Wash Fault from south of the caldera complex in Kane Springs and northern Coyote Spring valleys (an area corresponding to about forty percent of the way up Kane Springs Valley) into central Coyote Spring Valley (SNWA 2009b, hydrogeologic framework model; and cross-sections B, C, and D, Page et al. 2006). It follows, if based only on geologic continuity, that pumping in the carbonate aquifer on the southeast side of the Kane Springs Wash Fault in Kane Springs Valley can be expected to impact water levels in the carbonate aquifer on the east side of the fault in central Coyote Spring Valley (e.g., the area of production wells CSI-3, CSI-2, CSI-1, RW-2, and MX-5), and other basins currently recognized as the LWRFS, consequently the Muddy River Springs and Muddy River. The similarity of water level trends in CSVM-6 and CSVM-4 is evidence of the hydraulic continuity of the carbonate aquifer from central to northern Coyote Spring Valley on the east side of the Kane Springs Wash Fault (Figure 7) [30]. Confirmation of the hydraulic continuity of the carbonates on the southeast side of the fault in Kane Springs Valley will depend on the installation of additional monitoring wells.

What is not known are the potential impacts of pumping within a “wedge” of the carbonate aquifer located northwest of the Kane Springs Wash Fault and east of the north-striking normal fault that passes through the areas of CE-VF-2 and CSVM-3 (and south of the caldera complex); some of which is located in Kane Springs Valley and some in northernmost Coyote Spring Valley (Figure 6). What is more, this “wedge” of carbonates may be “compartmentalized” by the Delamar thrust fault (east and west of the thrust) in view of the potential for significant gouge in the reverse fault zone, which may account for the dissimilarity of water level trends in CSVM-3 versus KMW-1 and all other carbonate monitoring wells in the area (e.g., prior to and during the Order 1169 pumping test). Given that interpreting water level responses (and responses to pumping) in KMW-1 is key to resolving this and other questions, downhole geophysical surveys should be conducted in the well and interpreted, if not already available, to determine whether the well is completed on the northwest side, southeast side, or through the Kane Springs Wash Fault zone.

Proposed KMW-1 Pumping Test

Whereas a pumping test has reportedly been performed in KMW-1, the details and results of the test are not widely known or evaluated. In view of existing, but yet undeveloped, underground

[30] Additionally, while only 0.4 to 0.5 ft of MX-5 induced drawdown was estimated in CSVM-4 in northern Coyote Spring Valley during the DOI 2013 SeriesSEE analysis (substantially less than the 1.6 to 1.5 ft estimated in CSVM-6 and other carbonate wells in Garnet Valley, the MRSA, and California Wash), the fit to measured water levels in CSVM-4 during the SeriesSEE curve fitting was poor (in retrospect); that particular estimate of MX-5 induced drawdown unreliable.

water rights in Kane Springs Valley, and the interest in additional applications of significant magnitude, a long-term pumping test should be performed in carbonate monitoring well KMW-1 after determining whether the well is completed on the northwest side, southeast side, or through the Kane Springs Wash Fault zone. If KMW-1 is completed outside the fault zone and on its northwest side, the test would allow the potential impacts of carbonate pumping on the northwest side of the fault in Kane Springs Valley to be evaluated. If KMW-1 is completed outside the fault zone and on its southeast side, the test would allow the effects of carbonate pumping on the southeast side of the fault in Kane Springs Valley to be confirmed and more fully characterized. If KMW-1 is instead completed through the Kane Springs Wash Fault zone (i.e., on both sides of the fault and within the fault), then the test would provide information about both of the above, although more difficult to interpret.

If undertaken, the test should utilize at a minimum the following observation wells: carbonate monitoring wells CSVM-4, CSVM-3, CSVM-6, and if available and un-pumped CSI-4; and basin-fill monitoring wells CSV30011, CSV3009, CSVM-7, and CE-VF-1 (Figure 9). If possible, the value of the test would be significantly enhanced by installing and utilizing two additional carbonate observation wells at locations previously specified in USFWS (2006). Pending the outcome of the pumping test, that portion of Kane Springs Valley located outside the caldera complex (the plutonic core; SNWA 2009b, hydrogeologic framework model), and northwest, southeast, and / or on both sides of the Kane Springs Wash Fault zone, as applicable, should be considered for incorporation into the LWRFS for conjunctive water management.

Proposed CSVM-3 Pumping Test

Given past interests in moving existing Coyote Spring Valley underground water rights from the central to the northern part of the basin, specifically north of the Kane Springs Wash Fault and east of the north-striking normal fault that passes through the areas of CE-VF-2 and CSVM-3 (and outside the caldera complex), as well as uncertainties regarding the impacts of pumping in this "wedge" of the carbonate aquifer, a long-term pumping test should be performed in carbonate monitoring well CSVM-3[31]. The test would allow the potential impacts of carbonate pumping in this area to be evaluated prior to the approval of change applications.

If undertaken, the test should utilize at a minimum the following observation wells: carbonate monitoring wells CSVM-4, KMW-1, CSVM-6, and if available and un-pumped CSI-4; and basin-fill monitoring wells CSV30011, CSV3009, CSVM-7, and CE-VF-1 (Figure 10). If possible, the value of the test would be significantly enhanced by installing and utilizing two additional carbonate observation wells at locations previously specified in USFWS (2006).

<u>Lower Meadow Valley Wash</u>

No wells appear to be completed in the regional carbonate aquifer in LMVW (NDWR 2018a, NDWR 2018c, SNWA 2012, and USGS 2019b), although the carbonate aquifer is present beneath the southern three-quarters of the basin as far east as the Meadow Valley Wash Fault

[31] If feasible to temporarily install a pump of sufficient capacity in this 6-inch diameter well.

(SNWA 2009b, hydrogeologic framework model), including the full sequence of Paleozoic carbonates (Page et al. 2006, cross-sections A through D); and the carbonate aquifer is within 1,000 ft or less of the land surface at any number of locations.

Moreover, carbonate units in the southern third of LMVW are continuous with those in central Coyote Spring Valley[32] and the MRSA (to the west) and California Wash (to the south), with minimal vertical offsets along mostly north-striking faults[33] (cross-sections C, D, and E, Page et al. 2006); while those in Coyote Spring Valley and California Wash are continuous with carbonates (of the same age) in Hidden and Garnet valleys and the northwest part of the Black Mountains Area (Page et al. 2006, cross-sections F, G, and H). If based only on geologic continuity, the carbonate aquifer underlying LMVW should be presumed to be in hydraulic connection with the portion of the carbonate aquifer underlying central and southern Coyote Spring Valley, the MRSA, Hidden and Garnet valleys, the northwest part of the Black Mountains Area, and California Wash; basins already recognized as part of the LWRFS[34]. Likewise, "lower valley fill" in the northern quarter of LMVW, described as consolidated fill composed of conglomerates, sandstones, siltstones, ash-flow tuffs, and air-flow tuffs (SNWA 2009b), should be presumed to be in hydraulic connection with the carbonate aquifer in the southern three-quarters of the basin[35].

Additionally, the alluvial aquifer of LMVW has been demonstrated to be a source of water in alluvium adjacent to the Muddy River in California Wash (and perhaps the MRSA), making a measurable contribution to the river in California Wash during the 2001 seepage run (Section 1.1.1). Since both the alluvial and carbonate aquifers of LMVW are geologically continuous and likely in hydraulic connection with basins already recognized as part of the LWRFS, Lower Meadow Valley Wash should be considered for incorporation into the LWRFS for conjunctive water management.

1.2 Superposition of Climate and Pumping Impacts in the LWRFS

Climate versus Pumping – Always Both

Much effort and time has been committed over the years to the question of whether changes in groundwater levels and spring flows in the LWRFS are the result of climatic forces or pumping. Rather, based on fundamental hydrologic principles, both stresses are always in play; one or the

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[32] Notwithstanding the presence of scattered outcrop of Pilot Shale, other Mississippian siliciclastic rocks, and Eureka Quartzite in the Meadow Valley Mountains (Crafford 2007).

[33] Similar faulting is common at many other locations in the portion of the carbonate aquifer that is known to be hydraulically continuous (Section 1.1.2).

[34] Although limited, the results of deuterium-calibrated mixing-cell modeling by Kirk and Campana 1990 and Thomas et al. 1996 may be partial evidence of the latter.

[35] Since all are part of the Meadow Valley Flow System, through which groundwater is known to flow over long distances from north to south based on numerous shallow groundwater level measurements (Heilweil and Brooks 2011, SNWA 2012).

other possibly predominating at any particular location and time, neither of which should be discounted.

Climate – Wet and Dry Periods

Whereas it is clear that climatic conditions influence conditions in groundwater systems (generally), parameters describing wet and dry climatic periods (e.g., drought indices and baseflow in distant rivers) are poor surrogates for net gains and losses to aquifers since the latter depend on a great many things. Exceptionally wet and dry climatic periods in Nevada Climate Division 4 (Division 4), the area of the LWRFS including Kane Springs Valley and LMVW, and Nevada Climate Division 3 (Division 3), areas immediately upgradient which are the primary source of groundwater in the LWRFS, are highlighted here for the limited purpose of identifying climate signals in hydrographs of carbonate water levels, alluvial water levels, spring flows, and flows in the Muddy River within the LWRFS; and, as a first approximation, characterizing their timing relative to changes in climatic conditions. Understanding the timing, in turn, is necessary but may not be sufficient to determine the mechanisms by which climatic conditions influence trends in groundwater levels and flows in the LWRFS and the availability of water.

Whereas data for both Divisions 4 and 3 are presented in Figure 11, basin-scale water budget analyses suggest that a net loss of water occurs from aquifers to evapotranspiration in basins composing the LWRFS (SNWA 2009a, Table I-7), with or without Kane Springs Valley and LMVW: roughly 5,000 to 8,000 acre-feet per year (afy). In comparison, total groundwater inflows to Coyote Spring Valley and LMVW from Division 3 is an estimated 58,500 afy. As such, climatic conditions in Division 3 may have an outsized influence on water resources in the LWRFS, particularly carbonate water levels and the Muddy River Springs, while conditions in Division 4 have their greatest effect on water levels in the alluvial aquifers and runoff to the river (or lack thereof).

Exceptionally wet and dry periods are highlighted in Figure 11 using Palmer Drought Severity Index (PDSI) values for Divisions 3 and 4, 1970 to present (NCDC 2018). In order of intensity, wet periods occurred in Division 3 in calendar years 2004 / 2005, 1983 - 1985, 1978 - 1980, and to a lesser extent in 1998, 1994 - 1995, 1972 – 1973, and 2010 – 2011. Periods of significant or extended drought in Division 3 (in order of intensity) occurred in calendar years 2002 – 2005, 1989 – 1991, ≤ 1970 – 1972, 2007 – 2009, 2013 – 2015, 1974, 1996 – 1997, 1981, and 1977. Unusually wet and dry periods were generally the same in Divisions 3 and 4 with the exception of a unique wet period in calendar years 1992 – 1993 and more intense dry period in 1996 – 1997 in Division 4.

Climate Signals in Carbonate and Alluvial Groundwater Levels, Spring and Stream Flows

Climate signals are identifiable in groundwater level and spring / stream flow records as periods of increasing water levels or flows at times when carbonate and / or alluvial pumping is known to have been steady or increasing; and periods of decreasing water levels and flows at times when pumping was steady or decreasing.

Wet and dry periods identified using PDSI values in Figure 11 are superimposed on hydrographs of carbonate and alluvial water levels and spring and stream flows in the LWRFS in Figures 12 – 15. Climate signals are primarily identified using trends in water levels and flows from 2000 to present because carbonate and alluvial pumping is only available from the State Engineer's office (NDWR 2018a) for that period. Trends in water levels and flows prior to 2000 are used only to confirm observations based on the more recent data. Whereas the coincidence of any single wet or dry period with a period of increasing or decreasing groundwater levels or spring / stream flows could be due to wet or dry conditions at some earlier time with a delay in the arrival of climate impacts, the coincidence of two or more such events is unlikely given the irregular timing of wet and dry periods in Divisions 3 and 4. The latter has been used to estimate, as a first approximation, the timing of the manifestation of climate impacts in water resources of the LWRFS in relation to changes in Division 3 and 4 climatic conditions.

Based on careful visual inspection of the hydrographs (Figures 12 – 15), the timing of climate impacts in the carbonate aquifer, alluvial aquifer of the MRSA, various springs in the MRSA, and the Muddy River at the Moapa gage are:

- **Carbonate Aquifer** (Figure 12): Groundwater levels in the portion of the carbonate aquifer currently recognized as part of the LWRFS responded to wet conditions in Division 3, Division 4, or possibly both, within about one year. No conclusions can be drawn concerning the response of carbonate water levels to dry periods due to the "overprint" of pumping impacts. Additionally, no distinction can be made between the effects of Division 3 and 4 climatic conditions based on inspection of the hydrographs due to the similarity of wet and dry periods in the two climate divisions from 2000 to present. Based on a broader inspection of trends in carbonate water levels in the Order 1169 study area (NDWR 2018a), wet climate signals (2000 to present) are evident in all monitored carbonate wells in the basins currently recognized as part of the LWRFS within about one year, but notably are not evident in carbonate monitoring wells located outside the area identified in Section 1.1.2 (e.g., Byron, EH-7, EH-3, CSVM-5).

- **Muddy River Springs** (Figure 13): Flow rates at Pederson Spring, Pederson East Spring, the Warm Springs West gage on Pederson stream, and likely Iverson Flume downstream of the Plummer springs, all known to discharge from the carbonate aquifer, also responded to wet conditions in Division 3, Division 4, or possibly both, within about one year. No conclusions can be drawn concerning the response of the springs to dry periods due to the "overprint" of pumping impacts. Additionally, no distinction can be made between the effects of Division 3 and 4 climatic conditions on the flow of the springs based on inspection of the hydrographs due to the similarity of wet and dry periods in the two climate divisions from 2000 to present.

  In contrast, no such climate signals are evident in the hydrographs for Jones and Baldwin springs or the Big Muddy Spring from 2000 to present which, moreover, responded very differently from the Pederson and Plummer springs. Nor is it possible to evaluate the potential for a delay in the arrival of climate impacts at Jones and Baldwin springs since no pumping data are available prior to 2000.

- **Alluvial Aquifer of the MRSA** (Figure 14): Groundwater levels in most of the alluvial monitoring wells in the MRSA[36], including LDS Central and LDS East which are influenced by alluvial inflows from LMVW (Section 1.1.1), responded to wet conditions in Division 3, Division 4, or possibly both, within about one year. No conclusions can be drawn concerning the response of alluvial water levels in the MRSA to dry periods due to the “overprint” of pumping impacts (carbonate and alluvial). No distinction can be made between the effects of Division 3 and 4 climatic conditions on alluvial water levels based on inspection of the hydrographs due to the similarity of wet and dry periods in the two climate divisions from 2000 to present.

- **Muddy River at Moapa Gage** (Figure 15): Although complicated by alluvial pumping in the MRSA of 5 to 8 cfs, upstream surface water diversions of up to 3 to 4 cfs, and runoff during storm events (NDWR 2018a), at least one wet period (2004 / 2005) coincides with a period of increased flow in the Muddy River at the Moapa gage at a time when alluvial pumping and diversions were increasing moderately; the timing of the response, like that in the alluvial aquifer of the MRSA, within about one year. Beyond that, no conclusions can be drawn due to the lack of pumping data (carbonate and alluvial) prior to 2000; but decreases and increases in flow through the Moapa gage prior to 2000 generally corresponded to dry and wet periods going back to 1970.

In conclusion, the only response to climate conditions that can be observed in all of these systems (springs, carbonate and alluvial wells, and the river) is a response to wet years. Any response to dry conditions in the record is either too incremental to observe or is obscured by the simultaneous effects of ongoing water supply pumping.

Potential Multidecadal Lag in Climate Impacts on the Big Muddy Spring – An Enigma

Notably, variations in the discharge of the Big Muddy Spring appear to be lacking obvious pumping impacts (Figure 13). Flow rates from the Big Muddy Spring gradually increased and then decreased over a period of about 12 years from roughly 1995 to 2007 (unlike other springs in the area), a pattern not seen in the PDSI trends for Division 3 since about 1977 to 1989 (Figure 11), or 18 years prior; (also clearly not replicated in PDSI trends for Division 4). This apparent 18 year lag is consistent with the results of a regression analysis prepared by Mifflin Associates on the behalf of the Moapa Band of Paiutes in their submittal to the 2016 Hydrologic Review Team (HRT) Annual Determination Report (HRT 2016, Appendix C.1); albeit the results of that regression suggest that changes in the discharge of the Big Muddy Spring are linked to climatic

[36] Based on a broader inspection of alluvial water level data (NDWR 2018a), Lewis 1 Old, Lewis 2, Lewis North, LDS Central, LDS East, Perkins Old, Behmer MW, and Abbott, from northwest to southeast across the MRSA, responded to wet conditions in 2004 / 2005, 2010 – 2011, or both; climate signals absent (or not discernable) in only Lewis South and LDS West.

conditions in the Humboldt River Basin more than 200 miles north in Nevada Climate Division 2, which is not physically tenable.

Climatic Trends – The Last 48 Years

Conditions in both Climate Division 4 (the immediate area of the LWRFS) and Climate Division 3 (areas which are the primary source of groundwater in the LWRFS) appear to have been "drying" for at least the last 48 years since 1970 (Figure 11). However, more analysis is needed to determine if this trend is real or not since neither linear trend line in Figure 11 is statistically significant. If conditions are getting warmer and drier, as expected with increasing air temperatures and decreasing precipitation, this would have significant practical ramifications for the availability of water in the LWRFS and determinations of its "sustainable yield".

1.3 Hydrogeologic Conceptual Model of the LWRFS

1.3.1 *Boundaries and Boundary Conditions*

Geologic mapping (Page et al. 2005 and SNWA 2007), geologic cross-sections (Page et al. 2006), the three-dimensional hydrogeologic framework of SNWA 2009b, and groundwater level data from readily available published sources (Heilweil and Brooks 2011, SNWA 2012, and NDWR 2018a), are used to identify the physical locations of the boundaries of the LWRFS and conditions on the boundaries.

Lateral Inflow Boundaries

Pahranagat Shear Zone

It is well established that groundwater flows across the Pahranagat shear zone into Coyote Spring Valley, supported by trends in groundwater elevations, water budget analyses, and deuterium calibrated mixing-cell modeling (e.g., Eakin 1964, 1966, SNWA 2009a Table I-7, Kirk and Campana 1990, Thomas et al. 1996). Moreover, this inflow must occur largely from Pahranagat Valley into Coyote Spring Valley west of the Delamar thrust fault due to the presence of the Kane Springs Wash caldera complex with its plutonic core to the east (SNWA 2009b, hydrogeologic framework model; Page et al. 2006, cross-section A); the latter all but precluding inflow from Delamar Valley to Coyote Spring Valley. Likewise, inflow across the shear zone from Delamar Valley into Kane Springs Valley is largely, if not entirely, precluded by the caldera complex and outcrop of basement rocks (SNWA 2009b, hydrogeologic framework model; and Crafford 2007)[37].

[37] Although some local recharge to Kane Springs Valley may occur in the Delamar and Meadow Valley mountains (SNWA 2012).

There are no carbonate wells in southern Pahranagat Valley or northernmost Coyote Spring Valley (other than CSVM-3)[38]. Basin-fill water levels drop about 800 ft from the southern end of Pahranagat Valley (Maynard spring pool) to a location roughly 9 miles south in Coyote Spring Valley (Eakin 1964), but may not be representative of gradients in the carbonate aquifer or, in particular, across the shear zone. Rather, assuming water levels in the basin fill and underlying carbonates of southern Pahranagat Valley are in equilibrium (a location where the water table is very close to the land surface and roughly 3,150 ft amsl; SNWA 2012 and Heilweil and Brooks 2011), and projecting carbonate water levels from the area of CSVM-4 in northern Coyote Spring Valley (about 1,875 ft amsl; NDWR 2018a) to the boundary with Pahranagat Valley using a gradient of 5 ft/mile, the difference in head across the Pahranagat shear zone in the carbonate aquifer is conservatively 1,200 ft. Consequently, changes on the order of many tens of feet in carbonate water levels in Pahranagat and / or Coyote Spring valleys (i.e., on either or both sides of the shear zone) would have no significant effect on the hydraulic gradient or rates of groundwater inflow across the shear zone into Coyote Spring Valley. The Pahranagat shear zone, at the boundary between Pahranagat and Coyote Spring valleys, is a constant inflow boundary for the foreseeable future.

Meadow Valley Flow System above LMVW

Although somewhat inconsistent with surficial geologic mapping by Crafford (2007), the hydrogeologic framework model of SNWA (2009b) shows that groundwater from Lake and Patterson valleys in the northern part of the Meadow Valley Flow System flows south through Panaca Valley (between and around plutonic rocks of the Caliente caldera complex and highs in basement rocks) through “upper valley fill”, “lower valley fill”, and the underlying carbonates into LMVW. Basin-scale water budget analyses by SNWA (2009a, Table I-7) estimate that about 4,700 afy of groundwater flow from Panaca Valley into LMVW. Whereas water level hydrographs for wells in the northern two-thirds of LMVW are not readily available (NDWR 2018c), and most if not all wells in northern LMVW and southern Panaca Valley are shallow and located along the wash, records for alluvial wells in southern Panaca Valley include long-term, as well as seasonal, variations in water level (e.g., wells 203 S02 E67 35A 1 and 203 S02 E67 02CD 1; NDWR 2018c). Groundwater inflows at the boundary between Panaca Valley and LMVW, unlike those across the Pahranagat shear zone, vary from year to year.

Lateral No-Flow Boundaries

The locations of likely no-flow boundaries, which largely define the areal extent of the LWRFS, are identified using a combination of geologic mapping (Page et al. 2005, SNWA 2007), geologic cross-sections (Page et al. 2006), the three-dimensional hydrogeologic framework of SNWA (2009b), and groundwater level data readily available from published sources (Heilweil

[38] CSVM-3 likely not representative of water levels elsewhere in the carbonate aquifer in northernmost Coyote Spring Valley (see Section 1.1.3).

and Brooks 2011, SNWA 2012, NDWR 2018a). The locations of likely no-flow boundaries on the LWRFS are as follows [basis for identification provided in brackets]:

- boundary of Delamar Valley with northern Coyote Spring Valley and Kane Springs Valley [groundwater flow precluded by plutonic rocks of the Kane Springs Wash caldera complex (SNWA 2009b, hydrogeologic framework model; Page et al. 2006, and cross-section A)];
- boundary of northern LMVW with Delamar and Dry Lake valleys [coincident with the likely direction of groundwater flow];
- boundary of northern LMVW with Clover Valley and northern Tule Desert to the intersection with a west-striking strike-slip fault intersecting Meadow Valley Wash Fault [coincident with likely directions of groundwater flow, then a strike-slip fault intersecting Meadow Valley Wash Fault shown in Page et al. (2005)];
- Meadow Valley Wash Fault south to its intersection with the boundary of Lower Moapa Valley [carbonates discontinuous across this portion of the fault from west to east, cross-sections A, B, and C of Page et al. (2006)];
- boundary of LMVW with Lower Moapa Valley from the Meadow Valley Wash Fault to the Muddy River near the Glendale thrust [carbonates discontinuous across the fault and thrust from west to east, cross-section D of Page et al. (2006); water levels in Lower Moapa Valley near the Muddy River and boundary with LMVW in carbonate wells EH-7 and EH-3 about 250 ft lower than in northern California Wash at carbonate well M-1, NDWR (2018a)];
- Muddy Mountain thrust on the east side of California Wash from the Muddy River south to the northern strand of the Las Vegas shear zone in northwest Black Mountains Area [carbonates discontinuous across a series of faults associated with the thrust, cross-sections E, F, and G of Page et al. (2006); water level in carbonate well Byron on the east side of a fault associated with the thrust 150 ft lower than in carbonate well M-1 in northern California Wash, NDWR (2018a); and water level in carbonate well EBM-3 in the northwest part of the Black Mountains Area 100 feet higher than in wells BM-ONCO-1 and BM-ONCO-2 completed in clastic rocks to the southeast, (NDWR 2018a)];
- northern strand of the Las Vegas shear zone from the Muddy Mountain thrust in northwest Black Mountains Area to the Gass Peak thrust in northern Las Vegas Valley [carbonates discontinuous across the shear zone, Page et al. (2006, cross-section H)];
- Gass Peak thrust from the northern strand of the Las Vegas shear zone to a location intermediate between cross-section F of Page et al. (2006) and CSVM-5 in southern Coyote Spring Valley [carbonates discontinuous across this portion of the thrust, cross-sections G and F of Page et al. (2006)]; and

- crest of the Sheep Range from a location intermediate between cross-section F of Page et al. (2006) and CSVM-5 in southern Coyote Spring Valley to the Pahranagat shear zone [no-flow conditions coincident with the topographic divide].

Lateral Outflow

Whereas some groundwater outflow may occur from the carbonate aquifer of California Wash to Lower Moapa Valley and / or the Black Mountains Area (or as suggested across some part of the Las Vegas shear zone), available estimates of the rate of outflow are based on Darcy flux approximations[39] and basin-scale water budget analyses (SNWA 2009a, Table I-7). Hence, the rate of any such outflow is poorly known (uncertain). Notwithstanding the potential for some outflow from the area currently recognized as the LWRFS, the difference in head in carbonate rocks on the west and east sides of the Glendale and Muddy Mountain thrusts is on the order of 100 to 150 ft as described in the previous section (based on water level measurements in wells M-1 and EBM-3 versus Byron and BM-ONCO-1 and BM-ONCO-2, respectively), while water levels in the carbonate aquifer in the LWRFS[40] have declined only two to five feet over the last 16 to 20 years through several periods of significant drought (e.g., 2.5 ft in GV-1 in Garnet Valley and 4.5 ft in MX-4 in Coyote Spring Valley, NDWR 2018a). Therefore, to the extent that outflow occurs across any portion(s) of the thrusts (or the northern strand of the Las Vegas shear zone), hydraulic gradients and rates of outflow are, for all practical purposes, constant, short of a change in head on either or both sides of the thrusts (or shear zone) of at least several tens of feet; the latter highly unlikely in the LWRFS given the significant areal extent of the carbonate aquifer underlying the LWRFS basins. Any outflow that occurs to Lower Moapa Valley or the Black Mountains Area from the LWRFS is fairly constant and, in particular, unlikely to change significantly with water management in the LWRFS.

1.3.2 *Areal Extent of the LWRFS – Proposed Boundaries*

Based on information developed in Sections 1.1.1, 1.1.2, 1.1.3, and 1.3.1, revisions to the areal extent of the LWRFS should be considered as shown in Figure 1 to include the following basins and parts of basins:

- the MRSA;
- most of Coyote Spring Valley;
- Hidden Valley;
- Garnet Valley;
- most of California Wash;
- northwest Black Mountains Area;
- Kane Springs Valley; and

[39] Testimony provided by Terry Katzer and David Donavan in a July 2001 administrative hearing on Las Vegas Valley Water District applications (NSE 2014a-f and NSE 2002).

[40] Specifically, that portion of the regional carbonate aquifer located west of the Glendale and Muddy Mountain thrusts and north of the northern strand of the Las Vegas Shear Zone.

- most of LMVW

1.3.3 *Relative Aquifer Transmissivities, Storativities, and Hydraulic Diffusivities*

Only an understanding of the relative transmissivities, storativities, and hydraulic diffusivities of the carbonate and alluvial aquifers of the LWRFS are required to address questions "b" and "d" posed in Order 1303 (NSE 2019).

<u>Regional Carbonate-Rock Aquifer</u>

Based on the DOI 2013 interpretation of the Order 1169 pumping test, the transmissivity of a large portion of the regional carbonate-rock aquifer underlying the LWRFS is exceptionally high at field-scales. The storativity of the aquifer is limited since composed of fractured consolidated rocks (elastic storage where confined and otherwise largely arising from secondary structures). As such, the hydraulic diffusivity of the carbonate aquifer is high (at least in this area), but finite; consistent with the 4 to 6 month lag observed in the initiation of measurable recovery at the Pederson springs and carbonate well EH-4 in the MRSA following the cessation of MX-5 pumping in southern Coyote Spring Valley (12 miles away) during the Order 1169 pumping test (Figures 12 and 13).

<u>Alluvial Aquifers</u>

The transmissivity of the alluvial aquifers of the LWRFS is considerably lower, storativity considerably higher, and hydraulic diffusivity considerably lower than that of the underlying regional carbonate aquifer.

1.3.4 *Groundwater Flow and General Response to Pumping and Climatic Conditions*

Pumping in the Carbonate Aquifer

A sizable portion of the carbonate-rock aquifer of the LWRFS has been demonstrated to possess exceptionally high field-scale transmissivity (Section 1.1.2); i.e., transmissivity of exceptional magnitude within the carbonate-rock province of southern and eastern Nevada. Based on the response to the Order 1169 pumping test (Section 1.1.2) and anomalously flat lateral hydraulic gradients documented in the carbonate aquifer over many years (Dettinger et al. 1995, NDWR 2018a), the high transmissivity portion of the aquifer extends from CSVM-6 in central Coyote Spring Valley to the east and south beneath the whole of MRSA and Hidden and Garnet valleys, most of California Wash, and the northwest part of the Black Mountains Area. Due to its exceptionally high transmissivity (and for no other reason), pumping in this portion of the carbonate aquifer creates nearly uniform drawdown throughout the high transmissivity part of the aquifer.

North of CSVM-6 in central Coyote Spring Valley, the carbonate aquifer has been demonstrated to be of lesser transmissivity, but nonetheless transmissive and in hydraulic connection with the exceptionally high transmissivity portion of the aquifer (Section 1.1.3). As a result, pumping in the high transmissivity portion of the carbonate aquifer creates drawdown in the carbonates of northern Coyote Spring Valley (e.g., the area of CSVM-4), but of lesser magnitude (the hydraulic gradient between central and northern Coyote Spring Valley made steeper by pumping in the central part of the basin or pumping to the south or east in the carbonate aquifer). By the same token, carbonate pumping in the area of CSVM-4 in northern Coyote Spring Valley would, in addition to creating local drawdown, create drawdown that extends into the high transmissivity portion of the aquifer to the south and east; which again would be nearly uniform and distributed throughout the highly transmissive portion of the aquifer. That is, pumping anywhere in carbonates that are hydraulically connected to the high transmissivity portion of the carbonate aquifer, including possibly large parts of Kane Springs Valley and LMVW, can be expected to create drawdown that is nearly uniform and distributed throughout the carbonates in the high transmissivity area. Which is to say, pumping in any “connected” carbonates (identified in Sections 1.3.1 and 1.3.2) will create drawdown of at least some magnitude over a large area; i.e., at least 650 square miles of southern Nevada from central Coyote Spring Valley through the MRSA, Hidden and Garnet valleys, the northwest portion of the Black Mountains Area, and most of California Wash based on the results of the Order 1169 pumping test (Section 1.1.2).

Pumping in Alluvial Aquifers

Notwithstanding the occurrence of flow from the carbonate aquifer into the alluvium in the MRSA and California Wash and possibly Garnet Valley (Section 1.1.1), and from the alluvium into the carbonate aquifer in Coyote Spring Valley (based on limited data from CE-VF-1 and CE-VF-2), the carbonate and alluvial aquifers of basins currently recognized as the LWRFS are generally in good hydraulic connection. Consequently, alluvial pumping within the LWRFS that is not captured directly from the river or evapotranspiration is captured from the underlying carbonate aquifer; with impacts to the Muddy River Springs and seepage from alluvium into the river over some period of time, although impacts to the springs should be somewhat delayed (compared to the effects of carbonate pumping) due to the relatively low hydraulic diffusivity of the basin fill.

Effects of Constant Inflow at the Pahranagat Shear Zone

No less unique and unusual than the exceptional transmissivity of the carbonate aquifer in the LWRFS is the presence of constant inflow into the LWRFS at the Pahranagat shear zone. Assuming the extent of any outflow to Lower Moapa Valley and / or the Black Mountains Area is fairly constant as hypothesized (Section 1.3.1), and for the sake of the current illustration that inflow to LMVW is also constant, any increase in pumping (carbonate or alluvial) within the LWRFS must eventually be captured from the Muddy River Springs (at least the Pederson and Plummer springs at Moapa Valley National Wildlife Refuge), the Muddy River, and / or evapotranspiration in the MRSA and California Wash on a roughly 1:1 basis:

$$Q_{inflows} - Q_{outflows} - Q_{pumping} = Q_{springs/river/ET}$$

If $Q_{inflows}$ *and* $Q_{outflows}$ are constant and pumping increases from one time to another, then:

$$\Delta\, Q_{pumping} = -Q_{springs/river/ET}$$

Effects of Variable Inflow at the North End of LMVW

Inflow to LMVW from Panaca Valley is limited compared to inflow at the Pahranagat shear zone. Based on water budgets prepared by SNWA (2009a, Table I-7), about 4,700 afy flow from Panaca Valley into LMVW; while an estimated 53,800 afy flow across the Pahranagat shear zone into Coyote Spring Valley. Nonetheless, increases in pumping in the LWRFS (carbonate and / or alluvial) could result in somewhat less than 1:1 capture of the refuge springs, river, and evapotranspiration to the extent that increased pumping induces additional inflow across the Panaca Valley / LMVW boundary (assuming inflow at the Pahranagat shear zone and outflow to other basins remains constant).

Causes of "Climate Signals" in Groundwater Levels and Flow Rates in the LWRFS

Given that inflow at the Pahranagat shear zone and outflow to other basins are roughly constant, climate signals identified in carbonate water levels, the discharge of the refuge springs, alluvial water levels in the MRSA, and flows in the Muddy River at the Moapa gage (Section 1.1.2) can only be the result of variable inflow at the boundary between Panaca Valley and LMVW and / or temporal variations in local recharge. Based on basin-scale water budgets prepared by SNWA 2009a, Table I-7), local recharge to basins of the LWRFS, including Kane Springs Valley and LMVW, is about 14,800 afy; roughly three-fold the estimated 4,700 afy flowing into LMVW from Panaca Valley. It seems likely that the bulk of climate-related variations in carbonate and alluvial water levels and spring and stream flows identified in Section 1.1.2 are due to changes in local recharge (to alluvium and carbonate outcrop); that is, in response to Climate Division 4 conditions, despite overall limited local recharge in the area. Moreover, local recharge as a prime driver of the identified "climate signals" is consistent with the one year or less lag in their manifestation in the observed wet-year responses of alluvial and carbonate water levels and spring / stream flows (Section 1.1.2). This is not to say that a longer lag in climatic impacts might also be associated with variable inflow to LMVW, only that it is difficult to detect. Assuming the latter is not insignificant, no means is currently available for distinguishing climate impacts transmitted through the carbonate aquifer versus the alluvial aquifer of LMVW, versus both.

Until such questions are resolved, the costs (both time and financial) of building or improving a numerical groundwater flow model that might be useful in conjunctively managing the water resources of the LWRFS may not be warranted. Alternatively, if an empirical or analytical "model" can be developed that would serve this same purpose, uncertainties regarding the specific mechanisms by which climatic conditions influence water resources in the LWRFS may be less consequential.

Effect of Decreased Local Recharge and / or Inflow to LMVW due to Changes in Climatic Conditions

Assuming inflows at the Pahranagat shear zone, any outflow to other basins, and pumping (carbonate and alluvial) within the LWRFS are relatively constant going forward, decreases in local recharge and /or inflow to LMVW will result in corresponding decreases in the flow of the Muddy River (inclusive of the contributions of the springs) and / or evapotranspiration in the MRSA and California Wash. Accordingly, if there are increasingly dry conditions in Climate

Division 4 (the immediate area of the LWRFS) and Climate Division 3 (areas which are the primary source of groundwater in the LWRFS) this would have significant practical ramifications for the future availability of water in the LWRFS and determinations of its sustainable yield.

Effects of Groundwater Availability Upgradient of the LWRFS Due to Groundwater Development

It follows that to the extent groundwater development upgradient of LMVW in the Meadow Valley Flow System (e.g., Lake Valley), or Dry Lake, Delamar, and Pahranagat valleys, results in reduced groundwater inflows to the LWRFS, the effects would be similar to drought, but indefinite.

1.3.5 *Time Lags in the Manifestation of Pumping Impacts and Recovery*

The hydraulic diffusivity of the carbonate aquifer is high, but finite; the hydraulic diffusivity of basin fill is even more finite. Consequently, there is a time lag between pumping in either the carbonate aquifer or alluvium and the initial manifestation of pumping impacts at distant locations, as well as the initial manifestation (first measurable signs) of recovery with the cessation of or reductions in pumping. During the Order 1169 pumping test (although complicated by changing climatic conditions), the time lag in both the initiation of impacts and recovery at EH-4 and the refuge springs following MX-5 test pumping in the carbonate aquifer was about 4 to 6 months (Figure 13). Time lags are longer in the case of alluvial pumping because, all other things being equal, the hydraulic diffusivity of basin fill is much lower than that of the carbonate aquifer.

Beyond the initiation of measurable recovery, full recovery of groundwater levels (and in this case spring flows) following the cessation of pumping (or a decrease in pumping) occurs asymptotically over a period of time that marginally exceeds the length of time a well was pumped before being shut off (or the length of time a well was pumped at a higher rate before the rate of pumping was reduced); this based on fundamental mathematics describing the recovery of pumping-induced drawdown in aquifers. This occurred during the recovery from MX-5 pumping in the Order 1169 test, where MX-5 was pumped for about 2 ¼ years (from about December 2010 to late April 2013, several months past the official end of the test in December 2012) before being shut off, and full recovery was achieved sometime in late summer of 2015 based on measured spring flows and groundwater levels in carbonate monitoring well EH-4; the exact timing of the recovery is somewhat obscured in the empirical data by the effects of ongoing water supply pumping and possibly drought.

In general, the rate of recovery from pumping, including the time for the first measurable signs of recovery at any given location, depends on all stresses acting on the affected aquifer system; e.g., local rates of evapotranspiration, any groundwater recharge, leakage from one aquifer to another, and rates of pumping, in addition to the locations of pumping and the impacted resources. As such, the time lag for the start of recovery at any particular location / resource is not a constant. Rather, it depends on the location of the pumping that is reduced or stopped and location of the resource, the rate of pumping (prior to being reduced or turned off), and many other factors affecting conditions in the aquifer in question; consequently, cannot be anticipated with certainty from one set of conditions to another (including one year to another).

1.3.6 *Source of the Big Muddy Spring – A Hypothesis*

The Big Muddy Spring may discharge from a zone of high permeability "massive limestone pebble fanglomerates" mapped by Maxey et al. 1966 in an area of otherwise low permeability Muddy Creek Formation at the general location of the spring (Maxey et al. 1966, Figure 2).[41] Moreover, if the transmissive zone allowing discharge to the surface is encased in "low permeability to impermeable" Muddy Creek Formation (Maxey et al. 1966, Figure 2), this could also account for the unique lack of pumping impacts to the Big Muddy Spring during the two-year Order 1169 pumping test (Figure 13).

Further, water discharged from the spring is warm (27 ^{o}C, Beck and Wilson 2006); consequently, likely discharges from depth. The source area in particular appears to be LMVW given the location of the spring downgradient of that basin within a north-striking channel of alluvium surrounded by Muddy Creek Formation in the MRSA (Crafford 2007). If the source area is LMVW, the source could be deep basin fill or the underlying carbonate aquifer, which over much of LMVW is located at depths of thousands of feet. If the latter, significant attenuation of what appears to be climate signals (1995 to 2007) in the hydrograph shown in Figure 13 suggests that water discharged from the spring flows through a great deal of basin fill before reaching the surface.

Water quality / chemical analyses could be helpful in determining the source of this important spring, if not already available. Since the discharge of the Big Muddy Spring is about 7 cfs, i.e., roughly 30 percent of the discharge of the Muddy River Springs and more than 15 percent of flow in the Muddy River at the Moapa gage (Beck and Wilson 2006), questions regarding the source of the spring and potential lags in climate response must be answered before conjunctive management of the LWRFS can be refined beyond some initial strategy.

1.4 Sustainable Levels of Pumping in the LWRFS

Carbonate versus Alluvial Pumping

Because the carbonate and alluvial aquifers of the LWRFS are generally in good hydraulic connection (Sections 1.1.1 and 1.1.2), total carbonate and alluvial pumping must be used to establish a sustainable level of pumping in the LWRFS.

Estimating Sustainable Levels of Pumping Based on Water Budget Estimates or Numerical Models

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[41] Maxey et al. 1966 further note that "this fanglomerate when cut by faults and joints (some enlarged by solution) may be a highly permeable though areally restricted… [and] seems to be closely related to the occurrence of many of the big springs in Moapa Valley." Specifically, Maxey et al. 1966 mapped a surficial occurrence of this fanglomerate in the northeast quarter of Section 16 of T 14 S R 65 E, on the fringe of which he mapped the Big Muddy Spring.

Basin-scale water budgets cannot be used to estimate sustainable levels of pumping because their formulation involves the subtraction of large numbers (representing estimates of groundwater inflows and outflows at the scale of whole basins) which themselves are in error. Likewise, there are too many significant outstanding questions regarding the hydrology / hydrogeology of the LWRFS, including factors affecting the availability and future availability of water within the system, for a numerical groundwater flow model to be constructed at this time that will be useful in "predicting" a sustainable level of pumping.

An Initial Threshold – Total 2015 – 2017 Carbonate and Basin-Fill Pumping

In 2015, 2016, and 2017, the combined rate of carbonate and alluvial pumping in this collection of highly connected basins and aquifers was relatively constant from year to year (more than at any other time since 2000); an average of 9,318 afy. Moreover, during that period the discharge of the Muddy River Springs was also relatively constant at an average of about 20.0 cfs (14,480 afy), while flow through the Moapa gage on the Muddy River was relatively constant at an average 30,550 afy or 42.2 cfs, and flow through the Glendale gage was an average 33,100 afy or 45.7 cfs. Although flow rates at the Plummer, Pederson, Jones and Baldwin springs were generally lower than before the Order 1169 pumping test (2010 and earlier), and remain so, and may be in gradual decline (perhaps in response to ongoing pumping and possibly climatic factors), the spring flows are also reasonably stable compared to earlier periods.

Additionally, compared to the average combined level of carbonate and alluvial pumping during the Order 1169 pumping test of 13,880 afy, an initial allowable level of pumping in the LWRFS of 9,318 afy would be conservative, but not likely overly conservative. At the time the pumping test was officially terminated in December 2012, the discharge of the majority of springs in the Muddy River Springs Area were in an undiminished state of decline. A new steady state had not been established as of the end of the test; the full effects of the test pumping were never realized because the test was terminated after ~25 ½ months, while the time required to reach a new equilibrium state was seen to be significantly longer (Section 1.3.5). Based on our current understanding of this hydrologic system, if the test pumping had continued until a new equilibrium state was reached, flow in the river as measured at the Moapa gage would have been reduced by approximately 2,890 afy (or 3.99 cfs) - i.e., the amount by which pumping during the test exceeded combined carbonate and alluvial pumping in the few years before the test (10,990 afy, 2008 – 2010). Consequently, flow in the Muddy River at the Moapa gage would likely have been reduced by about 11 percent; a 3.99 cfs reduction from its 2010 average of 36.3 cfs. Because the discharge of the Muddy River Springs represented about half of flow through the Moapa gage in 2010 prior to the test, the flow of the springs would also have been reduced by roughly 11 percent, with several of the highest elevation springs going dry, if the test pumping had continued until a new steady state was reached.

Consequently, assuming a flow rate of 30,550 afy through the Moapa gage is sufficient to meet senior, decreed water rights on or along the Muddy River (the domain of the State Engineer's office), an initial threshold of combined carbonate and alluvial pumping within the LWRFS of 9,318 afy, based on actual observations / data at a time when no alternative quantitative approach yet exists, appears to be the best initial estimate of the sustainable yield of the system and the best available method currently available for arriving at an estimate of the maximum allowable rate of pumping in the LWRFS (inclusive of Kane Springs Valley and any pumping in LMVW that is already occurring). It may be possible to assess the degree to which this initial threshold of 9,318 afy is under versus overly conservative by compiling total combined rates of carbonate and alluvial pumping within the LWRFS (including LMVW and Kane Springs Valley) over the last 16 to 20 years; a period during which water levels in the carbonate aquifer of the LWRFS declined a documented two to five feet (e.g., 2.5 ft in GV-1 in Garnet Valley and 4.5 ft in MX-4 in Coyote Spring Valley, NDWR 2018a).

Projections Based on Historical Pumping and Flows in the River

Alternatively, if estimates of total pumping (carbonate and alluvial) in the LWRFS can be compiled for at least the last two decades (since 1998 or earlier), it may be possible to create a simple "empirical" model (based on empirical verifiable data) that can be used to project (estimate) the level of combined pumping in the LWRFS that will allow the required amount of water to go down the Muddy River. The model would be developed (subject to periodic updates) by plotting estimates of total annual pumping (carbonate and alluvial) in the LWRFS as a function of annual average flows recorded in the river at location(s) critical to meeting senior, decreed surface water rights (e.g., at the Moapa and Glendale gages). This simple approach would also have the advantage of including the effects of progressively drier conditions, at least to the extent experienced in past years.

Periodic Adjustment for Groundwater Availability Upgradient of the LWRFS Including Climate Impacts

Given the development of increasingly dry conditions in Climate Division 4 (the immediate area of the LWRFS) and Climate Division 3 (areas which are the primary source of groundwater in the LWRFS) since at least 1970, and additional possible groundwater developments upgradient of the LWRFS, adjustments should periodically be made to the "sustainable yield" of the system that reflect significant changes in the availability of water.

1.5 Effects of Moving Carbonate and Alluvial Pumping within the LWRFS

Carbonate Pumping

Since the Muddy River Springs (at least the refuge springs) are derived almost entirely from the carbonate aquifer, total carbonate pumping should not be increased, for example in exchange for reductions in alluvial pumping, even if total carbonate and alluvial pumping is maintained at a "sustainable" overall level. Beyond that, existing carbonate pumping should not be moved closer to any springs (or the river), which could reduce the time lag in the development of impacts possibly before the impacts are detected based on periodic data collection and processing.

Alluvial Pumping

Likewise, since (in addition to the contributions of the springs) the remainder of water in the river comes from alluvium adjacent to the river in the MRSA and California Wash, alluvial pumping should not be increased, for example in exchange for reductions in carbonate pumping elsewhere, even it total alluvial and carbonate pumping is maintained at a "sustainable" overall level. Beyond that, existing alluvial pumping in the vicinity of the river should not be moved closer to the river, reducing the time lag in the development of impacts possibly before the impacts are detected based on periodic data collection and processing.

1.6 Groundwater and Spring Discharge Relationships in Muddy River Springs Area and Their Relation to Trigger Levels in the 2006 MOA

This portion of the report updates our analysis of spring discharge and groundwater levels in the MRSA, with a special focus on the springs on the Moapa Valley National Wildlife Refuge (refuge). As presented in the 2006 MOA (USFWS 2006a), Mayer and Congdon (2008), and the DOI Order 1169 report (DOI, 2013), we hypothesize that changes in spring discharge will be proportional to the changes in the hydraulic head differential at each individual spring and that the higher elevation springs with the smallest hydraulic head differential will be the most sensitive to any increase or decrease in carbonate water levels. Here we update the relationships between spring discharge and EH4 well level data to show that this hypothesis is still valid. The conclusion to be drawn from this work is that protecting the highest elevation springs on the refuge, by way of the trigger levels established at Warm Springs West in the 2006 MOA, will protect the springs and dace habitat on the refuge and elsewhere.

1.6.1 Theoretical Groundwater Level/Spring Discharge Relationships

It is well established that spring discharge in the MRSA emanates from the regional carbonate-rock aquifer (Eakin 1966, Thomas et al. 1996). The regional carbonate-rock aquifer is confined and the potentiometric surface of the aquifer (the level to which water would rise if it was not trapped or confined by an impermeable layer) is greater than the land surface elevation of the springs. This hydraulic head differential between the potentiometric surface and the land surface causes groundwater in the carbonate rock aquifer to rise to the land surface, along fissures and fractures that occur in the area, and flow as spring discharge. We assume that the flow at any spring is governed by Darcy's Law, which states that flow through a porous medium is proportional to the hydraulic head differential or hydraulic gradient (Fetter 1994). The greater the difference between the water surface elevation at the spring and the hydraulic head of the aquifer, the greater the spring discharge, other factors being constant.

The high transmissivity of the carbonate rock aquifer in the Coyote Spring Valley (CSV)-MSRA corridor creates a consistent and fairly uniform potentiometric surface beneath the landscape with little variation in hydraulic head in the aquifer. The difference in land surface elevations between MX-4 in CSV and the springs in the MRSA, some 15 miles to the east, is about 350-450 feet, but the difference in the potentiometric surface of the regional aquifer between carbonate monitoring wells MX-4 in CSV and EH-4 in MRSA is only about 5-6 feet. The high transmissivity and associated low hydraulic gradient results in a fairly uniform potentiometric surface elevation across the MRSA. However, the elevations of springpools in the area vary by more than 70 feet (Beck et al. 2006). This potentially leads to a large range of hydraulic head differential between the individual springs in the MRSA. Higher elevation springs have a much smaller hydraulic head differential than lower elevation springs. This concept is illustrated in Figure 16.

Groundwater pumping leads to the development of a drawdown cone around the pumping center. As the drawdown cone extends to the springs, the hydraulic head differential at the springs will be reduced. Darcy's Law states that a reduction in the hydraulic head differential will result in a proportional decrease in flow rate, all other factors being constant (Mayer and Congdon 2008). If, for example, a lowering of the potentiometric surface leads to a 25% decrease in the hydraulic head differential at a spring, one would expect a similar percentage reduction in flow at that spring. It follows that the springs in the system with the smallest hydraulic head differential, i.e., the highest elevation springs, will be relatively more sensitive to a uniform decline in the potentiometric surface of the carbonate rock aquifer resulting from groundwater pumping (Mayer and Congdon 2008). This concept is illustrated in Figure 17.

1.6.2 Data Sources and Data Quality

For this update, we focus on the springs on or just downstream of the refuge. Figure 18, from the DOI report (DOI 2013), shows the location of all the monitoring sites described here. For surface water monitoring sites, we found it convenient to distinguish between spring monitoring sites (those sites located directly at the springpool outflows) and flow monitoring sites (those sites located some distance downstream of the springpools). All data presented here, along with the graphical and statistical analyses, are available on request.

The closest carbonate monitoring well in the MRSA to the Refuge is EH-4 (Figure 18). This well is monitored by Nevada Energy and has periodic measurements since 1986, with continuous data available since 1997. The water level elevations and trends at this monitoring well are very similar to other carbonate wells in the LWRFS (see Figure 12). We assume that the water level in EH-4 is representative of the elevation of the potentiometric surface in the regional carbonate-rock aquifer in the MRSA. In the DOI report (DOI 2013), the EH-4 data were used to develop relationships between carbonate water levels and discharge at various sites in the MRSA. Here we update those relationships.

The Moapa Valley NWR consists of three units: the Pedersen[42] Unit, the Apcar Unit, and the Plummer Unit (Figure 18). The springs on the Pedersen Unit are the highest elevation springs in

[42] There are two different spellings of this name: Pedersen with an "e" at the end is the correct spelling of the landowner's last name. Pederson with an "o" at the end is the incorrect spelling, adopted by the USGS for the spring and stream names. We will use both spelling here, in context.

the MRSA. Given the expected sensitivity of the higher elevation springs and the importance of the Warm Springs West site to trigger levels in the 2006 MOA, we mainly focus our analyses on this area. There are three monitoring sites on the Pedersen Unit: Pederson Spring (USGS Site No. 09415910), Pedersen East Spring (USGS Site No. 09415908), and Warm Springs West (USGS Site No. 09415920)

Pederson Spring (USGS Site No. 9415910) has been monitored continuously by the USGS with a v-notch weir since 1986. The weir was replaced in April 2004, and for this reason, we only consider measurements since 2004. Pederson Spring is the highest elevation spring on the refuge and in the MRSA.

Pedersen East Spring (USGS Site No. 09415908) has been monitored continuously since 2002 with a v-notch weir. Pedersen East Spring is the highest elevation spring in the Pedersen East Spring group and the second highest elevation spring on the refuge. There are several other springs in the Pederson East spring group that are comparable in flow.

Warm Springs West (USGS Site No. 09415920) has been monitored continuously with a flume since 1985 but we only use the measurement record since 2000, after irrigation diversions ceased upstream. The Warm Springs West gage captures the discharge produced from a number of springs on the Pedersen Unit. The majority of flow at the gage is produced by the four major spring groups (M-11, M-12, M-13, and M-19) that are larger and downstream of the Pederson and Pederson East springs, as well as any groundwater seepage that enters the channel upstream of the gage.

Other spring and flow monitoring sites examined in this section include the Warm Springs confluence at Iverson flume (USGS Site No. 09415927) which measures the collective discharge from springs on the Plummer Unit of the refuge and Jones spring, which emanates from the Apcar Unit of the refuge and is measured by Moapa Valley Water District. For the Iverson Flume discharge, we only use the measurement record after 2010 to avoid any effects from the channel restoration work here prior to 2010. For Jones Spring discharge, we only consider data from 2004 on. Measurements at this site are much less variable following a data gap in 2004, indicating a possible change in the measurement location, equipment, or method. These measurements are reported in gallons per month rather than cfs and we retained those units here.

1.6.3 Methods

We examined the relationship between discharge and carbonate water levels by correlating monthly discharge with monthly carbonate water levels in EH-4 for the period of record (POR) at each of the sites. We calculated the slope and r^2 values for these relationships and estimate the maximum, minimum, and change in discharge observed over the POR. For each site, we also estimated the maximum, minimum, and change in the hydraulic head differential over the POR by computing the difference between the water surface elevation at the spring(s) contributing to the site and the carbonate water levels observed in EH-4. We then compared the estimates of the changes in hydraulic head differential, expressed as a percent relative to the max water level, with the observed changes in discharge at each site, expressed as a percent relative to the max discharge. Our assumption, as discussed above, is that the estimated changes in head differential should be equal to the measured changes in discharge, in relative terms.

1.6.4 Results and Discussion

Pedersen Unit

The first spring considered is the Pederson Spring, the highest elevation spring in the area (the gage datum or zero point of flow is 1810.99 ft). The correlation between spring discharge and water level in EH-4 is very high (r^2 = 0.97) (Figure 19). The slope coefficient of the discharge-water level relationship is statistically significant (p<0.0001) and equates to -0.058 cfs per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline in the EH-4 water level, Pederson Spring loses about 0.06 cfs of discharge (about 19% relative to the maximum discharge observed). The next question we address is: "How does this compare to the estimated change in head differential for this site?"

The maximum and minimum monthly EH-4 carbonate water level elevations observed over the POR were 1816.52 ft and 1812.54 ft, respectively. Pederson Spring has a water surface elevation of 1811 ft. The estimated hydraulic head differential was 5.52 ft at the maximum groundwater level elevation of 1816.52 ft and 1.54 ft at the minimum groundwater level elevation (the "head differential" being estimated as the difference between EH-4 water level elevation and the spring water surface elevation). The difference represents a 72% reduction in head differential at the spring, relative to the maximum head differential of 5.52 ft. Under the assumption that flow is proportionate to head, we should expect a similar percentage decline in flow. As shown in Figure 19, the flow at the spring ranged from a maximum of 0.3 cfs to a minimum of 0.08 cfs. This represents a 73% change in flow, relative to the maximum flow, over the range of carbonate water levels observed during the POR. The observed decline in flows agrees almost exactly with the estimated decline in flow based on the change in head. The spring continues to respond to the decline in carbonate water levels and head differential as expected.

The x-intercept of the discharge/water level regression is 1811.2 ft, using the exact coefficients from the regression equation (Figure 19 and Table 1). This is the predicted carbonate water level elevation at which the spring discharge goes to zero (the spring dries up), based on the relationship between spring discharge and EH-4 levels. This is the most sensitive spring in the MRSA and will be the first to stop flowing with further declines in carbonate water levels.

Next, we consider Pederson East Spring, which is the second highest elevation spring in the area, with a gage datum or zero point of flow of 1807.7 ft. The correlation between spring discharge and water level in EH-4 is also quite high (r^2 = 0.85) (Figure 19). The slope coefficient of the discharge-water level relationship is statistically significant (p<0.0001) and equates to -0.036 cfs per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline in the EH-4 water level, Pederson Spring loses about 0.036 cfs of discharge (about 14% relative to the maximum discharge observed). As above, the next question we address is: "Is this reasonable and close to what we expect for this site?"

As with Pederson Spring, the maximum and minimum monthly EH-4 carbonate water level elevations observed over the POR were 1816.52 ft and 1812.54 ft, respectively. Pederson East Spring has a water surface elevation of 1807.7 ft, lower than Pederson Spring. The hydraulic head differential is therefore greater. It is estimated to be 8.82 ft at the maximum groundwater level elevation of 1816.52 ft and 4.84 ft at the minimum groundwater level elevation. The difference represents a 45% reduction in head differential at the spring, relative to the maximum head differential. This is less than Pederson Spring, as expected, since Pederson East Spring is slightly lower in elevation and has a greater hydraulic head differential, and therefore, should be less sensitive to drawdown. The flow at Pederson East ranged from a maximum of 0.255 cfs to a minimum of 0.109 cfs. This represents a 57% change in flow, relative to the maximum flow, over the range of carbonate water levels observed during the POR. The observed decline is very close to the estimated decline in flow. The spring is also responding to the decline in carbonate water levels and head differential as expected.

The relationship of Warm Springs West flow to carbonate water levels in EH-4 is shown in Figure 19. The correlation between discharge and water level for Warm Springs West is quite high again for the entire POR ($r^2 = 0.84$). The slope coefficient of the discharge-water level relationship is statistically significant ($p<0.0001$) and equates to -0.155 cfs per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline in the EH-4 water level, Warm Springs West loses about 0.155 cfs of discharge (about 4% relative to the maximum discharge observed). As above, the next question we address is: "Is this reasonable and close to what we expect for this site?"

The flows at Warm Springs West ranged from a maximum near 4 cfs to a minimum of 3.24 cfs. This represents a 19% change in flow, relative to the maximum flow, over the range of carbonate water levels observed during the period of record. The measured change in flow is lower than at Pederson and Pederson East springs. As noted above, this site measures the combined discharge from a number of individual springs. Estimating the hydraulic head differential at the site is more involved and we did not do it for this report (although we did do it in our 2013 report). Suffice it to say that most of the springs contributing to this site are lower in elevation than the Pederson Spring or Pederson East Spring and are therefore expected to be less sensitive to any decline in carbonate water levels.

Apcar Unit and Plummer Unit Sites

Next, we examine the observed and/or expected reductions in discharge at springs on the Apcar and Plummer Units, given the changes in carbonate water levels observed during the pumping test. Springs in all of these areas are lower in elevation than the springs on the Pederson Unit, so they are expected to be less sensitive to declines in carbonate water levels.

At Jones Spring, the correlation with EH-4 elevations is not as strong ($r^2 = 0.44$) but the slope coefficient of the regression is significantly different from zero ($p<0.0001$) (Figure 19). The regression slope equates to 863,955 gallons per month per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline in the EH-4 water level, Jones Spring loses about 863,955 gallons per month (or about 2.5% of the discharge relative to the maximum discharge observed).

Beck et al. (2006) gives the elevation of a benchmark located 140 ft northwest of the Jones Spring pumphouse as 1775.72 ft. The actual spring elevation can't be determined, since the springhead is buried, but assuming the spring is roughly the same elevation as the benchmark, then the estimated hydraulic head differential is about 40 feet at the spring at the maximum water level elevation. The 3.98 ft drawdown in carbonate water levels observed over the POR represents an estimated 10% decrease in the total head differential at the spring. Based on this, we would expect a 10% decrease in flow. The maximum and minimum flows for the POR, as estimated from the regression line, are about 34,000,000 and 30,000,000 gallons per month. (we estimated the max and min discharge from the regression line because of the variability in the data). So the observed decline in flow, 4,000,000 gallons per month or 12% relative the maximum discharge, is very close to what is expected at this spring.

The relationship of Iverson Flume flows to carbonate water levels in EH-4 during the pumping test is shown in Figure 19. The variance captured by the relationship is not very high ($r^2=0.25$) because of the variability in flows, but the slope coefficient is significantly different from zero ($p<0.0001$). The site is located a considerable distance from the springs (about 0.25 miles downstream) and measurements may be responsive to shallow basin-fill aquifer water levels and rainfall runoff, as well as carbonate-rock aquifer water levels. The regression slope equates to 0.1 cfs per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline in the EH-4 water level, Iverson flume loses about 0.1 cfs of discharge (or about 2% relative to the maximum discharge observed).

Discharge measurements at the Iverson Flume gage range from a maximum of 4.7 cfs to a minimum of 4.4 cfs (again, we estimated the max and min discharge from the regression line because of the variability in the data). This represents a decline of 0.3 cfs or 6% over the range of carbonate water levels, relative to the maximum discharge. The springs contributing to the Iverson Flume are much lower in elevation than those on the Pederson Unit. Based on measurements in Beck et al. (2006), the head differential at the springs is estimated to range from 58 to 66 ft. As with Warm Springs West, it is more involved to estimate the head differential for the numerous springs contributing to this site, so we did not do that here. Nevertheless, this site is expected to be much less sensitive to carbonate water level declines, as the data suggest.

1.6.5 Conclusions for Impacts to Springs

Table 1 summarizes the results from the analyses. The springs and flow monitoring sites are ordered in terms of high to low elevation in the table, corresponding to their expected sensitivity to changes in groundwater levels. The results demonstrate that sites are behaving as expected, with the highest elevation springs on the refuge showing the greatest relative decreases in response to declines in groundwater elevations at EH-4. This implies that the triggers for Warm Springs West flows that were established in the 2006 MOA are still valid and important for protecting these springs on the Pedersen Unit of the refuge, the most sensitive springs in the MRSA. Protecting these springs protects the other springs on the refuge as well as much of the dace habitat in the MRSA.

Three other monitoring sites, Baldwin Spring, the Muddy Springs at LDS Farm, and the Muddy River near Moapa, did not show a relationship to EH-4 elevations. Baldwin Spring has an anomalous increase in flows in 2014 (Figure 13), which may indicate a change in site or measurement conditions. The Muddy Springs is the lowest elevation spring in the MRSA and therefore may be expected to be the least sensitive to changes in carbonate groundwater levels. Moreover, as discussed above, the unique geologic conditions at the spring may be related to the lack of any relationship with groundwater levels. In addition, the spring may be affected by recent land use changes upstream and in the area. The Muddy River gage shows an increase in flow since the early 2000s, in contrast to carbonate groundwater levels and most of the springs in the MRSA.

1.7 Unresolved Technical Questions – LWRFS Hydrogeology

- Hydraulic Character of the Kane Springs Wash Fault – specifically, within Kane Springs Valley and northern Coyote Spring Valley.
- Kane Springs Valley as Part of the LWRFS (a proposed pumping test) – hydraulic continuity of the carbonate aquifer in Kane Springs Valley with that underlying Coyote Spring Valley.
- Effects of Pumping in Northern Coyote Spring Valley (a proposed pumping test) – effects of moving carbonate pumping from central to northern Coyote Spring Valley.
- Influence of the Meadow Valley Flow System on Groundwater Levels, Springs and the River – characterize the effects of variable groundwater inflow from Panaca Valley into LMVW on groundwater levels (alluvial and carbonate) in the remainder of the LWRFS.
- Source of and Factors Influencing the Discharge of the Big Muddy Spring – After utilizing water quality characteristics or more specific chemical signatures in an attempt to identify or confirm the source of discharge from the Big Muddy Spring, characterize the timing of climate impacts on the discharge of the spring.
- Develop Early-Warning Triggers for Effective Conjunctive Water Management of the LWRFS – a major undertaking, other fundamental questions to be resolved first.

- Frequency of Pumping Inventory Updates Needed to Implement Conjunctive Management in the LWRFS – TBD; likely minimum biannual since the effects of over-pumping on the Muddy River Springs can take up to 6 months to manifest, and up to 6 months to begin recovering (approximated from the response to the cessation of MX-5 pumping following the Order 1169 pumping test).

- Outstanding Hydrologic Data Needs within and Upgradient of the LWRFS – Additional carbonate monitoring wells in Kane Springs Valley and LMVW.

- Role of "Models" in Effective Conjunctive Management of the LWRFS – Consider at a later date following the resolution of fundamental questions regarding how the system works and responds, for example, to changes in climatic conditions and more generally the availability of groundwater upgradient of the LWRFS.

Section 2 – Description, Status and Recovery of the Moapa dace

2.1 Biology and Management of Moapa Dace

2.1.1 *Brief Background on the Biology of the Moapa Dace*

The Moapa dace (*Moapa coriacea*) is a thermophilic minnow that exists as a relict species of the Colorado River fauna that historically inhabited the pluvial White River system in southeastern Nevada, running approximately 200 miles from the present-day White River to the Colorado River near Lake Mead. Today, few sections of this historic channel exhibit surface flow, and among the largest of these now isolated spring systems are those supporting the Muddy River. The Muddy River springs that form the headwaters (referred herein as the Muddy River Springs Area), now support eight endemic aquatic taxa, and among them the endangered Moapa dace (Figure 20). This species is taxonomically unique, and the sole extant member of the genus *Moapa*. Threats to Moapa dace and other native fish of this system are typical of the desert Southwest, including the introduction of nonnative fishes, and the modification of stream habitat for human development (e.g., agricultural, municipal, and recreational). In the 1960s, significant concerns in declining population size, unique biodiversity, and heavily human-impacted spring habitats resulted in the listing of Moapa dace under the Endangered Species Preservation Act of 1966, and later the ESA of 1973 (USFWS 1996).

The Moapa dace is unusual among minnows (family: Cyprinidae) given its unique biological requirements for both thermal and flowing spring water. The Muddy River Springs collectively discharge approximately 50 cfs from approximately 20 spring outflows at 31.0 to 32.0 ℃ degrees (88-90 °F). Waters cool with distance from the source, and Moapa dace occupy the upper two kilometers between 26.0 and 32.0 ℃ (Scoppetone 1993). Their habitat include spring pools, tributaries and the main stem Muddy River. Spring pools are characterized by pebble and organic substrate, with tributaries exhibiting areas of clay, sand, pebble and cobble substrates. Habitat use varies by life-stage, with larval fish found only near the spring sources with low velocity. Juvenile fish occur in tributaries and faster moving water as they grow larger. Adult dace historically occurred throughout the system, and frequently in the cooler and larger mainstream habitats, but also traverse upstream to spawn (Scoppetone et al. 1992). Moapa dace spawn year-around, but predominantly in the spring, and to a lesser extent in the fall (Scoppetone et al. 1992). The largest adults historically occurred in the mainstream river (Scoppetone 1987) where more abundant food items drift downstream. Stomach contents reveal that their diet is omnivorous and diverse, and variously include beetles, moths and butterflies, true flies, true bugs, caddisflies, mayflies, damselflies and worms, as well as algae, vascular plants, and detritus (Scoppetone 1987). The maximum size and age of Moapa dace is believed to be about 120mm fork length (~4.7 in.) and approximately four years (Scoppetone et al. 1992).

2.1.2 *Anthropogenic Impacts and Conservation at the Moapa Valley National Wildlife Refuge*

Negative impacts to aquatic species have occurred through two parallel processes: the modification of natural habitat by water development for irrigation, recreational and domestic uses, and the introduction of exotic and invasive plants and animals. These factors have variously affected most areas of the Muddy River Springs Area, both independently and synergistically, and resulted in harm to Moapa dace (USFWS 1996).

Although some modifications to the MRSA occurred prior to the discovery of Moapa dace in 1938, such as the introduction of western mosquitofish (*Gambusia affinis*), Moapa dace was relatively common, and remained so until approximately 1950 (Hubbs and Miller 1948, La Rivers 1962). Notable species-level declines in the abundance of Moapa dace occurred primarily after the introduction of non-native shortfin mollies around 1963 (Deacon and Bradley 1972). The need to understand the interaction between shortfin mollies and Moapa dace led to several investigations, showing that mollies overlap in occupied habitat with Moapa dace (Deacon and Bradley 1972, Scoppetone 1993), and that laboratory experiments reported that shortfin mollies predate on fish larvae (Scoppetone 1993).

Concurrent with the introduction of short-fin mollies, increases in water development combined to threaten the persistence of the species, and resulted in the establishment of the Moapa Valley National Wildlife Refuge (MVNWR) in 1979. This refuge was unique for its time, as few refuges were established expressly for endangered fishes. Presently, the Refuge is comprised of three spring systems (Plummer, Pedersen, and Apcar, Figure 20) and represents approximately 10% of the species' historic range. When acquired, no Moapa dace remained in the spring systems protected as Refuge, as the Plummer and Pedersen streams were previously converted to chlorinated swimming pools for recreational use, and Apcar was modified from its natural course for municipal water supply. Many of the historic channels were modified to earthen and concrete ditches (USFWS 1996). Since these areas were now part of the Refuge, habitat restoration efforts have returned much of the wetted habitat back to flowing streams and Moapa dace repatriated to most spring systems. Restoration efforts up through the early 1990s were extremely successful and estimates for population size of Moapa dace ranged from 1565 - 3841 fish as estimated by snorkel surveys (Scoppetone et al. 2005). However, the invasive blue tilapia (*Oreochromis aureous*) invaded the Muddy River Springs Area in 1995 (Scoppetone et al. 2005) and dramatically reduced the entire population. Current knowledge of this system suggests that the negative interaction between tilapia and Moapa dace was so severe that recovery of this species depended on the removal of tilapia from the system, a major recovery action only recently completed in full (Muddy River Biological Action Committee, *pers. comm*.).

Major events in the conservation history of Moapa began again in 2005, with the Southern Nevada Water Authority acquiring the Warm Springs Natural Area, which provided access and direct management of nearly all of the historic range of Moapa dace outside the MVNWR. At this time, more habitat became available for future restoration efforts. Concomitantly, the establishment of the Memorandum of Agreement between the USFWS and area stakeholders

(USFWS 2006a) was drafted due to increasing concerns for adequate water to support Moapa dace in the future. The MOA was especially significant for protection of the Moapa dace for two reasons. The first was that this document outlined specific water-level triggers (discussed below, Section 2.1.4) to protect in-stream flow, but also provided explicit financial commitments from most parties. Most important was the acknowledgement that all parties work cooperatively to improve the status of the endangered Moapa dace. The resources afforded by the MOA provided the necessary impetus to fund a mix of on-the-ground restoration projects, increased awareness of imperiled aquatic species, and provided funds for research necessary to guide effective management. This period of collaboration and funding was significant, as it occurred during a period of historically low population estimates of less than 500 total individuals of Moapa dace (Figure 21). Major accomplishments at the MVNWR included major stream reconstruction, public education for native fishes of the Muddy River, and the stream-side viewing window on the Plummer Stream.

The most recent phase of recovery actions began in the early 2010s, and include the costly installation of removable and permanent fish barriers to exclude invasive tilapia, along with the stepwise piscicide treatments to remove non-native fishes throughout the system. Working from upstream to downstream, the entire Muddy River system from the headwaters springs to the Wells Siding diversion had been treated to remove non-native fishes at least once by spring of 2019. Beginning in the early 2010s with coordinated restoration activities with partner agencies, the population of Moapa dace has rebounded in some streams, but still remains low in others.

2.1.3 *Connectivity and Fish Passage*

The complex life-history of Moapa dace requires stream habitats from the low-velocity headwaters to the mainstream Muddy River, and presents challenges for both habitat restoration and the management of invasive species. Logistical concerns for both piscicide treatments and restoration activities necessitate that stream segments are restored in manageable sections. Therefore, site restorations often require the temporary installation of fish barriers to prevent non-native fishes from entering stream segments. However, Moapa dace are particularly ill-suited to habitat fragmentation given their short lifespan and habitat needs. Specifically, headwater reaches are required for spawning and the inability for fish to gain access for as few as three or four consecutive years (i.e., the life-span of Moapa dace) could potentially drive a stream reach toward extirpation. However, the significant time and resources required to install or remove non-native fish barriers represent a considerable and complex decision.

A recent study to investigate habitat fragmentation and fish abundance employed a stochastic individual-based modeling approach to understand the relationship of how changes in carrying capacity of specific stream segments influence the potential for extirpation, and the overall population size of the species (Perry et al. 2015). In this study, empirical data (Scoppetonne and Burge 1994) and basic theoretical information on fishes were used simulate individual survival and estimate carrying capacity. Carrying capacity of stream segments is variously affected by many factors such as physical habitat characteristics, barriers to migration, and invasive species interactions, among others. Perry et al. (2013) simulated migration barriers to upstream and downstream travel on carrying capacity, and how carrying capacity is related to overall population size. Of particular importance in this study was the finding that barriers to migration resulted in extirpation of populations upstream of barriers when populations were very small, and that migration buffered these effects. The second finding was that when population sizes were calibrated to current estimates of abundance, the carrying capacity of the mainstream Muddy River was twice that of the smaller tributaries. This is significant at present as almost no Moapa dace occur in the mainstream habitat in recent years (Table 2). These results highlight the importance of fish passage and connectivity for the recovery goals of Moapa dace.

As numerous restoration actions have targeted individual reaches, the lack of connectivity has become an increasingly important next-step in the recovery of the species. Prominent examples for increasing fish passage in the Muddy River Springs Area include the road crossing and stream gauge for the upper and lower Pedersen stream (reaches 5 and 5.5, respectively; Figure 22). At present, this example highlights a situation where the largest population (reach 5.5) exists immediately adjacent to a very small population (reach 5). The relatively high quality of habitat both above and below the road crossing likely suggests that the near-absolute lack of fish passage may be responsible for the low population size in the upper Pedersen Stream (reach 5).

2.1.4 *Protection of Spring Flow and Habitat Needs of the Moapa Dace*

As restoration efforts continue to improve the quality of stream habitats with respect to introduced fishes and the biological interactions harmful to Moapa dace, biologists have increasingly considered the role of water diversions and groundwater pumping on the recovery of Moapa dace. At present and within the last decade (see Section 2.2, *below*), Moapa dace occur almost entirely within the tributary springs and streams emanating from the MVNWR (Table 2). Given that the carbonate rock aquifer extends with relatively homogeneity under the MRSA (Dettinger et al. 1995), and that spring discharge in this area reflects head pressure in the aquifer (Section 1.6, *herein*), flows in the MRSA provide an indication of available surface water required to support aquatic species (USFWS 2006a, Mayer and Congdon 2008). In particular, the springs on the Refuge are among the highest elevation in the MRSA (Section 1.6, *herein*; DOI 2013), and provide the basis for several agreements between the United States Fish and Wildlife Service and nearby water users (USFWS 2006a, USFWS 2006b). The USGS water gauging station *Warms Spring West near Moapa* (gage # 09415920), collectively measures the two highest elevation springs (Pedersen and Pedersen East springs) and were therefore used to define protective water flow triggers and their associated curtailment of water resources.

The first agreement, the 2006 Memorandum of Agreement (USFWS 2006a) pertains to groundwater pumping and diversions between the USFWS and four water users (Southern Nevada Water Authority, Moapa Valley Water District, Coyote Springs Investment, and Moapa Band of Paiutes) in the immediate MRSA and adjacent Coyote Springs Valley. Here, protective triggers aim to ensure springflows remain at approximately current discharge levels; presumptively, levels where Moapa dace have been maintained or increased in the past. As defined in this MOA, specific triggers begin when spring flow at the gauge *Warms Spring West near Moapa* drops below 3.2 cfs, at which point signatories initiate formal discussions to reduce water usage. Flows below 3.0 cfs subsequently trigger a series of thresholds that result in the curtailment of pumping for the four stakeholders. The second agreement, a Stipulated Agreement with Lincoln County Water District and Vidler Water Company, arose from concerns of USFWS and the potential protest of future groundwater withdrawal in the upstream Kane Springs Valley, a nearby upgradient basin with potential effects on the MRSA (USFWS 2006b; Section 1.13, *herein*). This Agreement was drafted at the same time and similarly initiates discussion of water conservation at triggers below 3.2 cfs, reduced groundwater pumping below 3.1 cfs, and total cessation of pumping below 3.0 cfs. The USFWS considers these agreements as central to the maintenance and recovery of the Moapa dace due to its complex habitat requirements.

The biology of Moapa dace simultaneously requires both a diversity of habitats (high temperature springheads, small tributaries, and high velocity reaches), and the need for ongoing migration between them. This complex life-history highlights the need to understand the interaction of hydrologic parameters and species needs. To date, one published study investigated the interaction of spring discharge and habitat availability for Moapa dace. The approach used in this study employed stream modeling to predict habitat use and the change in habitat availability with change in springflow. The study was conducted by Hatten et al. (2013), *An Ecohydraulic Model to Identify and Monitor Moapa Dace Habitat*, and was explicitly designed to investigate the potential of groundwater pumping and the associated reduction in springflows. This study evaluated the uppermost reaches of Moapa dace habitat on the Moapa Valley National Wildlife Refuge, and the springflows associated with the Plummer, Pedersen and Apcar springs (Figure 22). The habitat modelling used traditional stream metrics to explain fish presence, and the change in spring flow simulated using River2D, a extensively verified modeling package developed for streams and rivers. The first part of this study involved the fine-scale determination of habitat used by Moapa dace, and determined what features of the habitat most explained where fish occur. Results of habitat modeling by univariate logistic regression identified that water depth was the most important stream parameter explaining where dace occurred, followed (in decreasing order) by substrate (sand, gravel, etc.), and Froude number (stream type such as pool, riffle, glide, etc.). Similar results using a multivariate model selection approach (AIC) showed that the top performing model included depth, substrate and stream velocity.

Most interesting, Hatten et al. used River2D to estimate amount of habitat available for Moapa dace and how the amount of habitat would change with increasing or decreasing stream flow. Simulations included an increase or decrease in flow by 10, 20 and 30 percent relative to base flow. Results varied among the three streams, but habitat simulations in all three streams for reduced flows (-10%, -20%, -30%) produced less habitat for Moapa dace. Increasing flow produced increasing habitat proportionally for Plummer and Apcar streams, while habitat for fish in Pedersen increased and plateaued at the 10% water increase. Thus, this study suggests that any reduction in flow will negatively affect the amount of habitat at all three springs on the refuge for Moapa dace.

2.2 Current Status of the Moapa Dace

2.2.1 *Historical and Current Population Estimates of Moapa Dace*

The population size of Moapa dace is estimated bi-annually in the spring and fall seasons. Early surveys for this species (Scoppetone et al. 1998) found that snorkeling was an effective method to estimate population size without handling stresses associated with other methods. Surveys are conducted from downstream to upstream in 16 stream segments (Figure 22) to eliminate turbid conditions caused by upstream counters. In recent years snorkel surveys have been conducted using trained representatives from USFWS, Nevada Department of Wildlife, and the Southern Nevada Water Authority. Surveys of Moapa dace have indicated fluctuations in population size. Figure 21 shows the biannual estimates for Moapa dace from 2005 to spring 2019. Abundance appears to be strongly influenced by both habitat restoration, restored or lack of connectivity, and the biological interactions of predatory non-native fishes, the impacts of which depend on site-specific habitat characteristics and species-specific interactions. Although the Muddy River Springs Area is now free of blue tilapia, western mosquitofish and short-fin mollies remain in the system.

The gradual increase in population size after 2012 (Figure 21) is suspected to correspond to the period following population expansion after blue tilapia was eradicated from the system. Concurrently, significant habitat improvements were completed between 2013 and 2016 on the Warms Springs Natural Area in reach 5.5 (Figure 22). Also noteworthy is that the mainstream Muddy River and upper areas of the North and South Fork (reaches 15 and 16, respectively), at present, do not support significant numbers of Moapa dace. The upper reaches have not been recolonized since the piscicide treatments to remove blue tilapia. The larger habitat of the mainstream Muddy River (reaches 11, 12 and 13) likewise do not support dace. Given the historical importance of the mainstream channel to support large numbers of large dace (and associated higher fecundity typical of larger fishes), understanding the causes for the current low numbers of fish in these reaches remain a research priority.

2.3 Summary

The Muddy River Springs Area support several rare and endemic aquatic species that occur nowhere else. The relative scarcity of water in the Mohave Desert and the long-term isolation of these springs has resulted in the evolution of unique species, among them the endangered Moapa dace. This species became endangered due to the combined threats of habitat modification and the introductions of invasive species in the Muddy River Springs Area.

This stream minnow is characterized by an unusual life-history, where its existence depends on the high temperature springs and their outflow streams. Even more specialized for the Moapa dace is its complex habitat requirements, whereby this species uses the spring headwaters to reproduce, the larger downstream habitats to effectively grow, and unobstructed fish passage to continually move between these habitat types during the lifespan of individual fish.

The USFWS established the Moapa Valley National Wildlife Refuge to protect water resources and improve habitat for this species. Over the course of 40 years (1979-2019) the Refuge and adjacent Warms Springs Natural Area have significantly improved the habitat for Moapa dace. Among the major recovery actions include the removal of non-native fishes by piscicide treatment, and the repair of barriers that prohibit fish passage between upper and lower sections of the streams. Estimates of population size for Moapa dace have fluctuated in different stream segments over time as recovery efforts have restored habitat and removed the invasive and predatory fishes from the system. Recovery success over the most recent decade as indicated by surveys, shows the population size of Moapa dace has increased from its lowest point of 500 fish in 2008 to approximately 1500 fish in 2019.

Integral to the recovery and future management of the Moapa dace beyond restoring streams to natural conditions and removing non-native fishes is the maintenance of adequate flow in the Muddy River. Several water-use agreements among water users and the United States Fish and Wildlife Service have afforded protection to aquatic species of the Muddy River Springs Area, based on evidence discussed above in this report (Section 1.1.3). The first agreement, the 2006 MOA, ensures that flows in the system are maintained at approximately the current rate that has maintained Moapa dace as measured at the Warms Springs West near Moapa gauge. The 2006 MOA provides for formal discussion among stakeholders to reduce groundwater pumping in the Muddy River Springs Area and Coyote Springs Valley when the flow drops below 3.2 cfs, and a curtailment at 3.0 cfs or below. The second agreement, an Amended Stipulation for Withdrawal of Protests between the Lincoln County Water District, Vidler Water Company, and USFWS pertains to groundwater pumping in the upstream Kane Springs Valley, and similarly initiates discussion of reduced groundwater pumping and total cessation of pumping at 3.2 cfs and 3.0 cfs, respectively. These agreements are important protective measures to ensure the maintenance of the endangered Moapa dace for several reasons. The first is that restoring streams via habitat improvement, although necessary, is not sufficient to recover the species. Water level is also important. Recent published studies (Hatten et al. 2013) show that water depth predicts the distribution of Moapa dace, and most importantly, water flow is directly related to the amount of habitat available. This study shows via simulations that any reduction in flow results in reduced habitat for Moapa dace. At present, most stream habitat has been significantly improved by ongoing restoration efforts by the USFWS and partners agencies over the last 40 years, and thus the most important factor likely to influence the successful recovery of this species moving forward is the maintenance of surface flows in the system.

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Section 4 - Figures and Tables

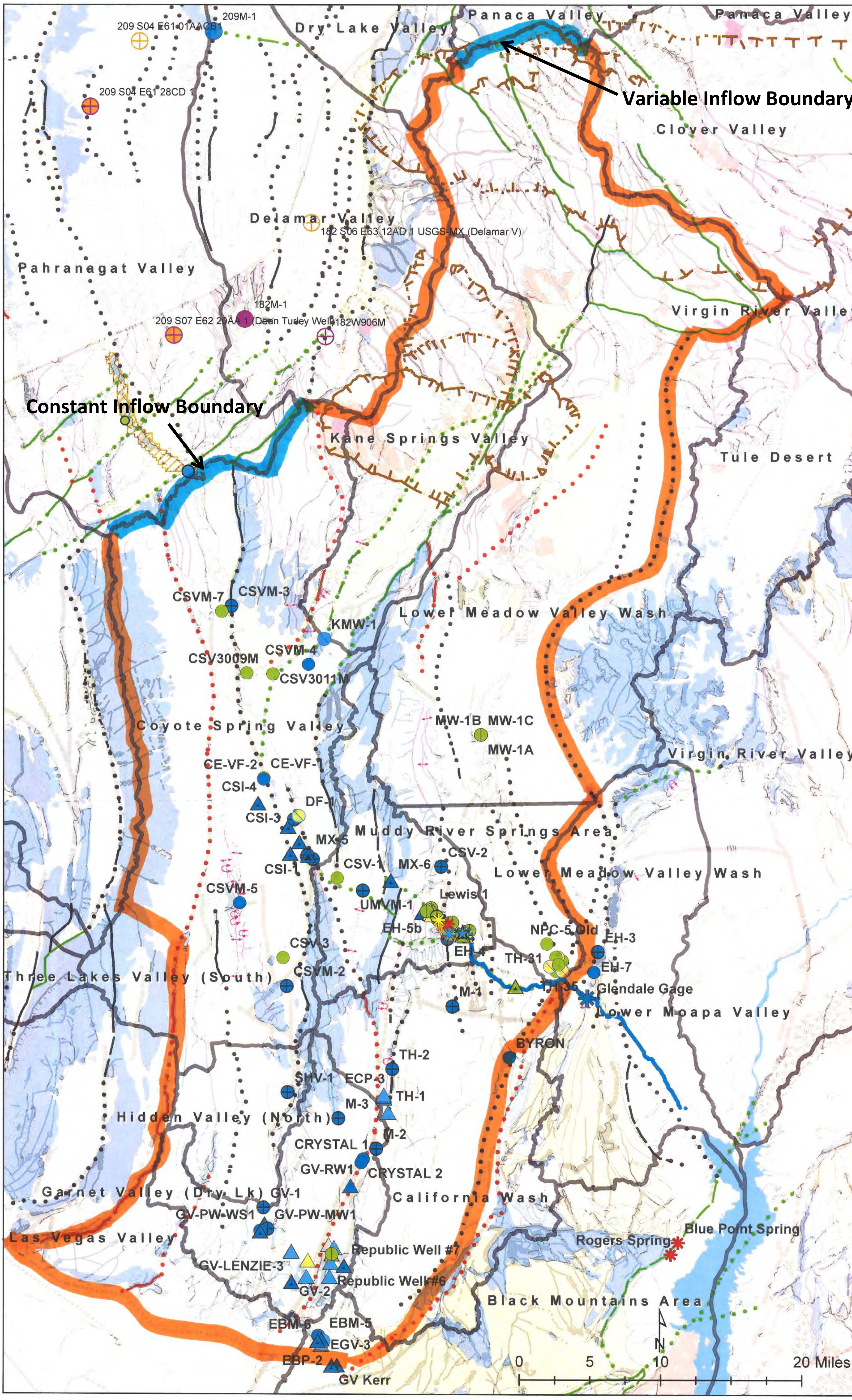

Figure 1. Lower White River Flow System; no-flow boundaries (with possible minor leakage across the Muddy Mountain thrust and northern strand of the Las Vegas shear zone) – orange, constant and variable inflow boundaries – blue.

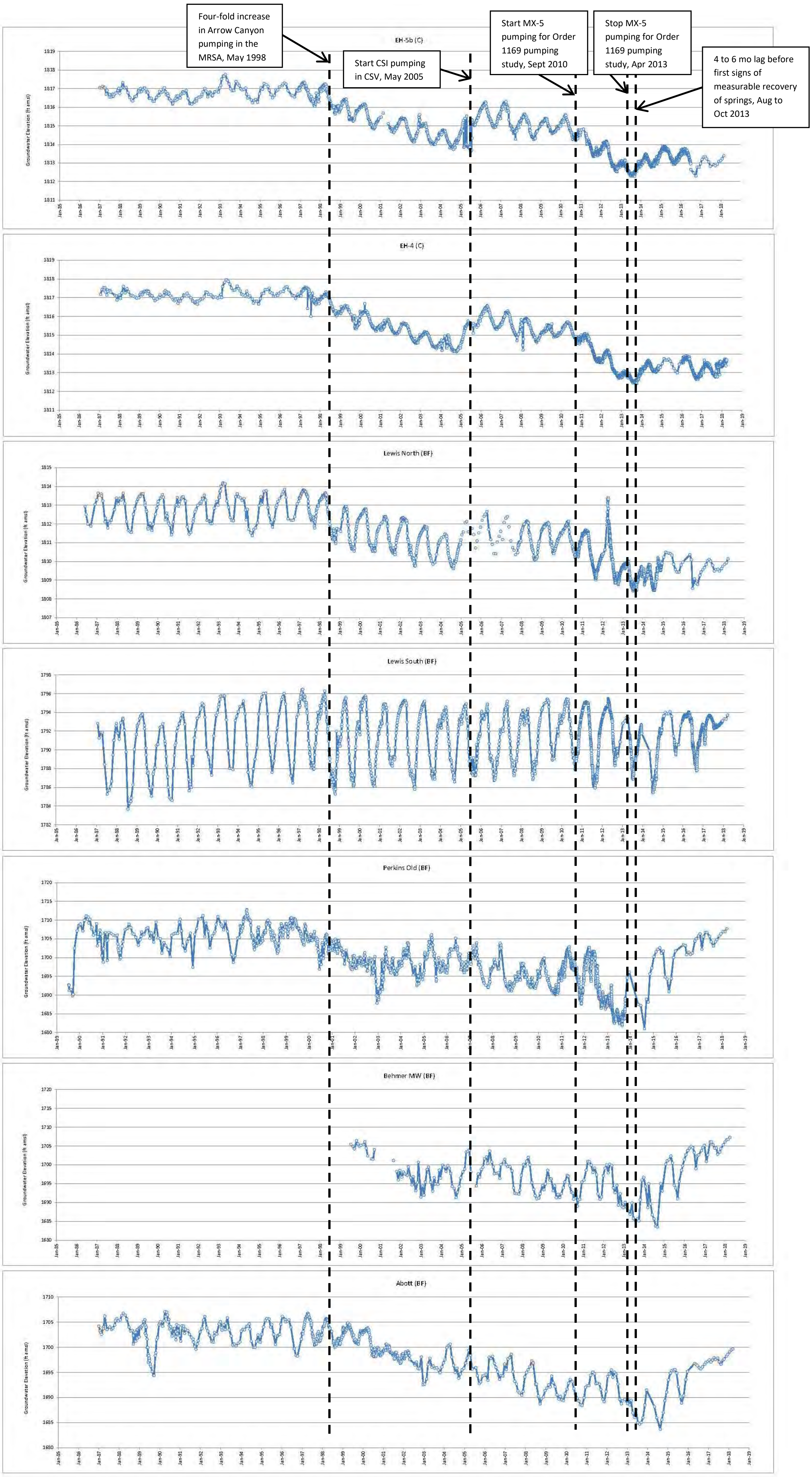

Figure 2. Water levels in alluvial and carbonate monitoring wells (NDWR 2018a) respond more or less in sync to significant increases / decreases in carbonate pumping in the MRSA and Coyote Spring Valley (annotation).

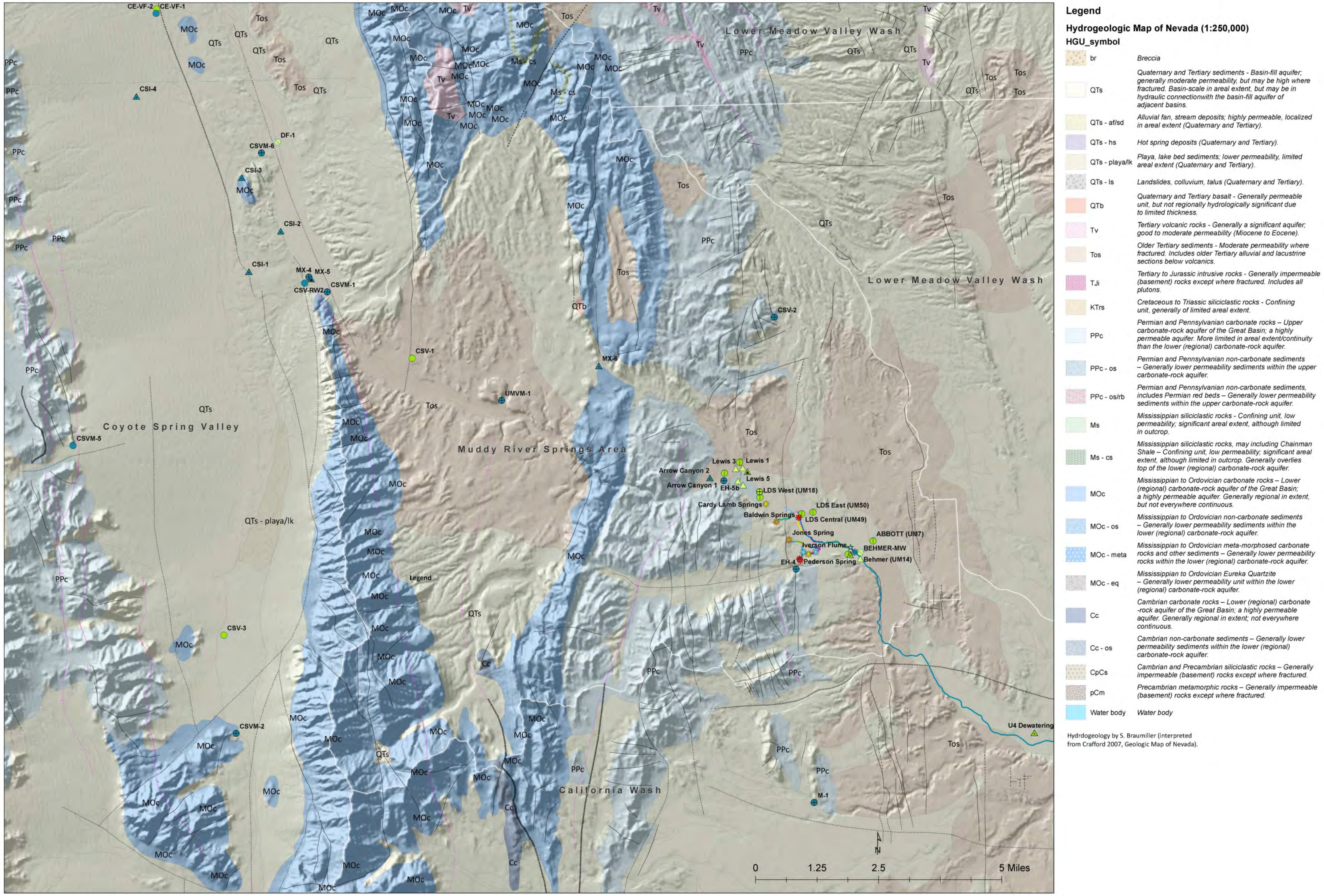

Figure 3. Hydrogeologic map showing the distribution of alluvium (QTs), Muddy Creek Formation (Tos), Permian to Pennsylvanian carbonate rocks typically associated with the "upper" carbonate-rock aquifer (PPc), and Mississippian to Cambrian carbonate rocks composing the regional ("lower") carbonate-rock aquifer within the MRSA (MOc and Cc). Hydrogeologic units interpreted by the author from the geologic map of Crafford 2007 (unpublished to date).

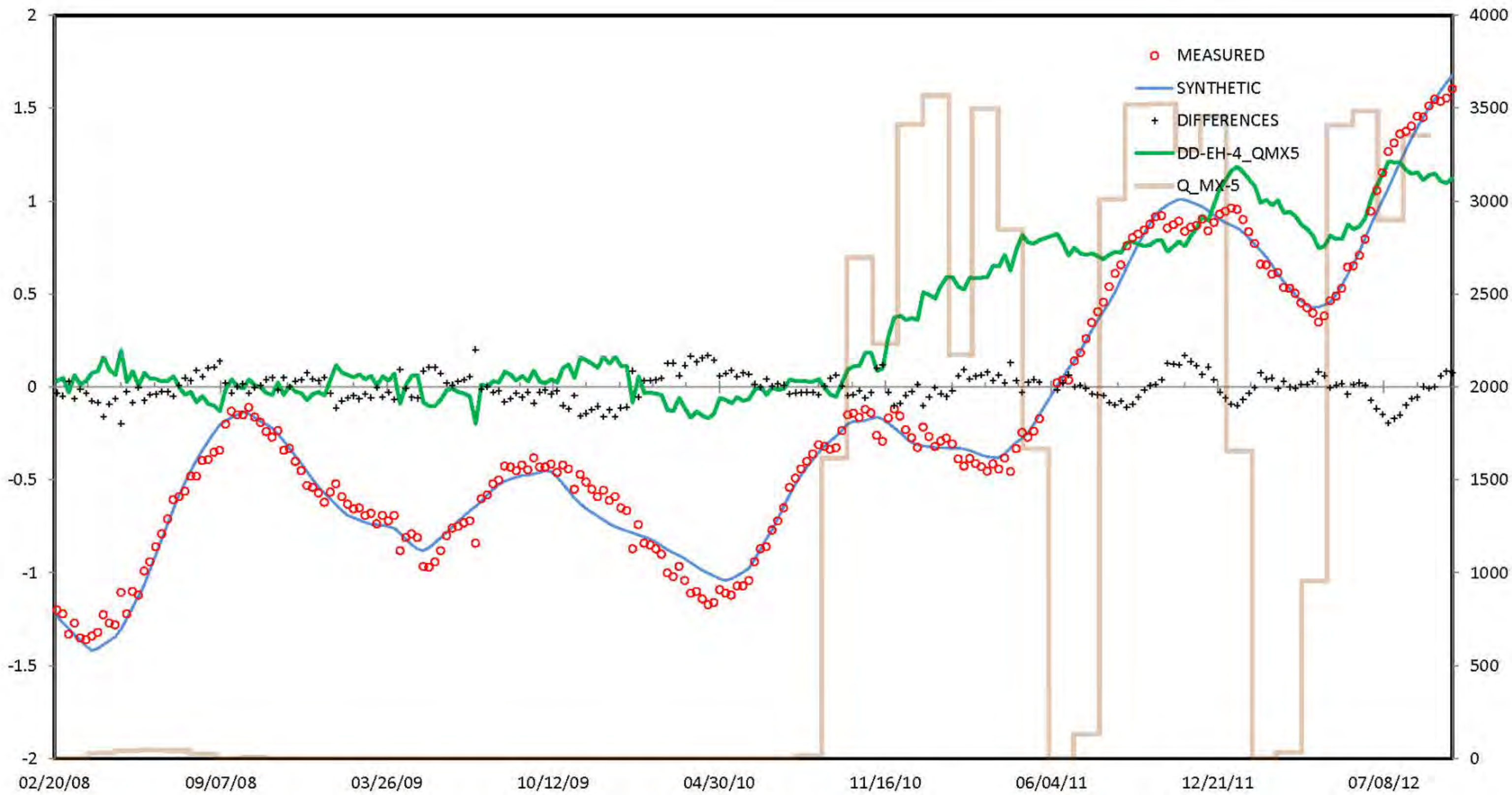

Figure 4. One of many possible examples from the Department of the Interior (2013) analysis of the Order 1169 pumping test, showing that the SeriesSEE approximation / simulation of (total) drawdown at carbonate well EH-4 during the test compares well, or even exceeds, that simulated by numerical models (SNWA 2009b and Tetra Tech 2012), providing a reasonable degree of confidence in our isolation (estimate) of drawdown induced by MX-5 pumping as of the official end of the test in December 2012 (also shown).

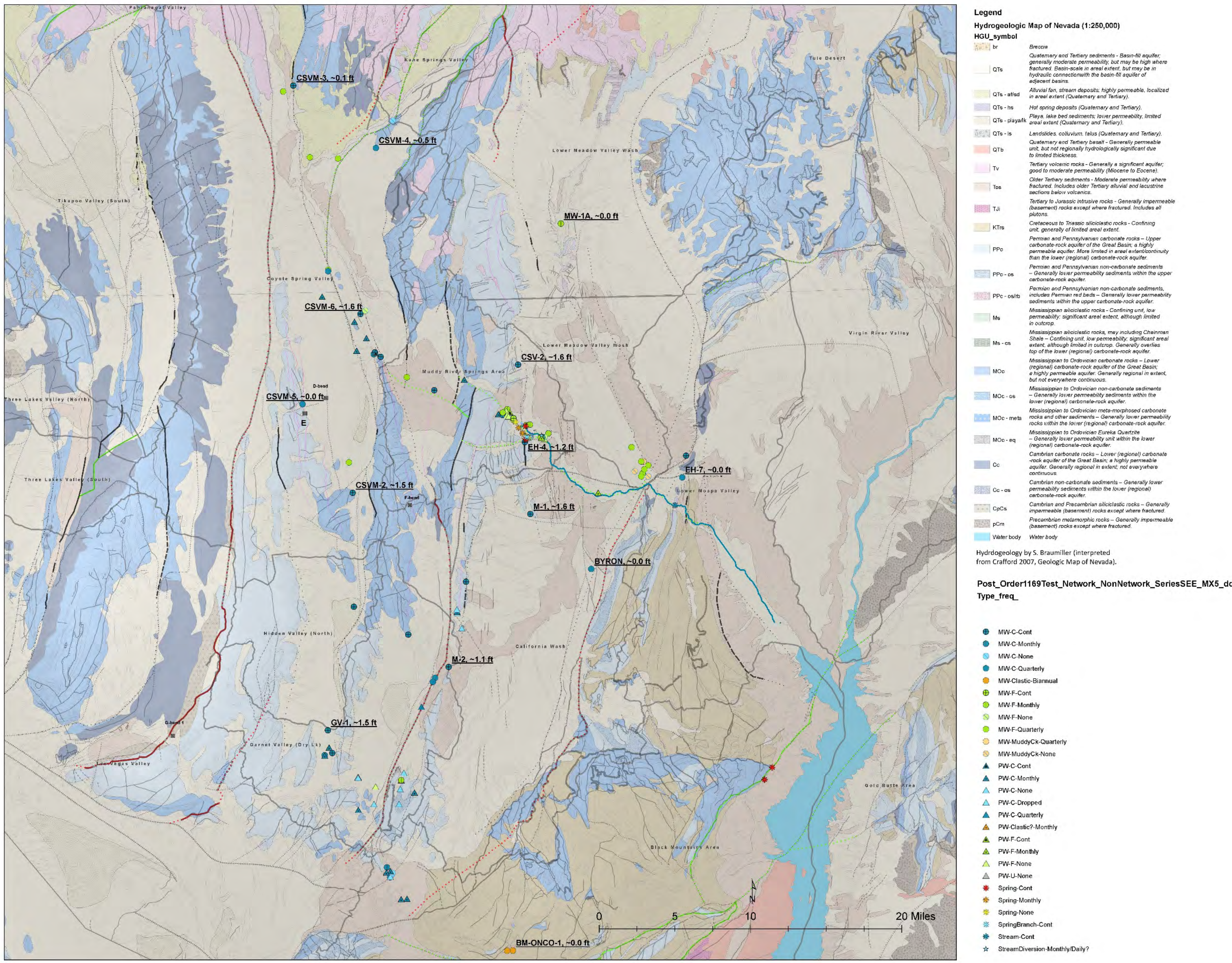

Figure 5. SeriesSEE estimates of drawdown induced by MX-5 test pumping during the Order 1169 pumping test, 9/15/2010 to 12/13/2012. Base hydrogeologic map interpreted by the author from the geologic map of Crafford 2007 (unpublished to date).

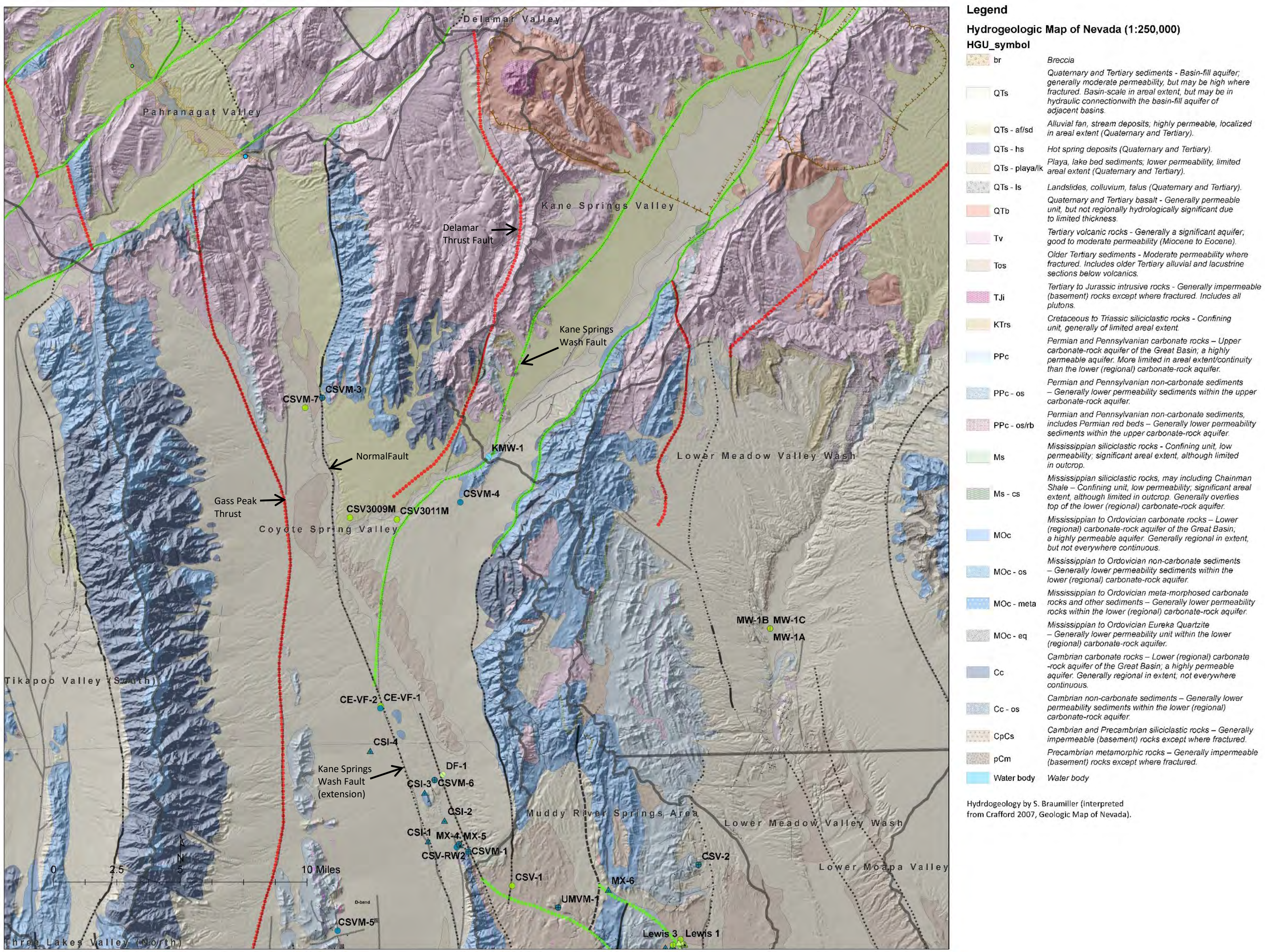

Figure 6. Hydrogeologic map showing Kane Springs and Coyote Spring valleys, carbonate monitoring wells, the Kane Springs Wash Fault (and extension), Delamar thrust fault, normal fault passing through the areas of CE-VF-2 and CSVM-3, Gass Peak thrust, and normal fault east of CSVM-6, MX-4, MX-5 and CSVM-1. Hydrogeologic units interpreted by the author from the geologic map of Crafford 2007 (unpublished to date).

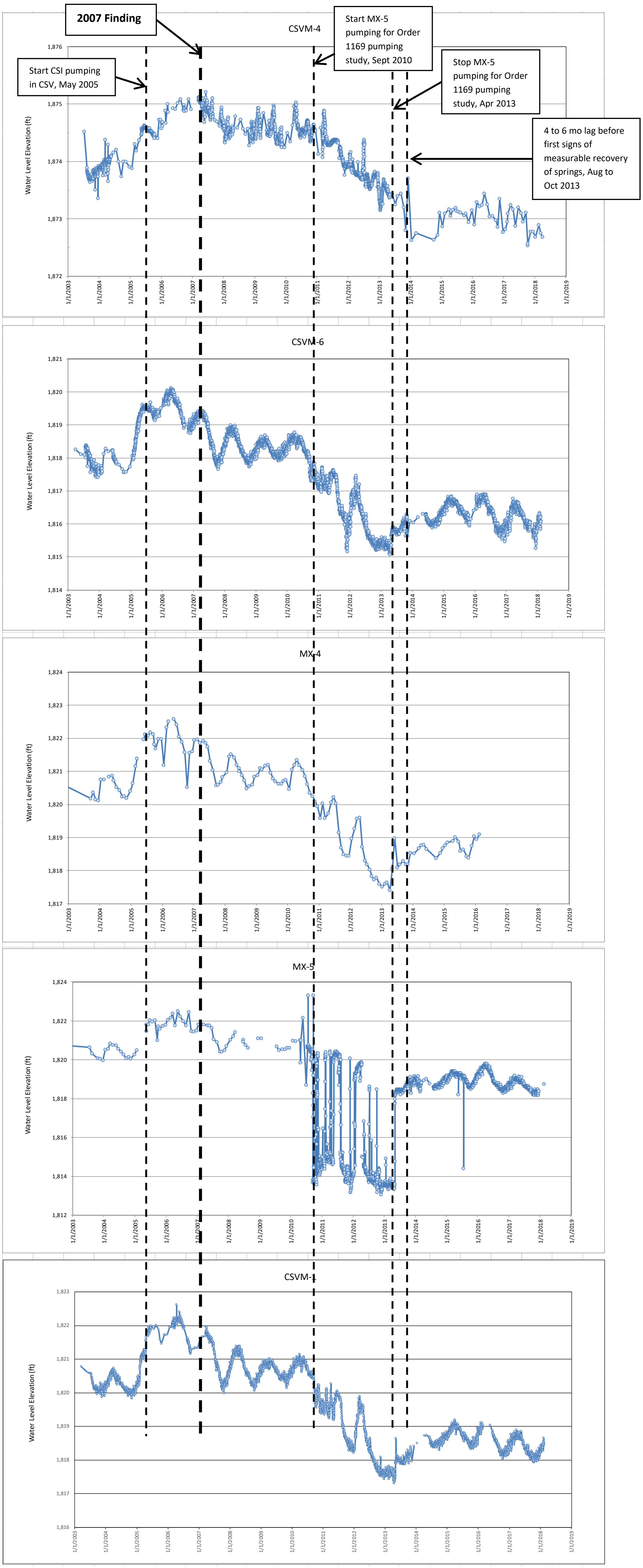

Figure 7. Change in water levels in carbonate well CSVM-4, northern Coyote Spring Valley, versus CSVM-6, MX-4, MX-5, and CSVM-1 in the central part of the basin prior to the 2007 finding (NSE 2007) and during the Order 1169 pumping test (NDWR 2018a); significant increases / decreases in carbonate pumping in the MRSA and Coyote Spring Valley (annotation).

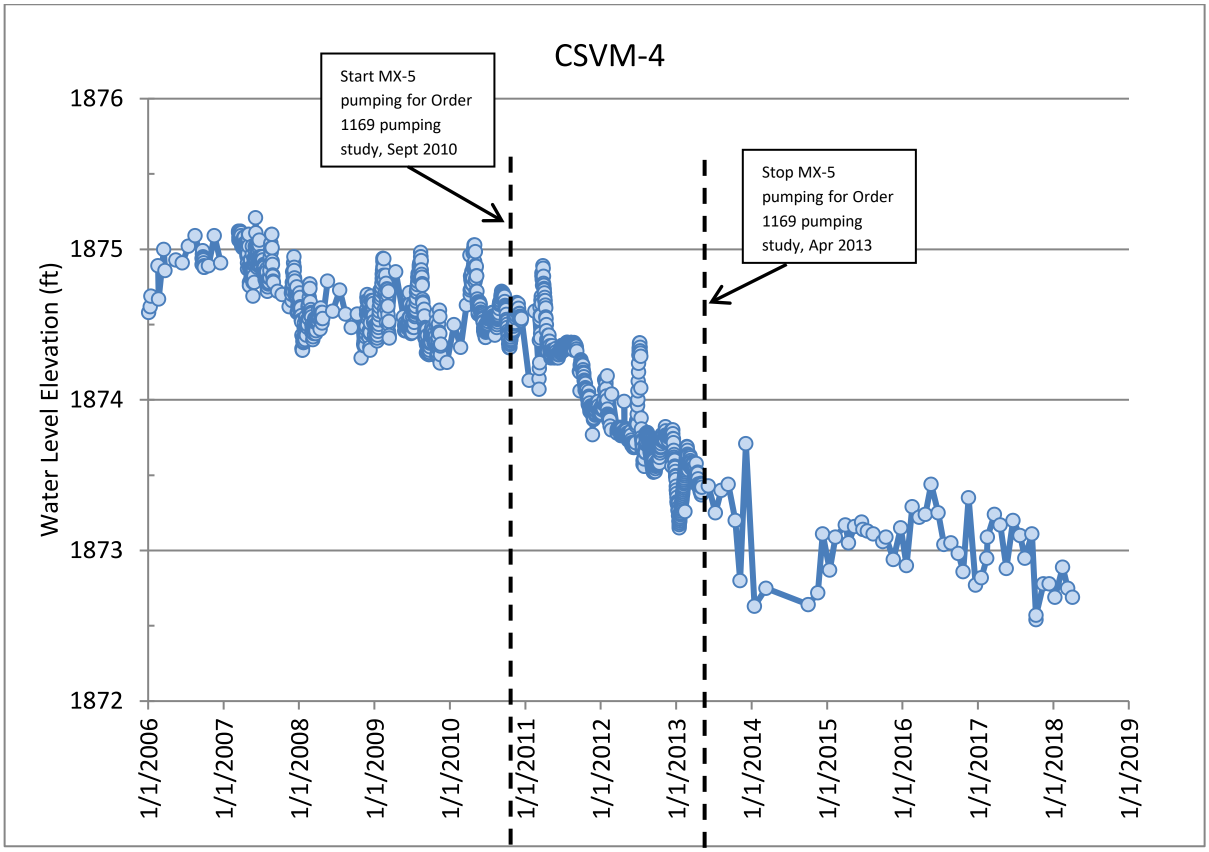

Figure 8a. Change in water level in carbonate monitoring well CSVM-4, northern Coyote Spring Valley, during the Order 1169 pumping test (~1.2 ft), September 2010 to December 2012 (NDWR 2018a).

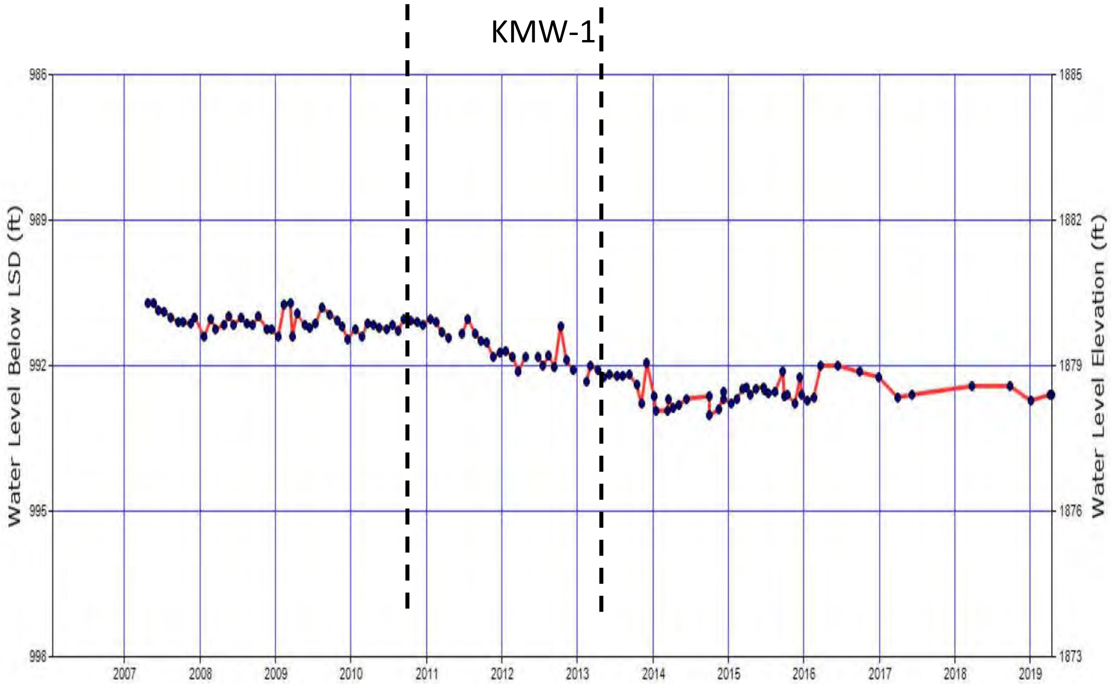

Figure 8b. Change in water level in carbonate monitoring well KMW-1, southern Kane Springs Valley, during the Order 1169 pumping test (~1.1 ft), September 2010 to December 2012 (hydrograph after NDWR 2019c).

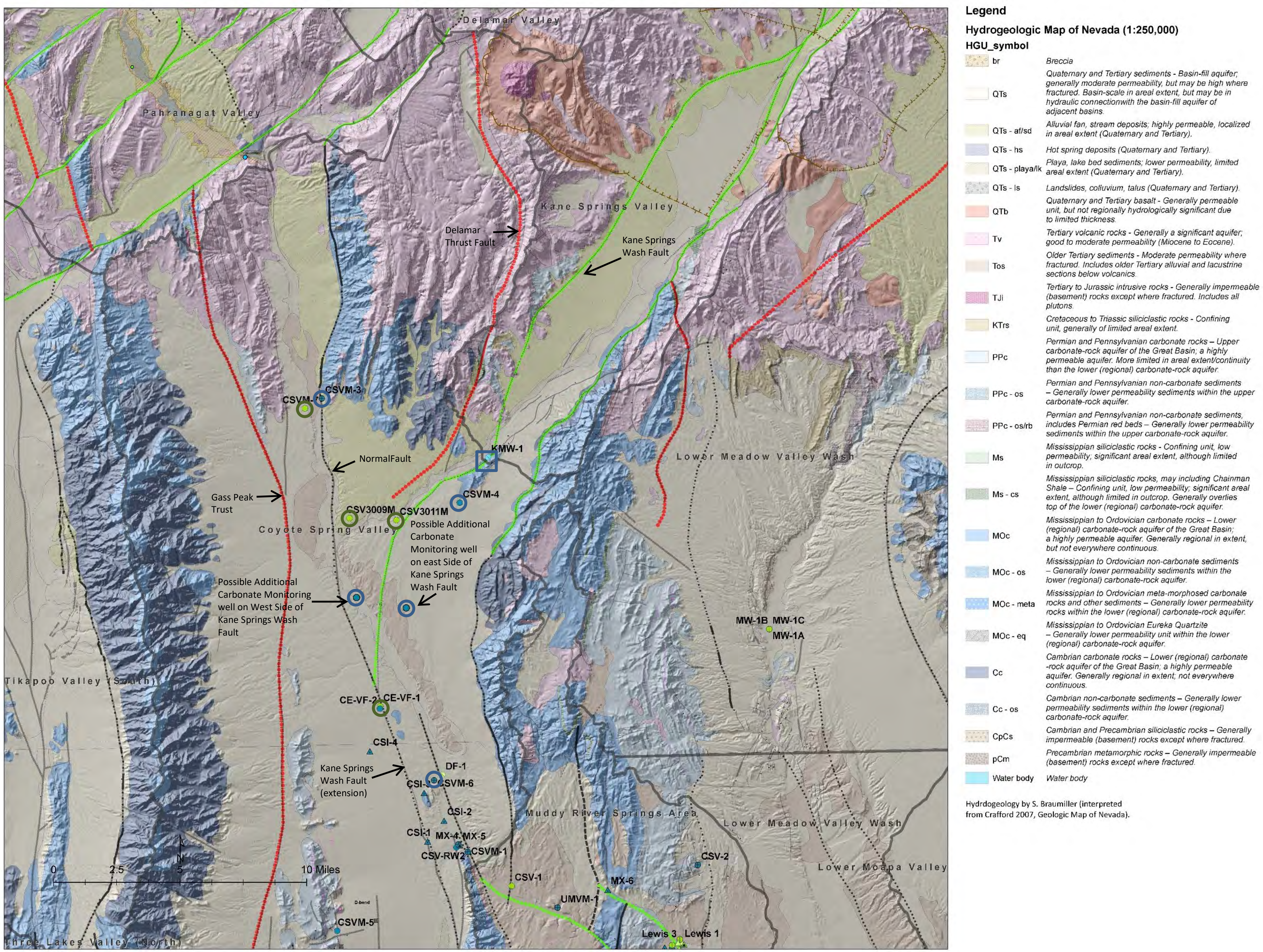

Figure 9. Hydrogeologic base map with locations of proposed observation wells (circles) for a long-term pumping test in carbonate well KMW-1 (square) in Kane Springs Valley. Hydrogeologic units interpreted by the author from the geologic map of Crafford 2007 (unpublished to date).

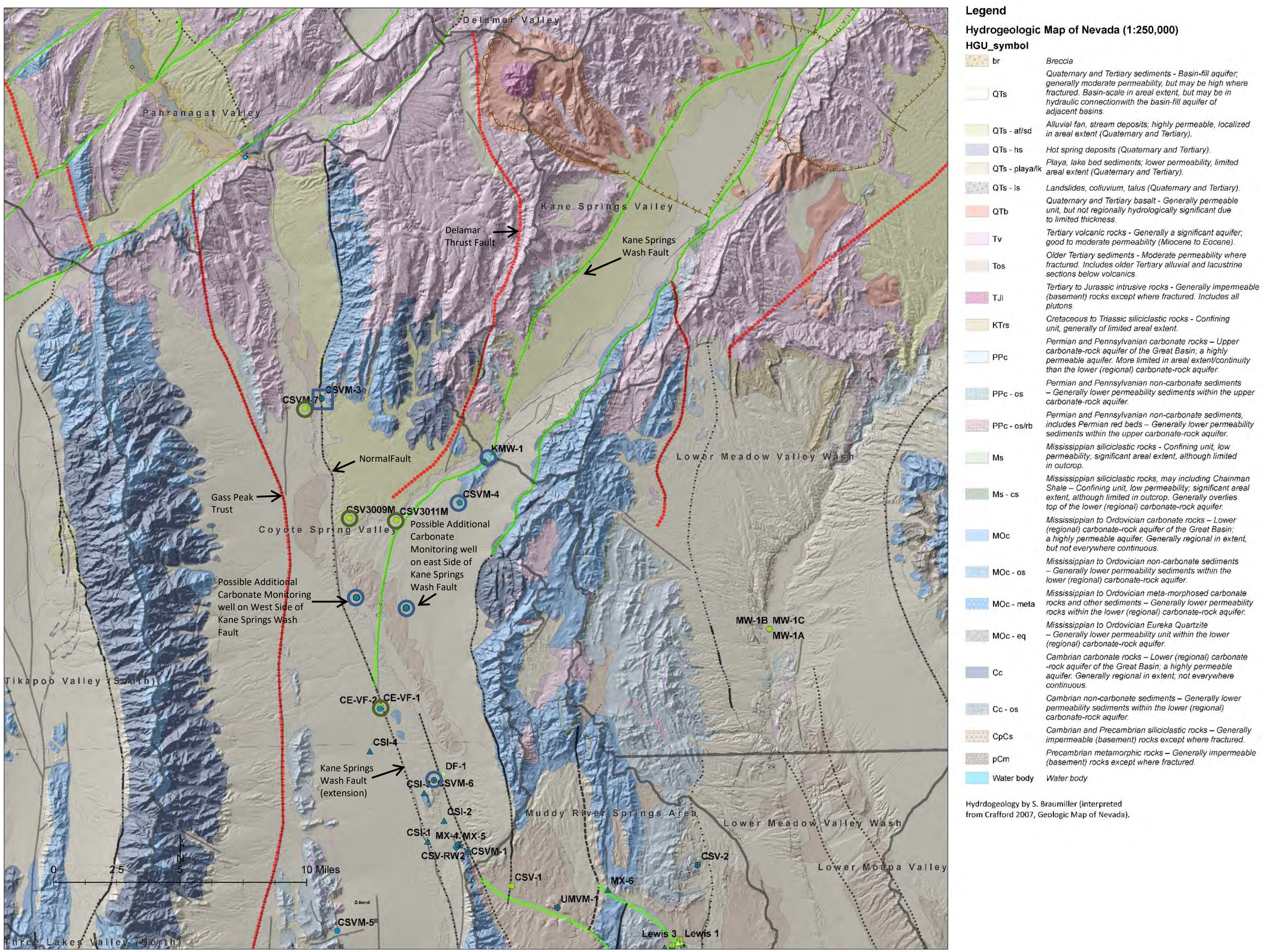

Figure 10. Hydrogeologic base map with locations of proposed observation wells (circles) for a long-term pumping test in carbonate well CSVM-3 (square) in northern Coyote Spring Valley. Hydrogeologic units interpreted by the author from the geologic map of Crafford 2007 (unpublished to date).

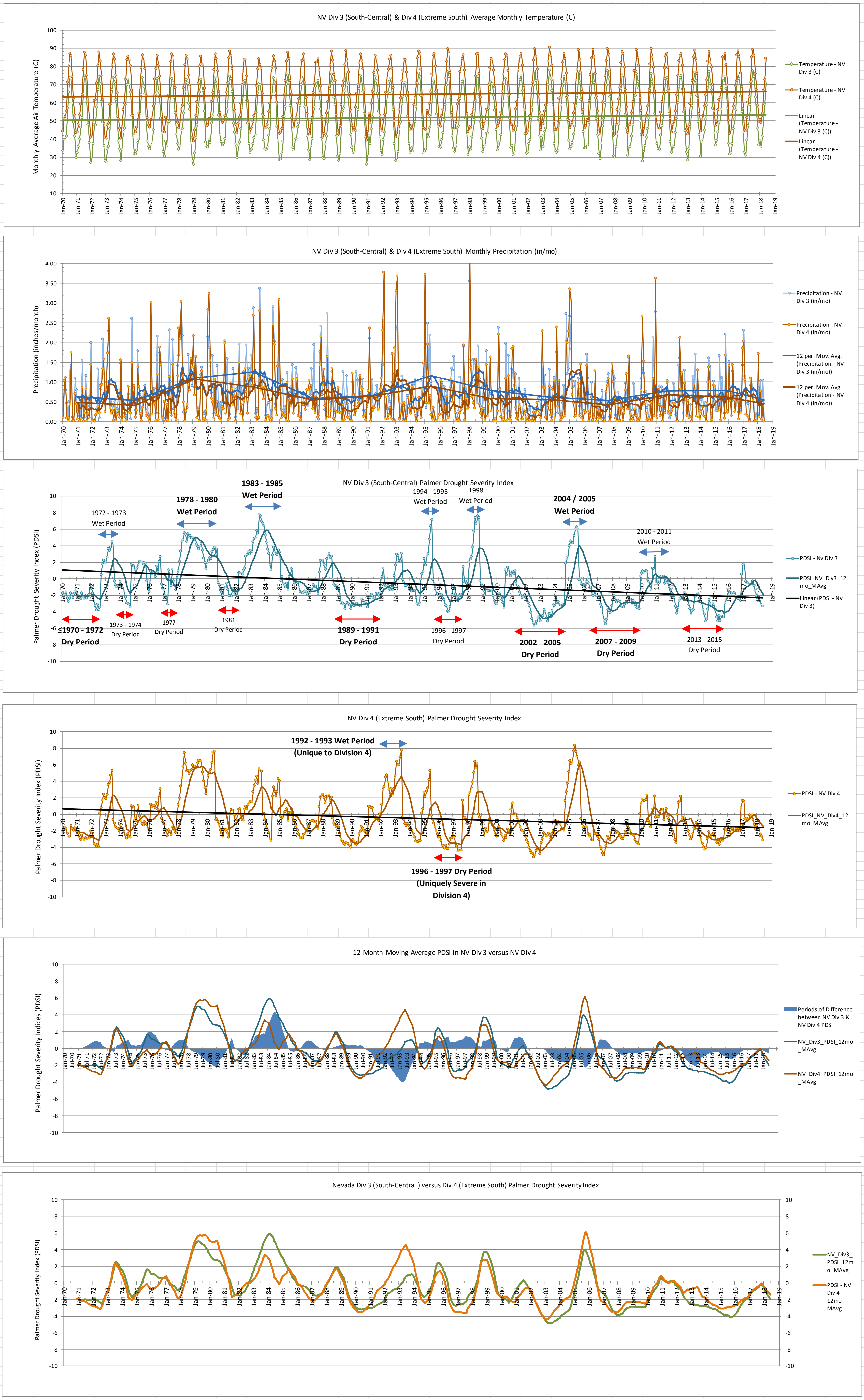

Figure 11. Climate data for Nevada Division 4 (Extreme South), the immediate area of the LWRFS, and Nevada Division 3 (South Central), areas immediately upgradient that are the primary source of groundwater in the LWRFS; January 1970 to May 2018 (NCDC 2018). Notable wet and dry periods based on Palmer Drought Severity Index (PDSI) values annotated.

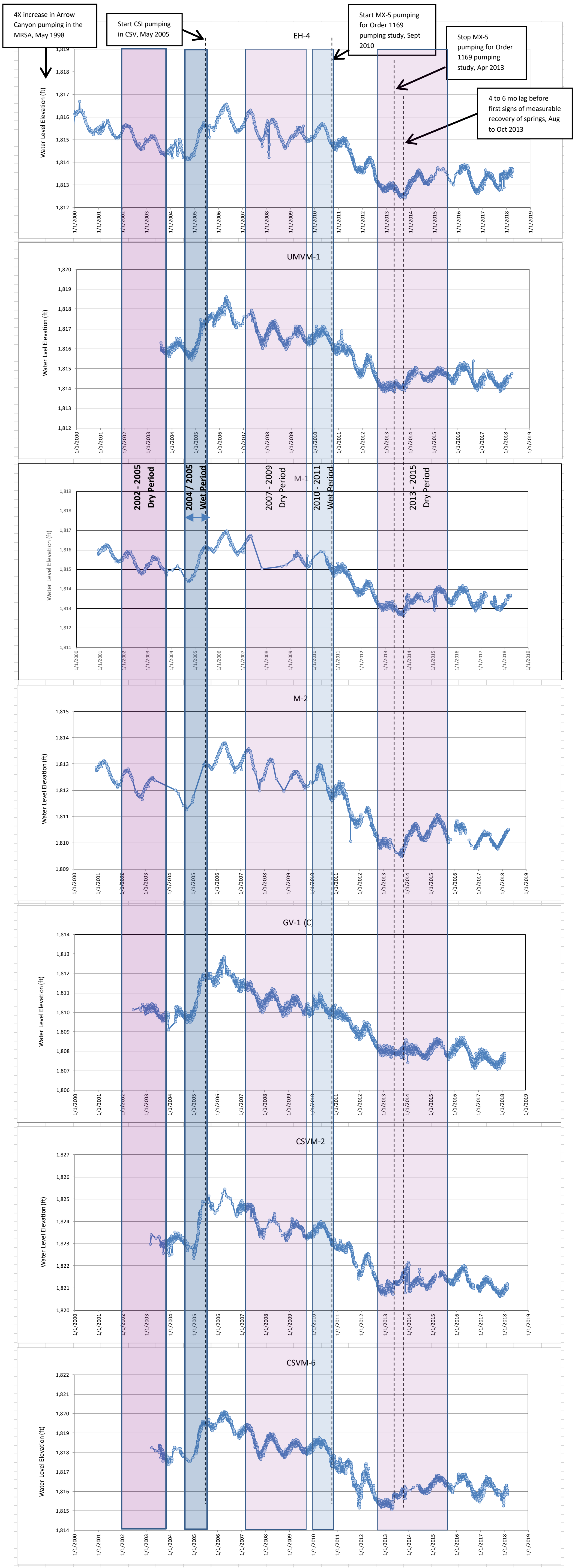

Figure 12. Wet climate signals (Nevada Divisions 3 and 4) in selected carbonate monitoring wells in the LWRFS. Notable wet and dry periods annotated relative to trends in groundwater level data, January 2000 to March 2018 (NDWR 2018a).

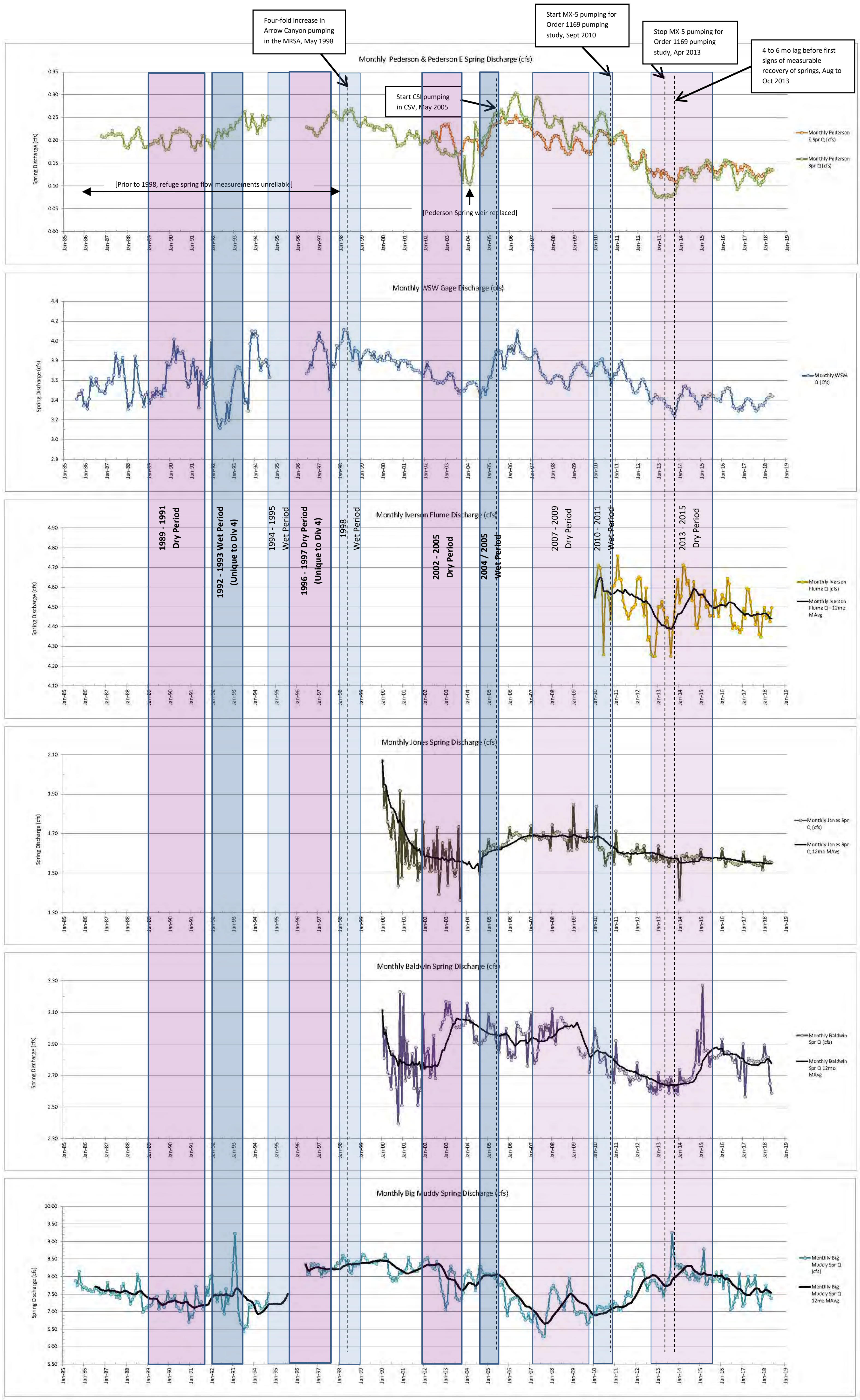

Figure 13. Wet climate signals (Nevada Climate Divisions 3 and 4) evident in the discharge records of most of the refuge springs, August 1985 to May 2018; less clear, absent, or anomalous in Baldwin and the Big Muddy springs (NDWR 2018a, USGS 2019). Notable wet and dry periods annotated relative to trends in groundwater level data, January 2000 to March 2018 (NDWR 2018a).

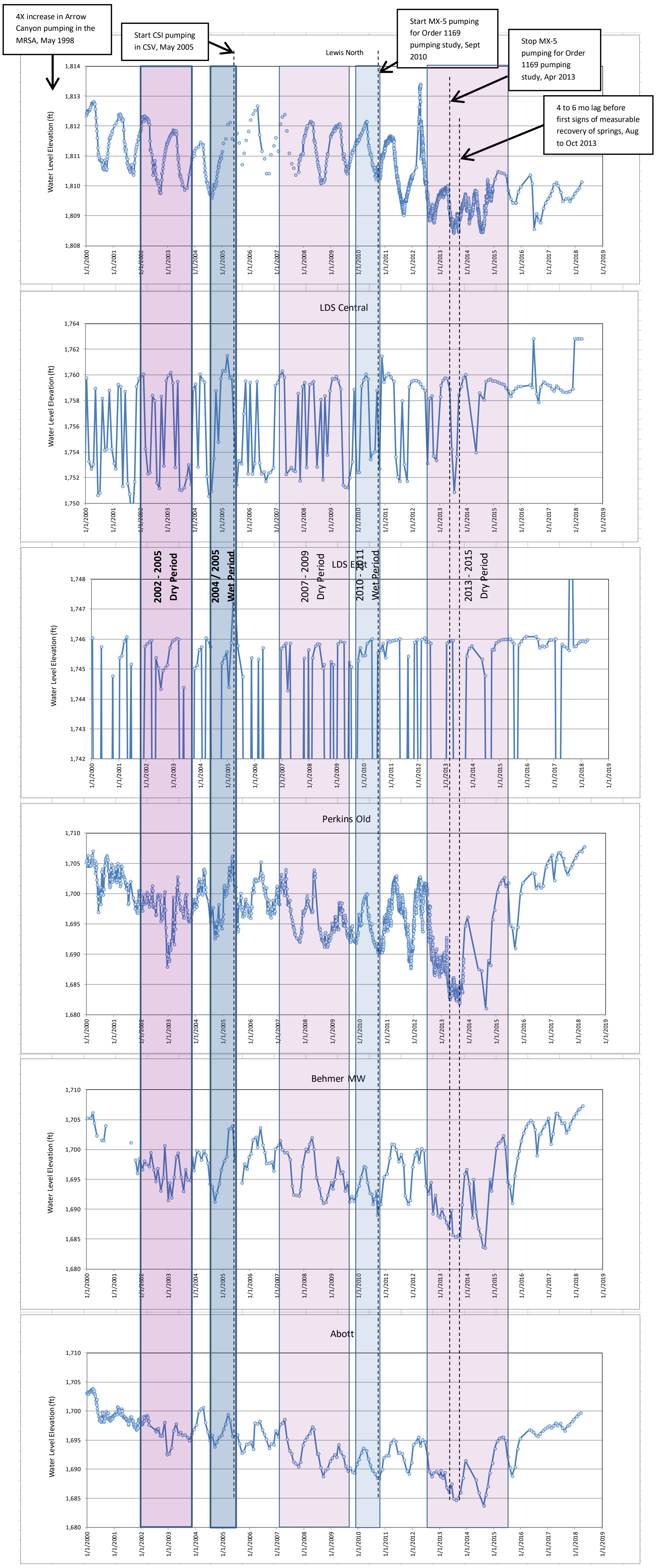

Figure 14. Wet climate signals (Nevada Climate Divisions 3 and 4) in selected alluvial monitoring wells in the LWRFS. Notable wet and dry periods annotated relative to trends in groundwater level data, January 2000 to May 2018 (NDWR 2018a).

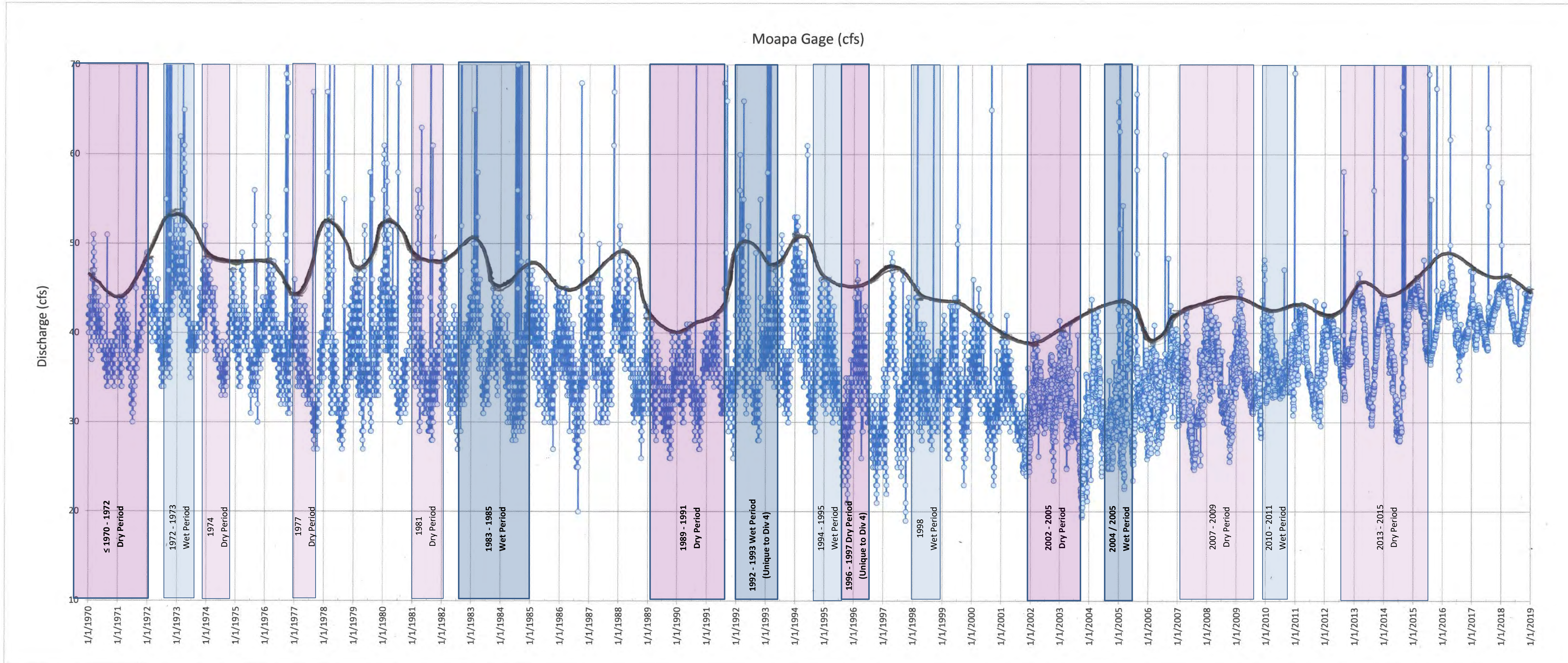

Figure 15. Wet and dry climate signals (Nevada Climate Divisions 3 and 4) evident in Moapa gage discharge record, January 1979 to January 2019 (USGS 2019). Notable wet and dry periods annotated relative to trends in discharge.

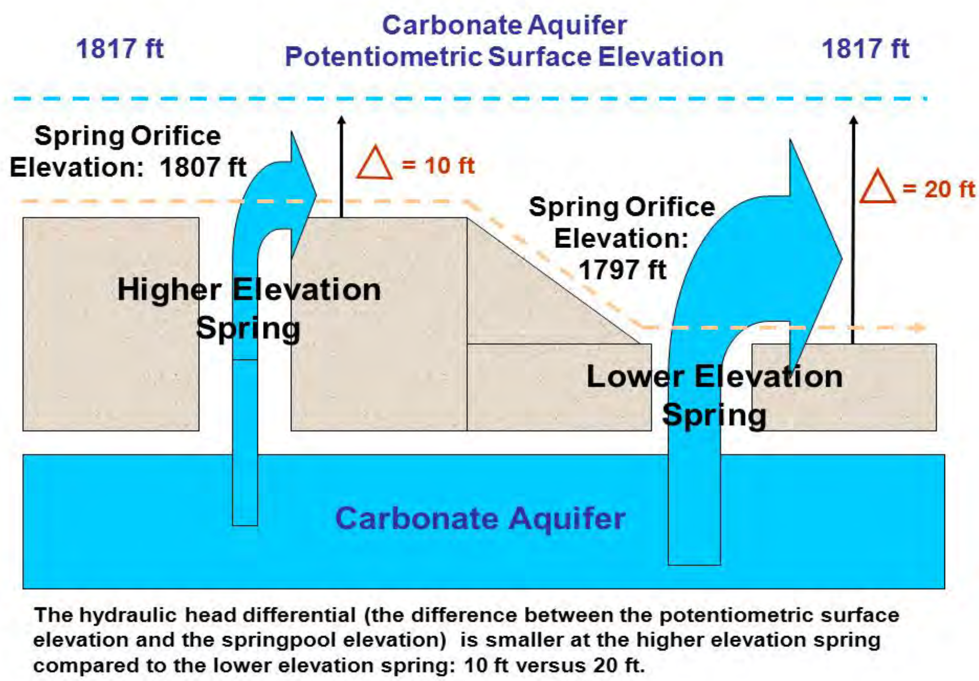

Figure 16. Theoretical head differential at springs of *different* elevation, assuming a uniform potentiometric surface in the regional carbonate-rock aquifer.

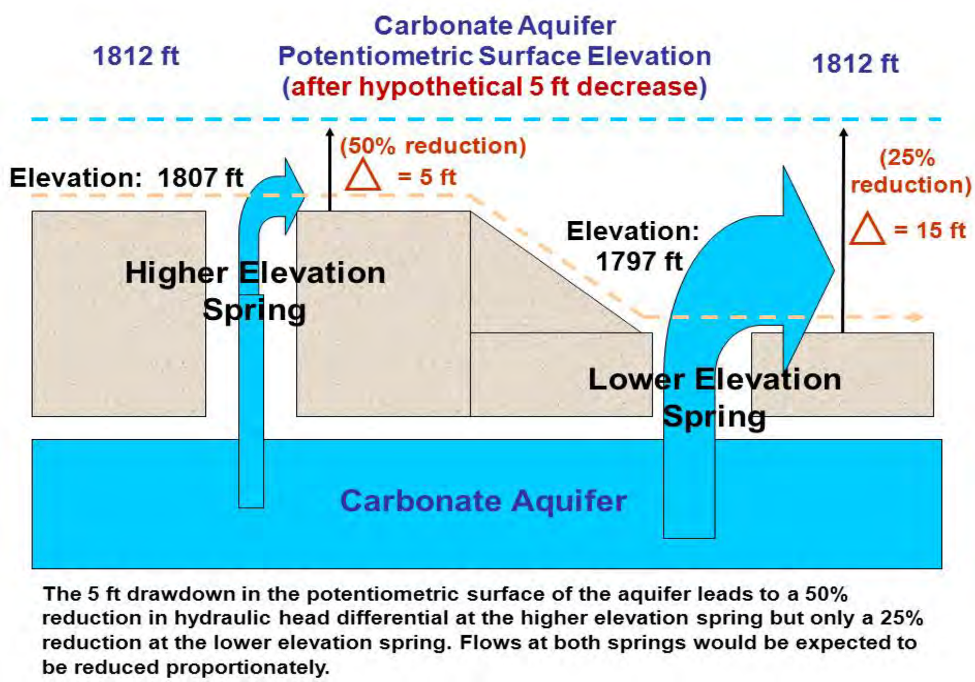

Figure 17. Theoretical effects of a uniform drawdown on head differential and spring discharge at higher and lower elevation springs.

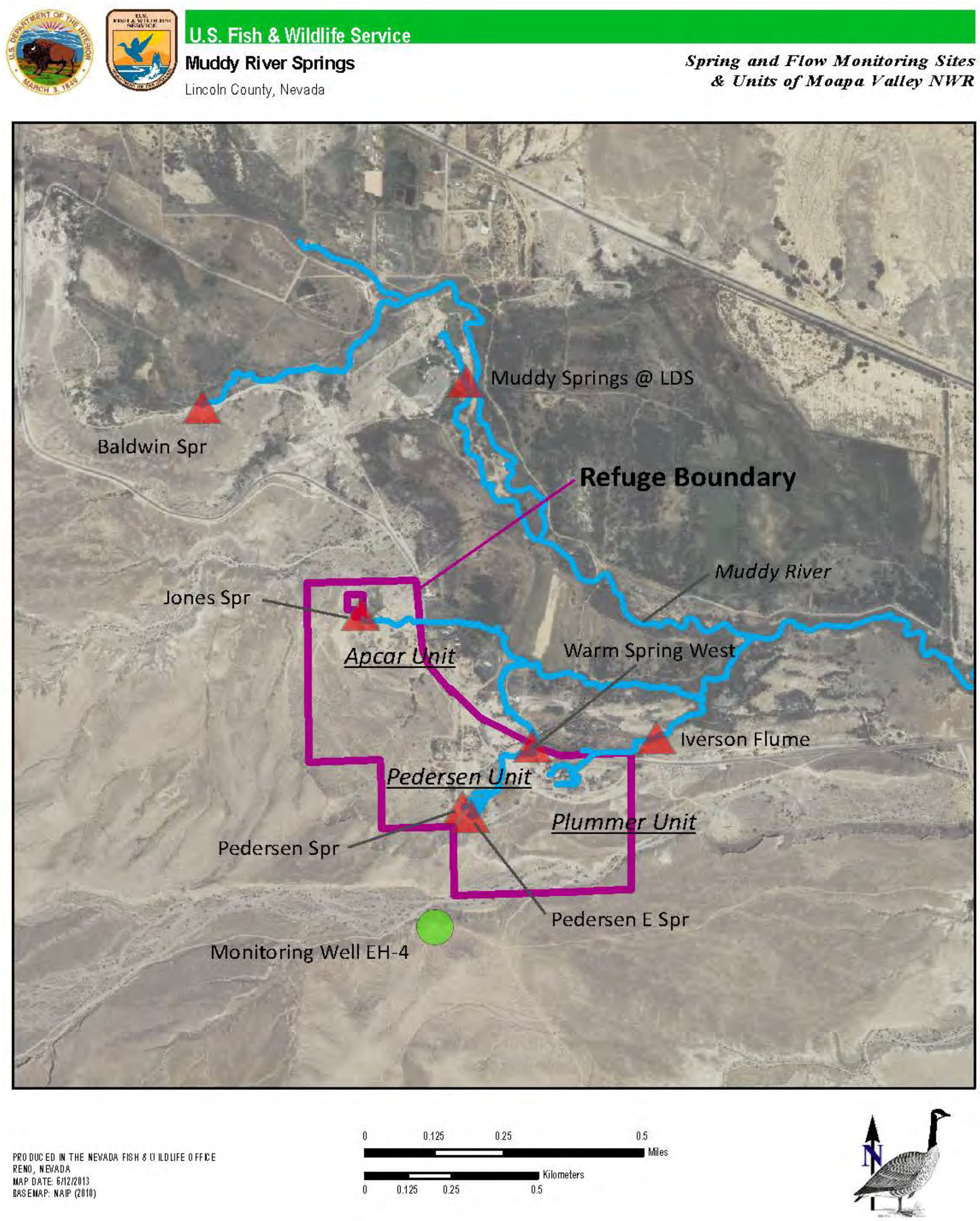

Figure 18. Map showing the locations of spring and flow monitoring sites; the boundary and three units of the Moapa Valley NWR; as well as the EH-4 carbonate monitoring well, all discussed in this section of the report.

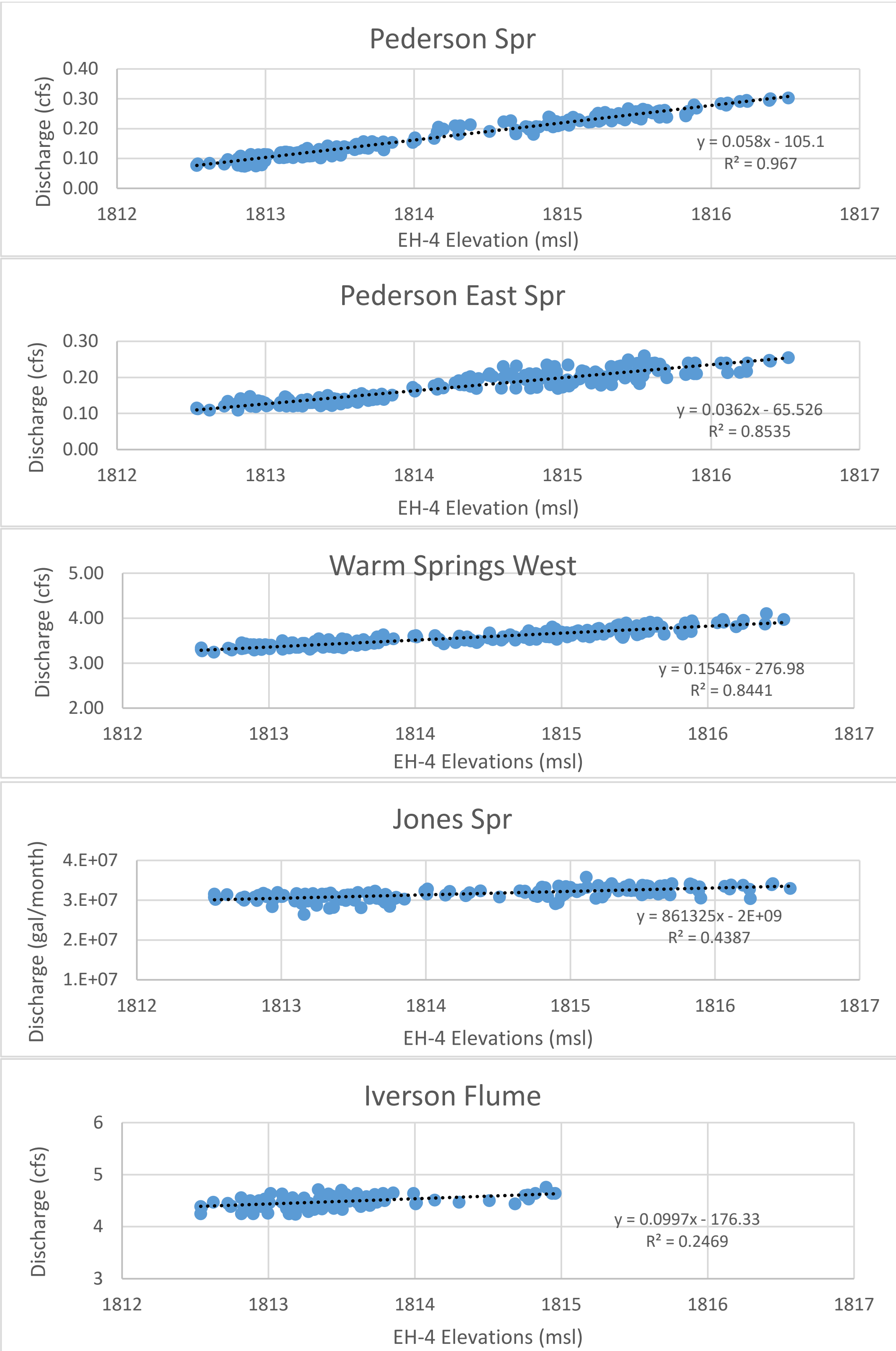

Figure 19. Discharge versus EH-4 elevations for five sites on or near the Moapa Valley NWR.

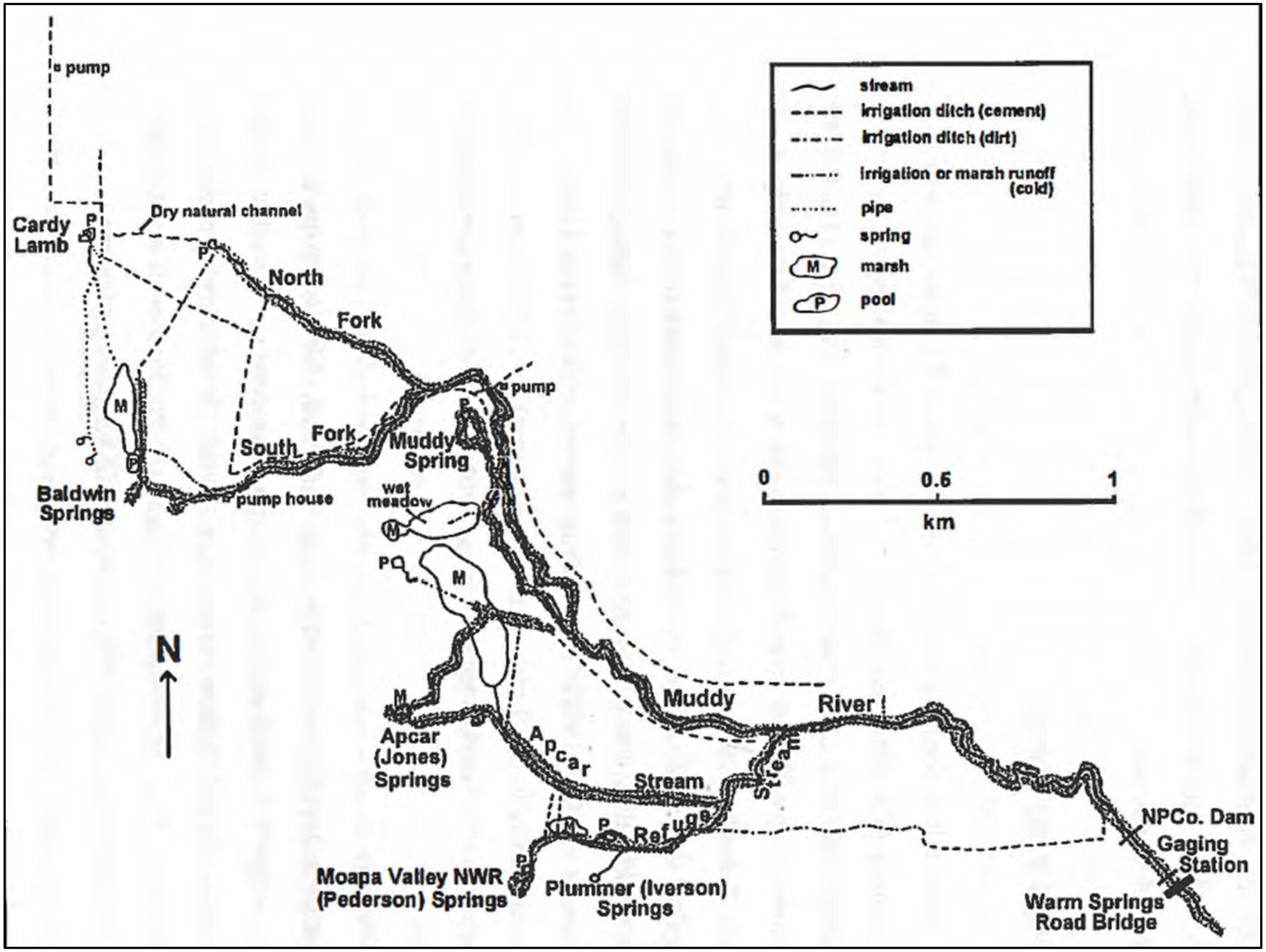

Figure 20. Map of the Muddy River Springs Area, showing the historical distribution of Moapa dace (shaded stream segments). Figure reproduced from USFWS Recovery Plan for the Rare Aquatic Species of the Muddy River System, revised 1996.

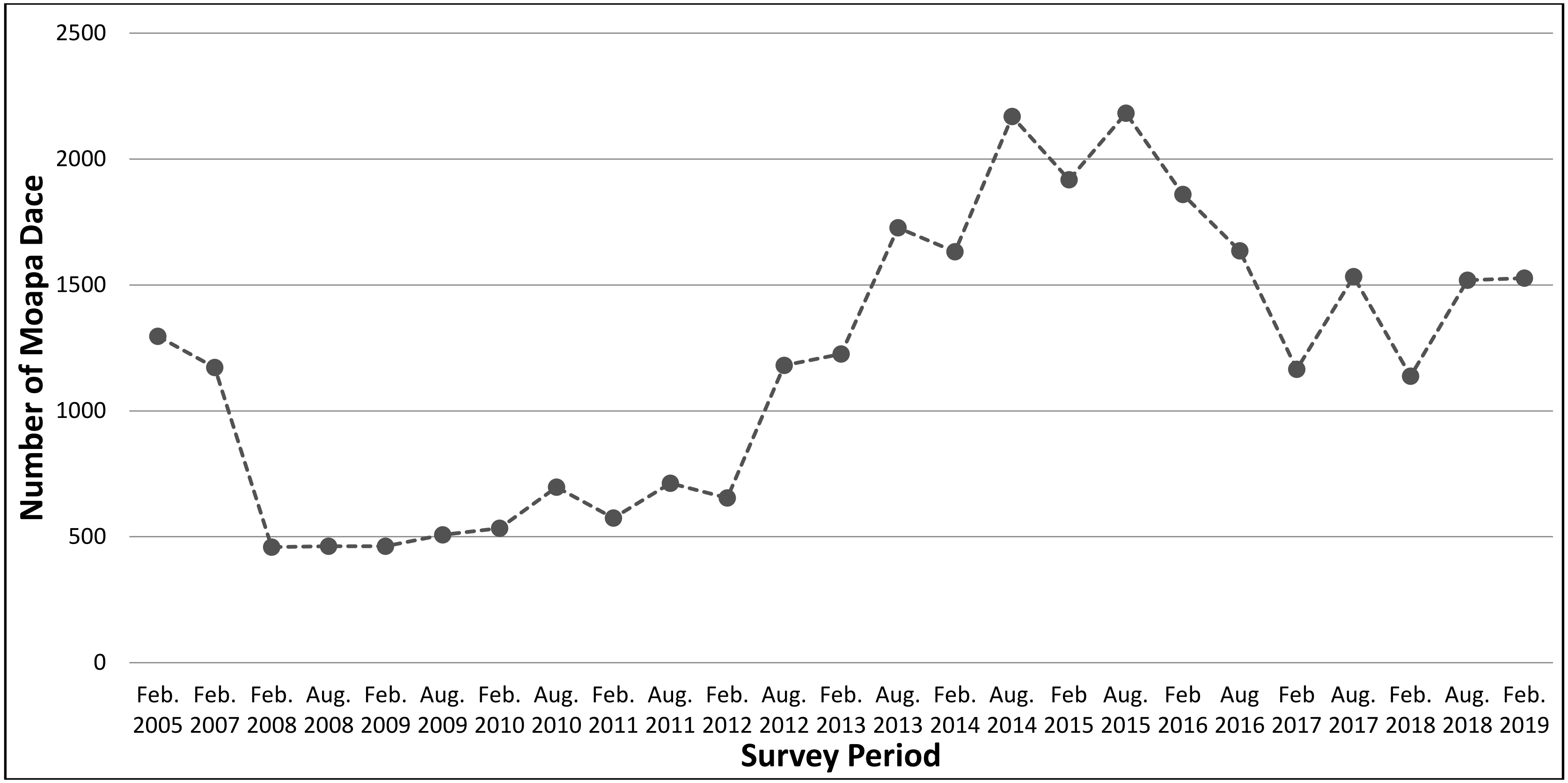

Figure 21. Population Abundance of Moapa dace for 2005 to 2019.

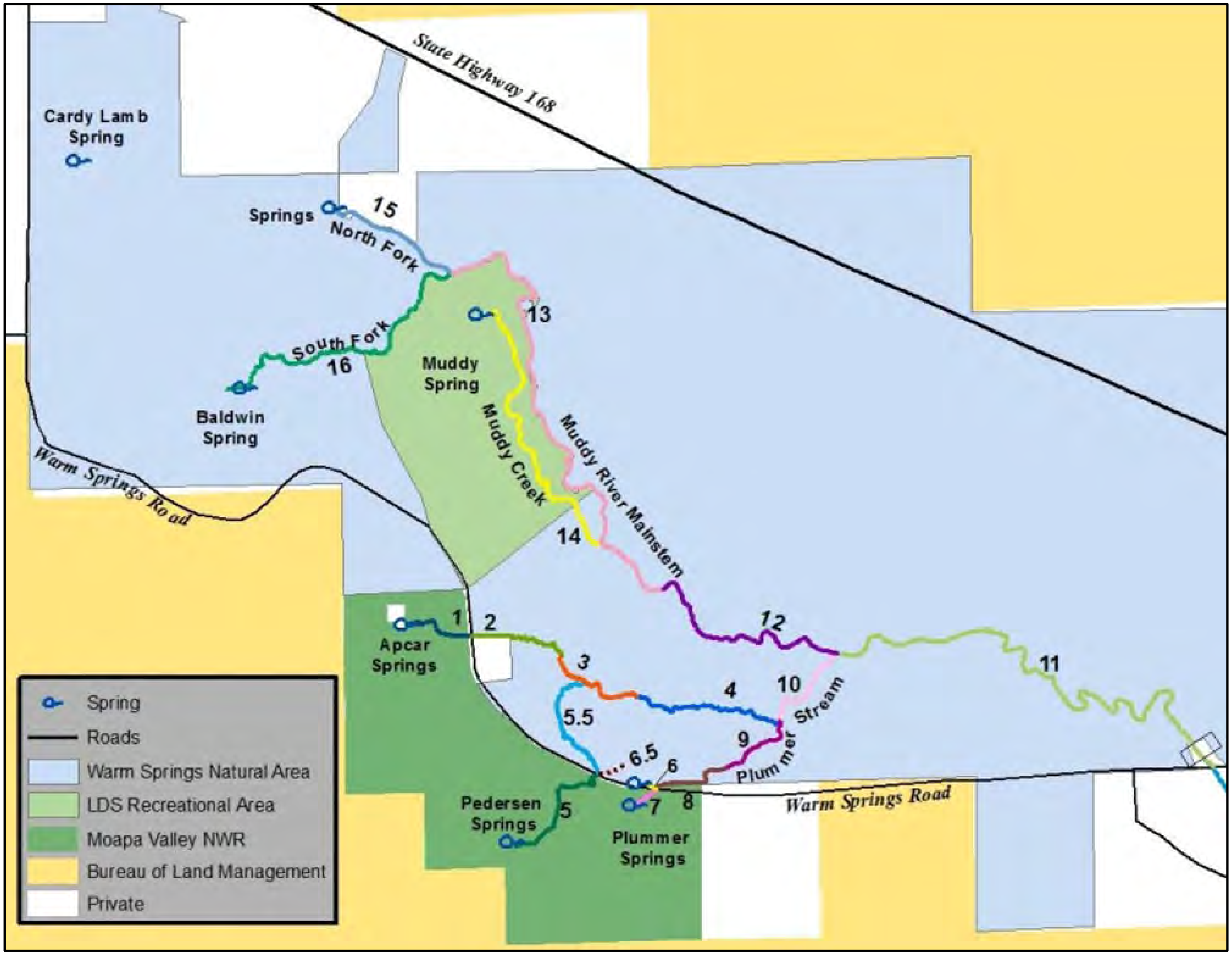

Figure 22. Stream Reach Map. Numerals (and corresponding colored segments) indicate stream reaches designated for the bi-annual spring and fall population surveys of Moapa dace.

Table 1. Summary of Results for Relationship of Discharge and Carbonate Water Level Elevations

Monitoring Site Name*	Type of Monitoring Site	Elevation of Springs Measured at Site (msl)	Correlation (r^2) with EH-4 Carbonate Water Levels over the POR	Slope Coefficient (and p-value) from Linear Regression	Relative Changes in Observed Discharge for the Range of EH4 Carbonate Water Levels in the POR	Estimated Change in Head Differential for the Range of EH4 Carbonate Water Levels in the POR
Pederson Spr	Spring Monitoring	1811	0.97	0.05803 (p=1.14E-129)	-73%	-72%
Pederson East Spr	Spring Monitoring	1807.7	0.85	0.03621 (p=1.59E-84)	-45%	-57%
Warm Springs West	Flow Monitoring	1792 to 1811	0.84	0.15463 (p=4.29E-87)	-19%	NA
Jones Spr**	Spring Monitoring	1776	0.42	861325 (p=5.29E-23)	-10%	-12%
Iverson Flume	Flow Monitoring	1749 to 1757	0.24	0.09971 (p=1.68E-7)	-6%	NA

* Spring and flow monitoring sites are ordered from high to low elevation, corresponding to their expected sensitivity to changes in groundwater levels.

** Units of flow for Jones Springs are gallons per month, all others are cfs. The values of the slope coefficients are dependent on the units.

Reach	Feb. 2005	Feb. 2007	Feb. 2008	Aug. 2008	Feb. 2009	Aug. 2009	Feb. 2010	Aug. 2010	Feb. 2011	Aug. 2011	Feb. 2012	Aug. 2012	Feb. 2013	Aug. 2013	Feb. 2014	Aug. 2014	Feb 2015	Aug. 2015	Feb 2016	Aug 2016	Feb 2017	Aug. 2017	Feb. 2018	Aug. 2018	Feb. 2019
1	6	0	0	N/A	N/A	1	7	20	28	67	74	84	69	72	66	66	119	158	106	135	105	129	64	87	53
2	87	42	50	22	29	34	13	35	20	54	78	79	139	310	271	335	429	227	349	208	169	296	230	256	382
3	52	14	0	4	2	4	3	0	1	8	10	31	127	248	229	309	244	299	218	182	170	236	300	377	371
4	18	0	0	3	0	10	7	0	2	1	0	13	62	156	133	198	187	190	93	66	44	56	10	100	125
5	174	395	50	82	80	84	82	90	99	108	66	94	128	85	70	206	118	90	105	46	29	32	49	51	88
5.5*	N/A	N/A	N/A	N/A	29	51	71	84	96	88	99	376	244	318	573	471	329	415	445	369	243	489	284	383	282
6*	80	128	56	67	9	5	8	5	22	27	10	59	36	48	20	49	31	36	17	84	15	24	6	12	25
6.5*	--	--	19	18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7	177	170	148	208	187	218	166	393	188	206	109	159	113	144	49	121	91	148	106	134	90	52	40	60	46
8	406	282	59	28	61	42	118	40	78	55	107	112	141	161	113	240	186	270	242	209	133	105	68	57	55
9	166	47	40	24	23	39	43	29	40	85	100	157	153	185	103	122	152	220	105	150	77	42	42	60	47
10	62	54	14	1	32	15	11	1	0	13	0	17	14	0	5	52	30	123	68	41	69	55	2	44	11
11	--	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
12	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	3	0
13	45	16	5	1	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1	0	1	0
14	0	0	0	0	N/A	0	0	0	0	1	1	0	0	0	0	0	1	6	2	11	12	14	42	28	22
15	9	15	17	0	7	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
16	10	9	1	4	1	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	20
Total	1296	1172	459	462	462	508	534	697	574	713	654	1181	1226	1727	1632	2169	1918	2182	1859	1635	1165	1533	1138	1519	1527

Table 2. Bi-annual population estimates of Moapa dace from 2005 to 2019. Specific stream reaches are identified numerically 1 to 16, and correspond to the Stream Reach Map (Figure 3).

GROUNDWATER LEVEL MONITORING PROGRAM

2009 ANNUAL REPORT
CLARK COUNTY, NEVADA

Prepared for:

NV Energy
6226 West Sahara Avenue
P.O. Box 230
Las Vegas, NV 89151-0001

Converse Project No. 97-35147-15

July 16, 2010

Converse Consultants
Over 50 Years of Dedication in Geotechnical Engineering and Environmental Sciences

July 16, 2010 97-35147-15

Mr. Robert Ott
Plant Engineering Manager
NV Energy
6226 West Sahara Avenue
P.O. Box 230
Las Vegas, NV 89151-0001

Subject: Groundwater Level Monitoring Program
2009 Annual Report
Reid Gardner Substation
Clark County, Nevada

Dear Mr. Ott:

Converse Consultants (Converse) is pleased to present this *2009 Annual Monitoring Report* for the NV Energy (formerly Nevada Power Company) Moapa Valley Monitoring Network located near Glendale, Nevada. This report contains periodic and semi-continuous measurement data, hydrographs of periodic and semi-continuous water level data, graphs of water quality data, a discussion of our findings, and recommendations for future monitoring.

Topographic maps showing locations of the wells and springs monitored in the NV Energy Moapa Valley Monitoring Network are included in Appendix A as Drawing Nos. 1 through 6. Hydrographs of the wells that were semi-continuously monitored during 2009 are presented in Appendix B. Appendix C contains hydrographs of periodic water-level measurements since 1986. The 2009 periodic water-level measurement data are contained in Appendix D. Periodic water quality data for 2009 are contained in Appendix E. Applicable references are listed in Appendix F.

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Introduction

NV Energy has actively studied groundwater issues in the Moapa Valley since the 1960s. Groundwater and surface-water resources in the Upper Muddy River Valley are vital because NV Energy has utilized these resources to supply the Reid Gardner Generating Station with cooling water since the 1970s. NV Energy later initiated the current groundwater level-monitoring program to assess the impact of groundwater withdrawals from the Lewis well field, the LDS well field, and the Perkins/Behmer wells on the local aquifer system.

Since 1986, this monitoring program has supplied NV Energy with annual water level changes and long-term trends that have helped provide insight into groundwater availability from the alluvial and carbonate aquifers within Moapa Valley. Monitoring of groundwater levels during the pumping season also provides early warning of potential problems that might result from modified pumping schemes or new production wells.

Throughout the past year, Converse has conducted a program of groundwater level and water quality monitoring for NV Energy in the Upper Muddy River Valley and adjacent areas. The objective of this program has been to evaluate short- and long-term hydraulic head and water quality conditions in the vicinity of NV Energy's well fields. Measuring, interpreting, and reporting groundwater levels in both the shallow alluvial and deeper carbonate aquifers using the established NV Energy Monitoring Well Network in the Meadow Valley, Muddy River Valley, Dry Lake Valley, and Coyote Spring Valley have addressed this objective. In addition to approximately 30 wells, water quality measurements were also obtained from 14 other spring or surface water sites.

This report presents data collected during 2009 from the wells and springs that comprise the NV Energy Monitoring Network. Although data was collected in several areas of Moapa and Dry Lake Valleys, this report focuses on the Upper Muddy River Valley where NV Energy currently produces all of its groundwater required for cooling purposes at the Reid Gardner Generating Station.

Hydrogeologic Setting

The hydrogeology of Moapa Valley consists of three primary units: Quaternary valley fill, Tertiary Muddy Creek Formation, and the Paleozoic carbonate system. In the Meadow and Upper Muddy River Valleys, unconsolidated sands and gravels, and fractures in consolidated alluvial or fluvial deposits provide high groundwater yields from valley-fill sediments. The NV Energy well fields in the Upper Muddy River Valley withdraw groundwater from this high-yield valley-fill aquifer system that is hydraulically connected to the Paleozoic carbonate aquifer. The Muddy Creek Formation, which underlies the valley fill in much of the valley, consists of unconsolidated and semi-consolidated fine-grained sediments. The Muddy Creek Formation is less permeable and contains poorer quality water than the overlying alluvial aquifer, and is utilized as a source of groundwater only in Meadow Valley. In the Upper Muddy River Valley, the Muddy Creek Formation is considered to behave as a semi-confining unit separating the carbonate aquifer from the alluvial aquifer.

Paleozoic carbonates extend below and surround the alluvial fill and Muddy Creek deposits. These carbonate rocks are part of the regional carbonate aquifer of the White River Flow System; a system of interconnected groundwater basins that extends more than 230 miles north to Long Valley (Eakin, 1968). The Muddy River springs are considered the primary regional discharge point of the White River Flow System (Eakin, 1968), although groundwater from other basins, namely Meadow Valley, may contribute to local discharge (Schroth, 1987; Kirk and Campana, 1988; Thomas, 1988). In addition, most groundwater recharge in the Sheep Range, which is located directly west, may be discharged at the Muddy River Springs (Thomas, 1988).

Locally, the Muddy River springs recharge both the Muddy River and the valley-fill aquifer via surface and subsurface spring leakage (Eakin, 1964), and associated fault- and fracture-flow. The total groundwater contribution to the Muddy River from the upper valley is estimated to be 36,000 acre-ft/year (Eakin, 1964) to 37,000 acre-ft/year (Prudic et al., 1993). Local spring discharge, river flow, and groundwater withdrawals from the valley-fill aquifer all depend on the quantity of groundwater available in the carbonate system and the nature of the hydraulic connections and boundaries between the various hydrogeologic units.

Because of this relationship, the carbonate aquifer will play an important role in future development of groundwater supplies in the area. The high yields that can be obtained from this aquifer were illustrated at NV Energy's RW-2 well (Converse, 2002) and the MX test well CE-DT-5 in Coyote Spring Valley (Bunch & Harrill, 1984). High carbonate aquifer yields have also been obtained by a Moapa Valley Water District (MVWD) production well near the mouth of Arrow Canyon (Buqo, 1993). Increased local pumping from the carbonate aquifer raises concerns about how future development might affect groundwater resources, including springs in the Upper Muddy River Valley.

Methodology

During 2009, water level data from each of the wells was obtained to determine primary water levels, and where applicable, verify depths to water recorded by each of the In-Situ data loggers. Converse acquired water level data using standard methods developed by the U.S. Geological Survey (USGS), U.S. Environmental Protection Agency, and the U.S. Bureau of Reclamation. Water level measurements to the nearest hundredth of a foot were obtained using calibrated 100 and 1,000 foot Solinst Water Level Tapes. A portable handheld computer was used to download semi-continuous, stored data from each of the thirteen (13) transducer/data loggers currently in use. Periodic depth to water measurements were recorded on standard data forms, which also included well name, frequency of measurement, date and time, initials of field personnel, total discharge of each pumping well monitored, data logger battery power, and well condition.

Pertinent details on the 30 monitoring wells in the network are listed in Table 1. The wells are grouped into six general areas: the upper Muddy River Valley (which contains the Lewis well field, the LDS well field, and the Perkins/Behmer production wells), Meadow Valley, Weiser Wash, Dry Lake Valley, Garnet Valley and Coyote Spring Valley. Maps showing the well locations are presented in Appendix A as Drawing Nos. 1 through 6.

Table 1
2009 NV Energy
Monitoring Network Wells

Well Name	Formation Monitored	Measurement Frequency	Well Depth (ft)
Muddy River Valley			
Abbott	Valley Fill	Monthly	100
Behmer	Valley Fill	Monthly	80
CSV-2	Carbonate	Monthly	478
EH-4	Carbonate	Semi-Continuous	285
EH-5b	Carbonate	Semi-Continuous	264
Lewis-1 Old	Valley Fill	Semi-Continuous	57
Lewis-2	Valley Fill	Semi-Continuous	66
Lewis North	Valley Fill	Semi-Continuous	70
Lewis South	Valley Fill	Semi-Continuous	111
LDS Central	Valley Fill	Monthly	52
LDS East	Valley Fill	Monthly	76
LDS West	Valley Fill	Monthly	80
Perkins Production	Valley Fill	Monthly	135
Perkins Old	Valley Fill	Semi-Continuous	60
Meadow Valley			
EH-6	Valley Fill	Quarterly	140
EH-8a	Muddy Creek	Quarterly	244
EH-8b	Valley Fill	Quarterly	105
NPC-4a	Muddy Creek	Quarterly	715
NPC-5 Old	Valley Fill	Quarterly	181
TH-8	Valley Fill	Quarterly	44
TH-12	Valley Fill, Muddy Creek	Quarterly	204
TH-31	Muddy Creek	Quarterly	104
TH-35	Muddy Creek	Quarterly	118

Well Name	Formation Monitored	Measurement Frequency	Well Depth (ft)
Mesa/Weiser Wash			
EH-3	Carbonate	Semi-Continuous	793
EH-7	Carbonate	Semi-Continuous	440
Dry Lake Valley			
RW-1	Carbonate	Semi-Continuous	833
Crystal 1	Carbonate	Semi-Continuous	565
Crystal 2	Carbonate	Semi-Continuous	497
Garnet Valley			
WS-2	Carbonate	Quarterly	1965
Coyote Springs Valley			
RW-2	Carbonate	Semi-Continuous	720

Semi-continuous monitoring was accomplished using In-Situ MiniTroll and LevelTroll transducers with self-contained data loggers that collect and store data hourly as programmed. It should be noted that the semi-continuous water level data is verified monthly and quarterly with manual readings.

Instantaneous and total pumpage observations were recorded monthly for production wells within the monitoring network. Total pumpage was recorded directly from an in-line totalizing flow meter at each monitored production well location. Discharge was recorded from the Behmer, LDS Central, LDS East, LDS West, Perkins Production, RW-1, and WS-2 wells (provided by NV Energy).

Beginning in April 2000, Converse has monitored water quality conditions in each of the wells and springs within the NV Energy Monitoring Network on a quarterly basis. Water quality monitoring of the various wells and springs has been conducted to evaluate any changes associated with NV Energy's summer pumping season. During each monitoring event, specific conductance, pH, salinity, and water temperature data were collected with a YSI 63 pH/conductivity meter at each of the wells listed in Table 1 and at each spring or surface water site listed in Table 2. All water quality data is presented in Appendix E.

Discharge measurements have not been collected for springs within the Monitoring Network this year for several reasons. As Nevada Power Company noted in a February 21, 1998, letter to Kleinfelder & Associates, only three of the ten original Parshall flumes have been maintained and are useful for collecting flow measurements. Of these three, only S20A, or the Pederson V-weir; the Parshall flume near the edge of the Fish and Wildlife property; and S2 are routinely monitored. Discharge data from other springs in the network were not collected due to the inherent difficulty in acquiring reasonably accurate flow measurements for seasonal comparison. In the near future, collection of accurate flow measurements will likely be critical for monitoring changes to spring flows.

Table 2
2009 NV Energy Monitoring Network
Springs and Surface Water Sites

Spring or Surface Water Site Name	Measurement Frequency
Warm Springs Resort	
M 15	Quarterly
M 16	Quarterly
M 20	Quarterly
Warm Springs East	Quarterly
U.S. Fish & Wildlife	
Parshall Flume	Quarterly
S20A	Quarterly
Big Muddy Spring Area	
S2	Quarterly
S6	Quarterly
S7A	Quarterly
S64	Quarterly
Apcar Property	
S52	Quarterly
S53	Quarterly

Spring or Surface Water Site Name	Measurement Frequency
Ernie Cognar Property	
S65	Quarterly
LDS Pool Area	
S15	Quarterly

Groundwater Pumping

NV Energy and the MVWD are the two largest groundwater consumers in Moapa Valley. Numerous private domestic and irrigation wells that draw water from the valley fill aquifer are located in the area, but the volume pumped from these wells is minor compared to the volume produced by NV Energy and MVWD. NV Energy pumps groundwater from the valley-fill aquifer at the Lewis well field, the LDS well field, and from the Perkins and Behmer production wells. NV Energy also withdraws surface water from the Muddy River located at the Warm Springs Road Bridge. In addition to spring discharge from Baldwin and Pipeline Jones Springs, MVWD withdraws its water from the carbonate aquifer at the Arrow Canyon Wells Nos. 1 & 2 and the MX-6 well.

Of the 2,481 million gallons, 7,615 acre-feet (ac-ft) or 10.52 cubic feet per second (cfs) annualized that were produced in 2009, NV Energy produced 1,333 million gallons (4,092 ac-ft or 5.65 cfs) while MVWD produced 1,148 million gallons (3,523 ac-ft or 4.87 cfs). By comparison, NV Energy and MVWD produced 2,476 million gallons (7,600 ac-ft or 10.5 cfs annualized) during 2008. Historically, groundwater production by NV Energy and MVWD averaged 2,625 million gallons (8,057 ac-ft or 11.13 cfs annualized) between 1988-2008 and 1992-2008 for NV Energy and MVWD, respectively.

NV Energy Pumpage

NV Energy's total Upper Muddy River Valley groundwater production from the alluvial aquifer during 2009 was 1,333 million gallons (Table 3), 190 million gallons (12.5%) less than the 1988-2008 average of 1,523 million gallons per year and 4.7% less than the previous year. Historical production by NV Energy is summarized on Figure 1.

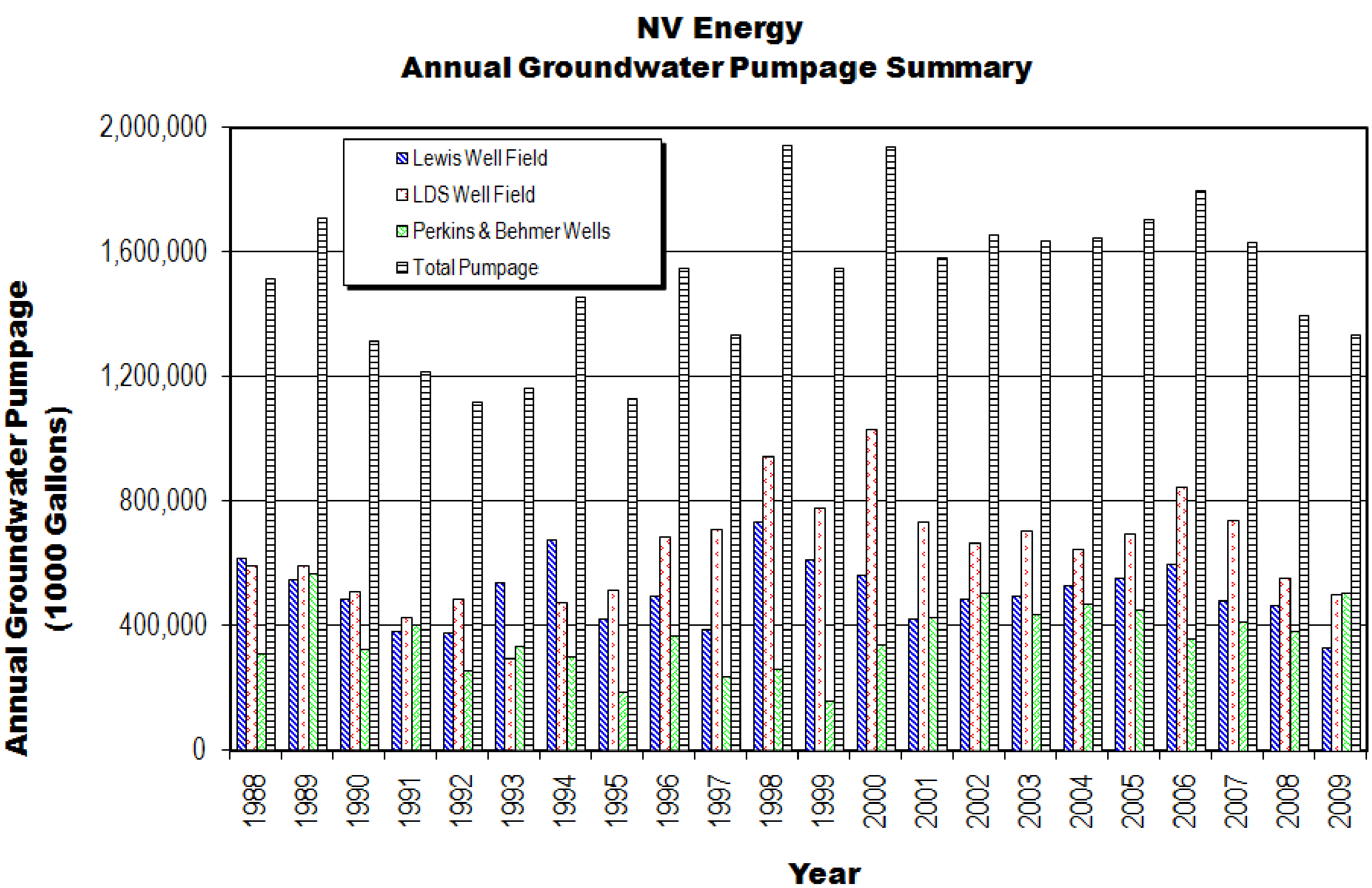


Figure 1: *Summary of NV Energy's groundwater production from the alluvial aquifer in the upper Muddy River Valley since 1988.*

Table 3
NV Energy Groundwater Withdrawals From
The Upper Muddy River and Meadow Valleys During 2009
(x1000 Gallons)

Month	Lewis Well Field	Behmer	LDS Well Field	Perkins Production	Meadow Valley Wells
January	0	14,756	0	17,599	0
February	0	19,225	5,579	14,199	0
March	0	16,147	0	12,689	0
April	2	16,939	0	16,158	0
May	72,219	22,291	51,060	16,764	0
June	61,777	17,092	90,916	17,307	0
July	99,930	34,901	62,212	19,884	0
August	59,101	31,571	63,428	19,886	0
September	35,169	52,568	98,608	32,513	0
October	0	0	34,263	8,154	0
November	0	40,233	14,354	19,614	0
December	7	30,074	78,623	15,438	0
Annual Recorded Pumpage	**328,206**	**295,797**	**499,043**	**210,205**	**0**
Total Pumpage	**1,333 million gallons**				

In 2009, groundwater production from the Perkins/Behmer wells was 41.7% above the 1988-2008 average. When compared to the previous year, groundwater production from the Perkins/Behmer wells increased by 32.2%. Production data from the Lewis well field indicates that annual production was steadily declining from 1998 through 2001; however, from 2001 through 2006 production increased each year. In 2007 and 2008, production from the Lewis well field began to decline again. The 328 million gallons produced by the Lewis wells in 2009 was 29.4% below the 2008 total for these wells and 36.6% below the 1988-2008 average. Production from the LDS well field continued to decrease by 9.5% from the previous year and was 23.1% below the 1988-2008 average.

Monthly averages were calculated for the Lewis, LDS, and Perkins/Behmer well fields to evaluate production differences between 2009 and previous year's data, as shown in Figure 2. Groundwater production from the Lewis well field in 2009 was below average for 11 of the 12 months. The largest pumpage deviation (from average withdrawals) for the Lewis well field occurred in September. Groundwater production from LDS well field in 2009 was below average in 8 of the 12 months while the largest above average deviation for the LDS well field occurred in December. In 2009, production from the Perkins/Behmer wells exceeded average withdrawals for 11 of the 12 months, with the largest above average deviations occurring in September and November.

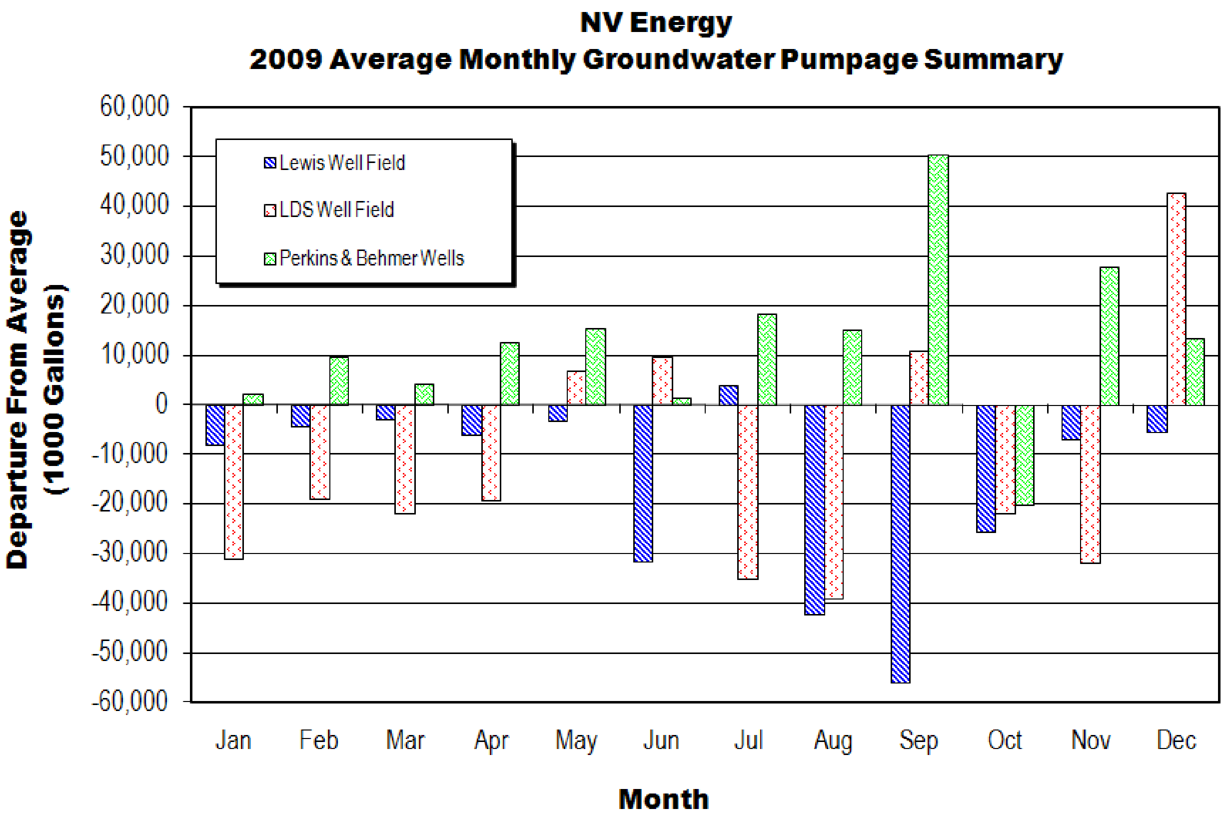


Figure 2: Average *monthly differences in groundwater production from the Lewis, LDS, and Perkins/Behmer well fields in the upper Muddy River Valley.*

MVWD's total spring and groundwater withdrawal of 1,148 million gallons in 2009 was 4.2% above the 1992 to 2008 average and 6.5% higher than the previous year. Out of the total amount, the Arrow Canyon Wells Nos. 1 & 2 accounted for approximately 57.7% of MVWD's groundwater production in 2009 compared to 57.1% during the previous year. Table 4 summarizes all MVWD production during 2009.

Table 4
MVWD Groundwater Withdrawals From
The Upper Muddy River Valley During 2009
(x1000 Gallons)

Month	MX-6 Well	Arrow Canyon Well #1	Arrow Canyon Well #2	Baldwin Spring	Pipeline Jones Spring	Logandale Irrigation Well
Jan	0	24,274	18,277	0	14,467	0
Feb	0	51,101	2,784	204	0	0
Mar	0	72,597	0	1	0	20
Apr	0	19,121	26,815	38,858	668	0
May	0	21,361	50,287	51,963	10,549	0
Jun	0	71,386	53	46,585	4,887	0
Jul	0	71,501	265	46,319	18,043	0
Aug	0	65,507	0	49,355	18,647	0
Sep	0	55,854	0	58,877	14,212	0
Oct	0	7,876	31,759	42,949	12,316	0
Nov	507	449	37,208	27,079	7,715	0
Dec	0	0	33,947	17,851	3,387	0
Annual Recorded Pumpage	**507**	**461,028**	**201,394**	**380,042**	**104,891**	**20**
Total Pumpage	**1,148 Million Gallons**					

As shown on Figure 3, production in 2009 from the three MVWD production wells and two springs indicate an increasing reliance on production from the Arrow Canyon Well No. 2 with a corresponding decrease in reliance from the Arrow Canyon Well No. 1 as compared to production in 2008. Withdrawals from the Arrow Canyon Well No. 1 decreased 20.9% in 2009 from the previous year; however production from Arrow Canyon Well No. 2 dramatically increased 526.8% from the previous year. Production from the MX-6 Well decreased by 99.6% from the previous year and was 99.4% below the 1992-2008 average. Diversions from the Pipeline Jones Spring decreased in 2009 (54.2%) compared to 2008. In contrast, diversions from the Baldwin Spring increased significantly by 272 million gallons, or 251% in 2009 compared to 2008, resulting in an increase of 89.4% above the 1992-2008 average of 179 million gallons.

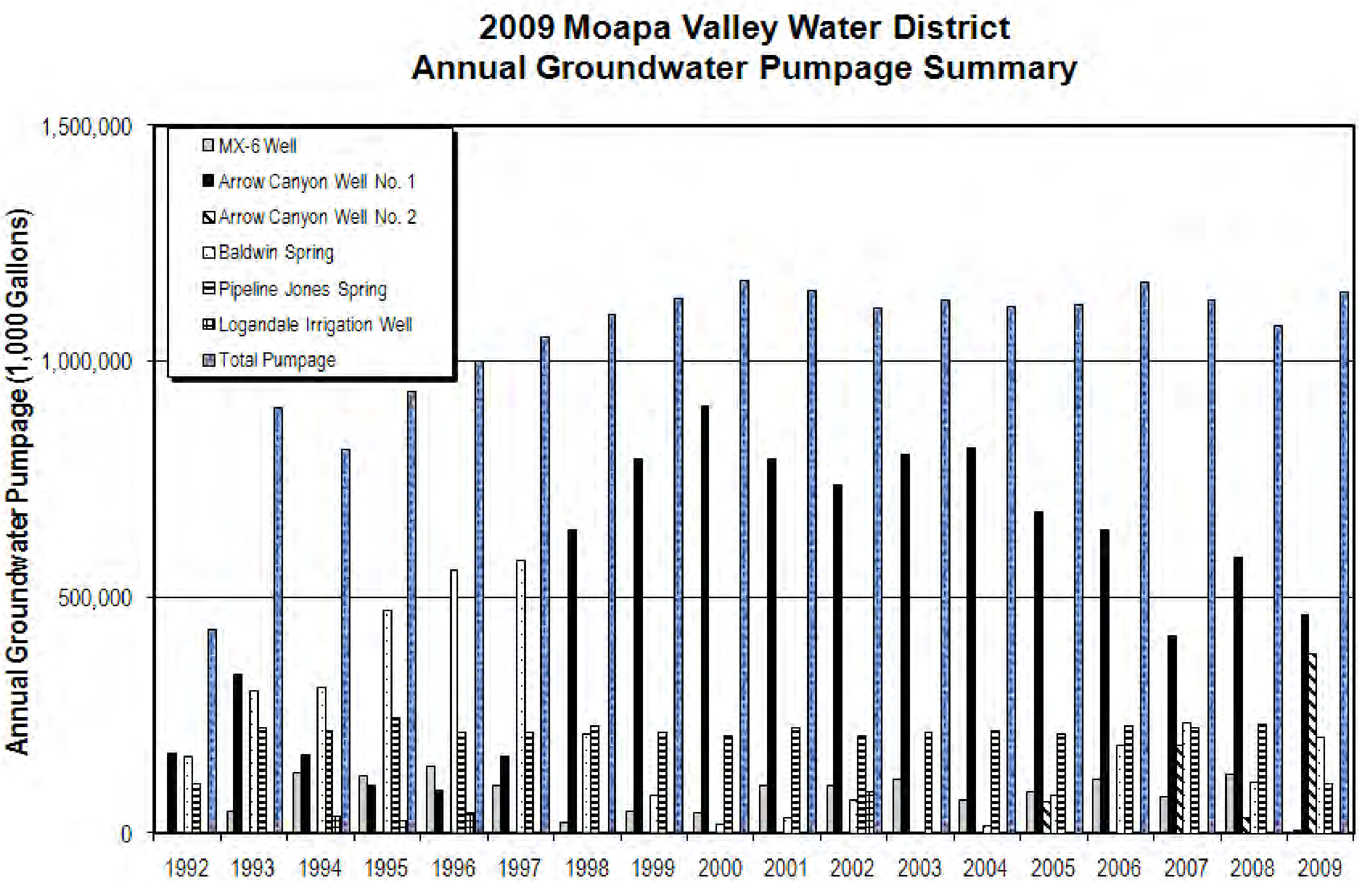


Figure 3: *MVWD's annual groundwater production from the carbonate and alluvial aquifers in the upper Muddy River Valley. Notice the shift in groundwater withdrawals from the Baldwin Spring diversion to the Arrow Canyon Well in between 1997 and 1998.*

Monthly averages were calculated for the six MVWD groundwater diversions to evaluate differences between 2009 and previous year's groundwater production data. Differences in the monthly pumpage data indicate MVWD relied on an increased pumpage from the Arrow Canyon Well No. 2 and an increase in diversions at Baldwin Spring; however, MVWD continues to rely on the Arrow Canyon Well No. 1 as its primary source of groundwater withdrawals even with the decrease in pumpage when compared to last year (2008). Overall, total withdrawal has slightly increased from the previous year mainly due to the increase in pumping from the Arrow Canyon Well No. 2 and the increase in diversions at Baldwin Spring. As summarized on Figure 4, groundwater production from the Arrow Canyon Well No.1 in 2009 was below the 1992-2008 average monthly productions during 8 of the 12 months. The largest deviations from average for Arrow Canyon Well No. 1 occurred in March (above average) and October (below average). Groundwater production from Baldwin Spring in 2009 was above the 1992-2008 average monthly productions during 9 of the 12 months. The largest deviation from average occurred in September (above average). Production from both Pipeline Jones Spring and MW-6 were slightly below average during the entire year, similarly the production for the Logandale Irrigation Well was slightly below average for the majority of 2009.

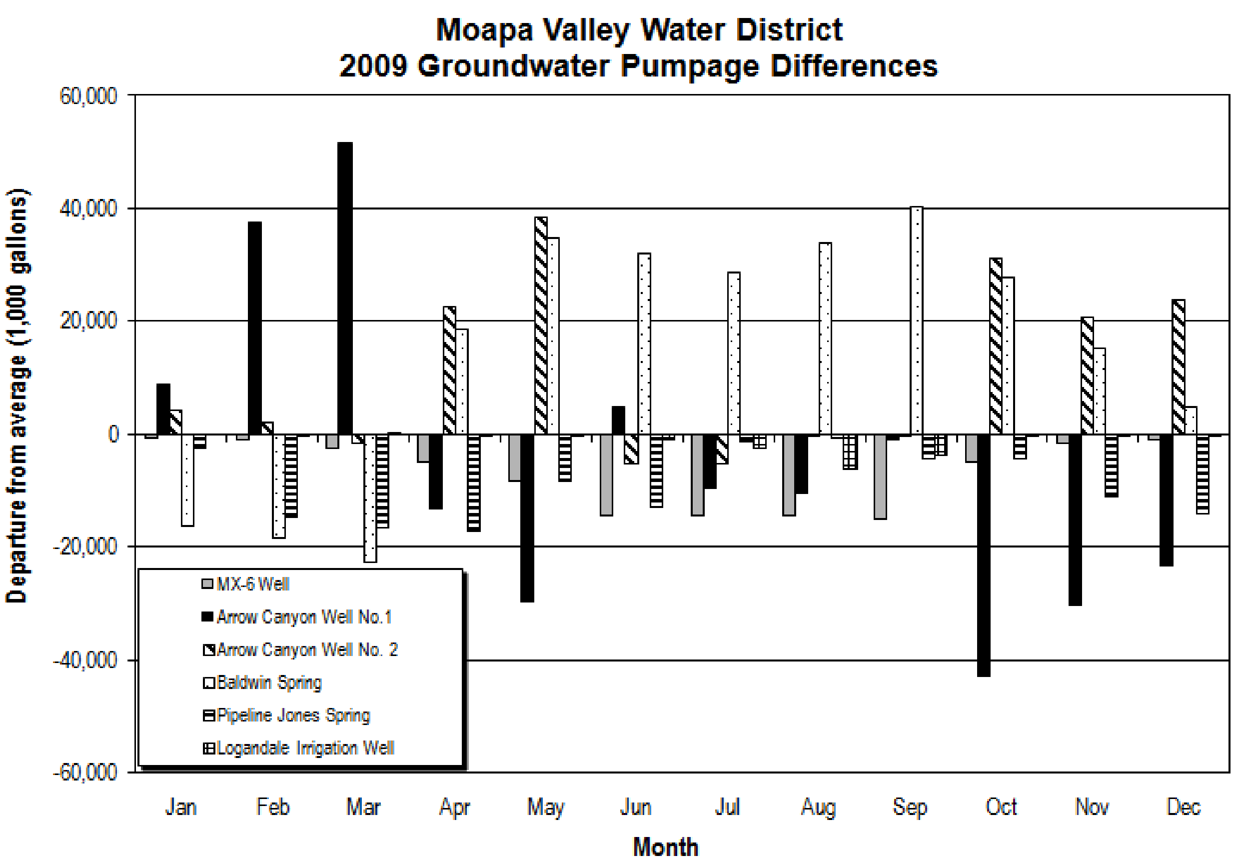


Figure 4: *Average monthly differences in groundwater production from the MX-6 well, the Logandale Irrigation Well, the Arrow Canyon Wells, and two spring diversions in the upper Muddy River Valley.*

Groundwater Levels in 2009

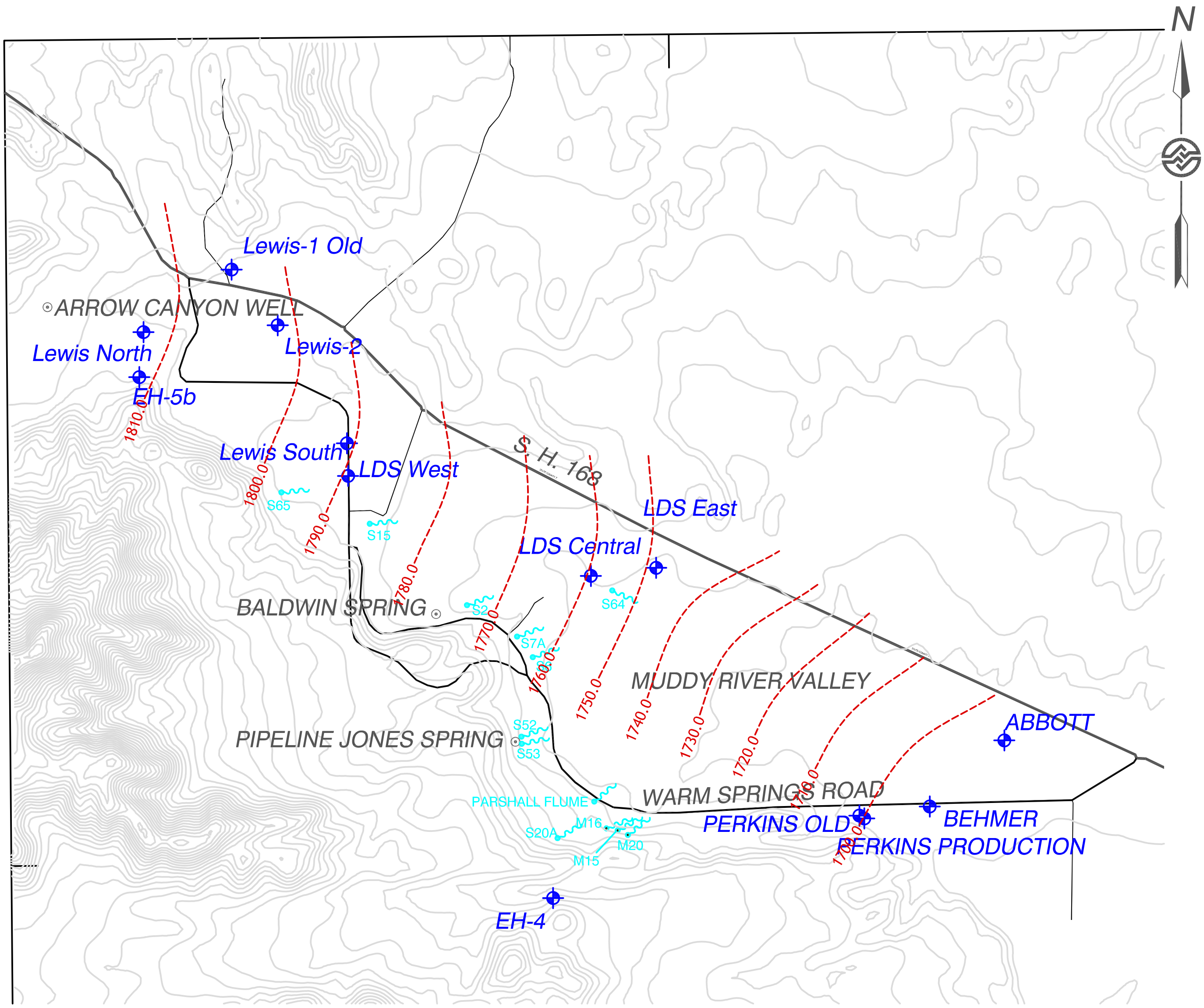
Upper Muddy River and Coyote Spring Valleys

As shown on Figures B-1 through B-7, C-1 through C-6, and Table 5 groundwater levels in some areas within the Upper Muddy River Valley alluvial aquifer did not recover to historic average levels. A little more than half of the monitored groundwater levels in the Upper Muddy River Valley alluvial aquifer wells did not recover to their 2008 maximum recovery levels, with the exceptions being the Lewis-1 Old, Lewis-2, Lewis S, LDS Central, LDS East and LDS West, all of which exceeded their 2008 maximum recovery levels. Maximum recovery levels were achieved in the spring months for the alluvial aquifer with the majority observed during the month of April. Maximum water level recoveries for Perkins, Abbott, and Behmer wells were lower than water levels observed during 2008 by an average of 4.9 feet. The observed LDS well field maximum recovery was approximately 0.7 feet higher (average maximum of LDS Central, East, West) than the previous year. The observed Lewis Well Field maximum recovery was approximately 0.5 feet higher than groundwater levels observed in 2008. Overall, groundwater levels in the alluvial aquifer for the Upper Muddy River Valley recovered to levels that were, on average, 1.3 feet below 2008 levels.

The lowest groundwater levels in 2009 were generally observed during the month of August. Minimum groundwater levels at Perkins, Abbott, and Behmer were higher than 2008 minimum levels by an average of 0.5 feet. A 1.2-foot increase was observed in the minimum water level in the Perkins Production well as compared to the 2008 minimum levels. The minimum water levels observed in the Lewis wells in 2009 showed an increase of 1.2 feet as compared to 2008 levels. The 2009 minimum water levels observed in the LDS wells showed an increase by an average of 0.1 feet as compared to 2008 minimum levels.

In comparison to historical groundwater levels as reported by Pohlmann (1996) overall (average of maximum and minimum) observed levels for the LDS Well Field were 0.2 feet lower during 2009. However, observed groundwater levels for the Lewis Well Field were 0.1 feet above historical levels. The water levels in the Abbott, Perkins, and Behmer Well Field were on average 9.3 feet below historical levels. Figures 5 and 6 generally illustrate groundwater flow patterns in the upper Muddy River Valley alluvial aquifer and illustrate the impacts of groundwater production on the potentiometric surface in 2009.

During 2009, water levels in the carbonate aquifer, as shown on Figures B-7 through B-10, C-2, C-7 and C-11 through C-14 recovered from the previous year's pumping season. Maximum water levels recorded in 2009 for the EH-4 well are lower than the 2008 maximum level by 0.4 feet, while maximum levels in the EH-5b were also lower than 2008 maximum levels by 0.5 feet. However, minimum levels observed in EH-4 and EH-5b wells were higher than 2008 levels by 0.3 feet and 0.4 feet, respectively. In addition, water levels are still on average 1.8 feet below average maximums and 1.9 feet below average minimum levels as referenced by Pohlmann (1996) (see Table 5). A similar response was observed in 2009 for RW-2 with water level observations lower than 2008 maximum levels by 0.2 feet, although minimum levels for 2009 were higher than the 2008 minimum water level by 0.2 feet (Figures B-12 and C-14). As shown in Figure C-13 water levels in CSV-2, as measured by the USGS, were approximately 0.7 feet above the previous year's maximum level; however, water levels were 3.3 feet below maximum levels as observed in 1997. The minimum water level observed for CSV-2 in 2009 was 0.2 feet higher than that of 2008 and 2.3 feet lower than 1997 minimum levels.



LEGEND:

- APPROXIMATE LOCATION OF NPC MONITORING WELL
- APPROXIMATE LOCATION OF SPRING OR SURFACE WATER
- APPROXIMATE LOCATION OF MVWD WELL OR SPRING

GRAPHIC SCALE

3000 0 3000 6000

(In Feet)

REF: Moapa quad base maps, 20' contour interval

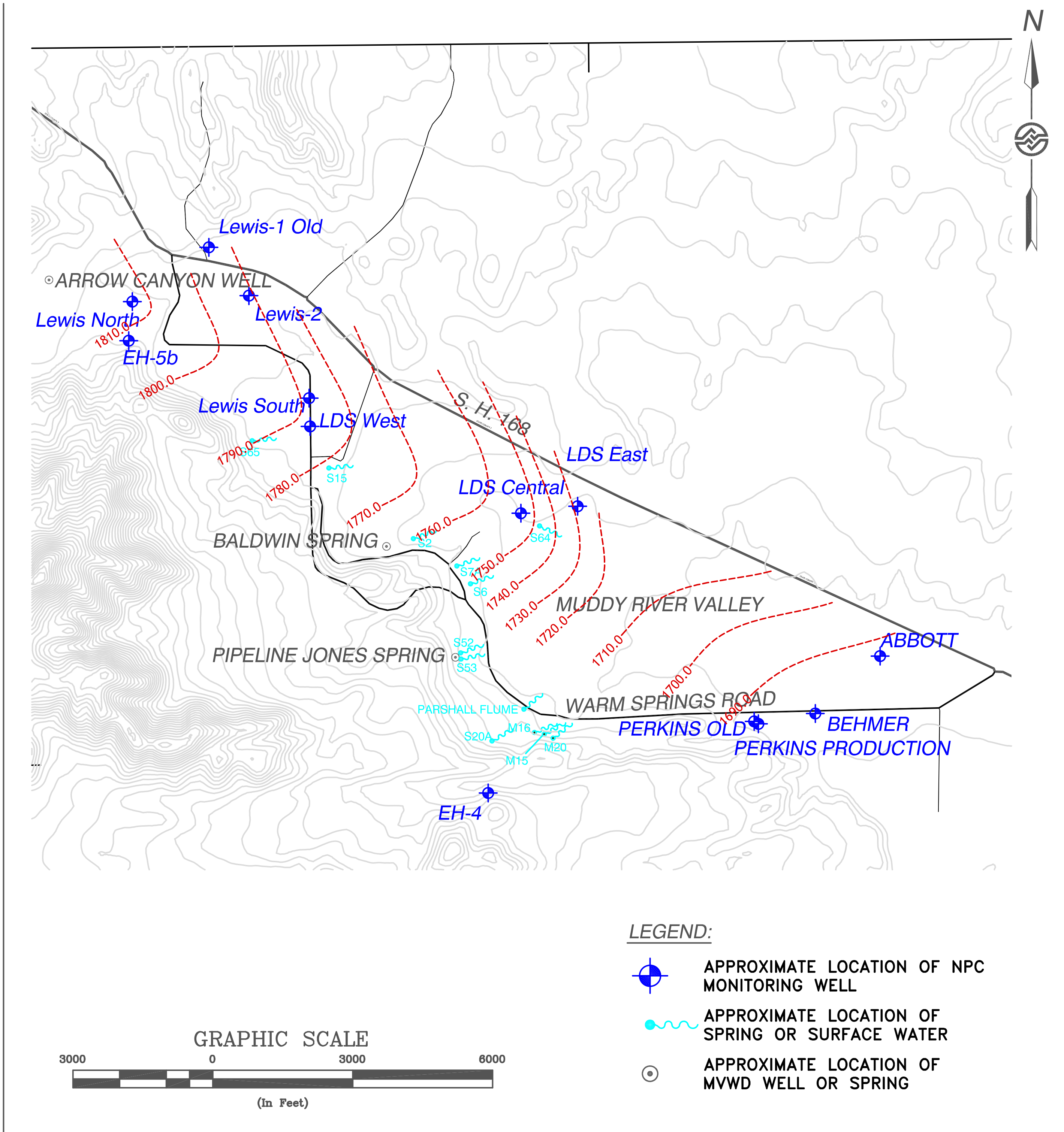
POTENTIOMETRIC SURFACE (APRIL 2009)

NV ENERGY
Water Level Monitoring
Moapa, Nevada

CONVERSE CONSULTANTS

Over 60 Years of Dedication in Engineering and Environmental Sciences

Scale 1" = 3000'	File No. 14715002
Date 01/18/10	Project No. 97-35147-15
Drafted By REP/GRD	Figure No. 5
Checked By KJH	
Approved By	



REF: Moapa quad base maps, 20' contour interval

POTENTIOMETRIC SURFACE (AUGUST 2009)

NV ENERGY
Water Level Monitoring
Moapa, Nevada

Scale 1" = 3000'	File No. 14715002	
Date 01/18/10	Project No. 97-35147-15	
Drafted By REP/GRD	Figure No.	
Checked By KJH	6	
Approved By		

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Table 5
Groundwater Elevation Extremes
In The Upper Muddy River Valley During 2009

Well Name	Maximum Elevation	Average Maximum[2]	Departure From Average	Date	Minimum Elevation	Average Minimum[2]	Departure From Average	Date
Abbott[1]	1694.2	1706.3	-12.1	4/14/2009	1689.4	1699.5	-10.1	11/12/2009
Behmer[1]	1696.9	1707	-10.1	4/14/2009	1690.9	1698.1	-7.2	8/20/2009
EH-4	1815.6	1817.5	-1.9	5/12/2009	1814.8	1816.8	-2.0	10/1/2009
EH-5b	1815.6	1817.3	-1.7	4/14/2009	1814.5	1816.3	-1.8	9/16/2009
Lewis-1 Old[1]	1800.8	1802.1	-1.3	4/14/2009	1791.1	1790.1	1.0	8/5/2009
Lewis-2	1799.6	1800.8	-1.2	4/14/2009	1786.0	1785	1.0	8/4/2009
Lewis North	1812.1	1813.7	-1.6	4/14/2009	1810.3	1811.6	-1.3	8/4/2009
Lewis South	1797.0	1796.1	0.9	4/21/2009	1790.3	1787.5	2.8	7/13/2009
LDS Central[1]	1759.8	1760.2	-0.4	3/18/2009	1751.2	1752.5	-1.3	8/20/2009
LDS East[1]	1745.9	1746.6	-0.7	2/19/2009	1724.7	1725.2	-0.5	8/20/2009
LDS West[1]	1790.2	1790.8	-0.6	4/14/2009	1777.5	1775.3	2.2	6/17/2009
Perkins Production[1]	1695.3	1709.1	-13.8	4/14/2009	1688.2	1691	-2.8	1/20/2009
Perkins Old	1699.4	1709.8	-10.4	4/14/2009	1691.4	1699.5	-8.1	9/2/2009

[1] Values based on periodic measurements, others based on semi-continuous measurements (all values reported in feet).
[2] Normal values based on Pohlmann, 1996.

During 2009, the Lewis well field was pumped approximately 36.6% below average (compared to pumping in years 1988-2008) and was also pumped significantly less than 2008 by 29.4% (see Figures 1 & 2). As shown on Figures B-1 through B-4, as well as C-1 and C-4, maximum recovery levels in 2009 for the Lewis well field generally reflected little change over the previous year despite the decrease in pumpage. Water levels observed at Lewis-2 and Lewis South were 0.8 feet and 1.0 feet above 2008 recovery levels, respectively. Recovery for the Lewis North water level was 0.1 feet below the previous year's maximum recovery while Lewis-1 Old recovery levels were 0.3 feet above the previous years.

Overall water levels in the alluvial aquifer within the western portion of the Upper Muddy River Valley were approximately 0.8 feet below average historical maximum levels.

Production from the LDS well field was 23.1% below average in 2009 (compared to pumpage from 1988-2008), and less (9.5%) than production in 2008. As shown on Figures C-3 and C-4 and in Table 5, maximum levels in 2009 were below historical averages by 0.5 feet (average from Table 5 of the three LDS wells) in spite of the below-average pumpage. Water levels observed at LDS Central, LDS West and LDS East were 0.3, 1.5 and 0.1 feet above 2008 maximum levels, respectively. It is important to note that these water levels are only read once a month and are largely dependent on whether or not the wells are pumping and for how long prior to each observation. As shown on Figure C-3, relatively consistent static water level measurements for LDS East and LDS Central since 1988 indicate that groundwater production has apparently not significantly impacted the aquifer at this location. Measured discharge at the Muddy Spring (measured by the USGS) suggests the lower-most springs in the valley have not been impacted by the additional groundwater withdrawals from the area as illustrated by the spring hydrograph shown on Figure 7.

Groundwater production for the Perkins/Behmer well field in 2009 was 41.7% above average (compared to pumping in years 1988-2008), and 32.2% above 2008 production. As shown in Figures B-5, C-5 and C-6, maximum recorded groundwater levels in the eastern portion of the valley-fill aquifer within the Upper Muddy River Valley did not recover to levels observed during the previous year (2008). However, minimum water levels observed from the Perkins Production and Perkins Old wells were 1.2 feet and 0.3 feet above 2008 minimum levels. The minimum water levels observed at the Abbott and Behmer wells were 0.7 feet above and 0.1 feet below 2008 minimum levels, respectively. Groundwater elevations in the vicinity of the Perkins/Behmer well field have been relatively stable since 2001, but have exhibited larger than normal fluctuations during 2007 through 2008. However, groundwater

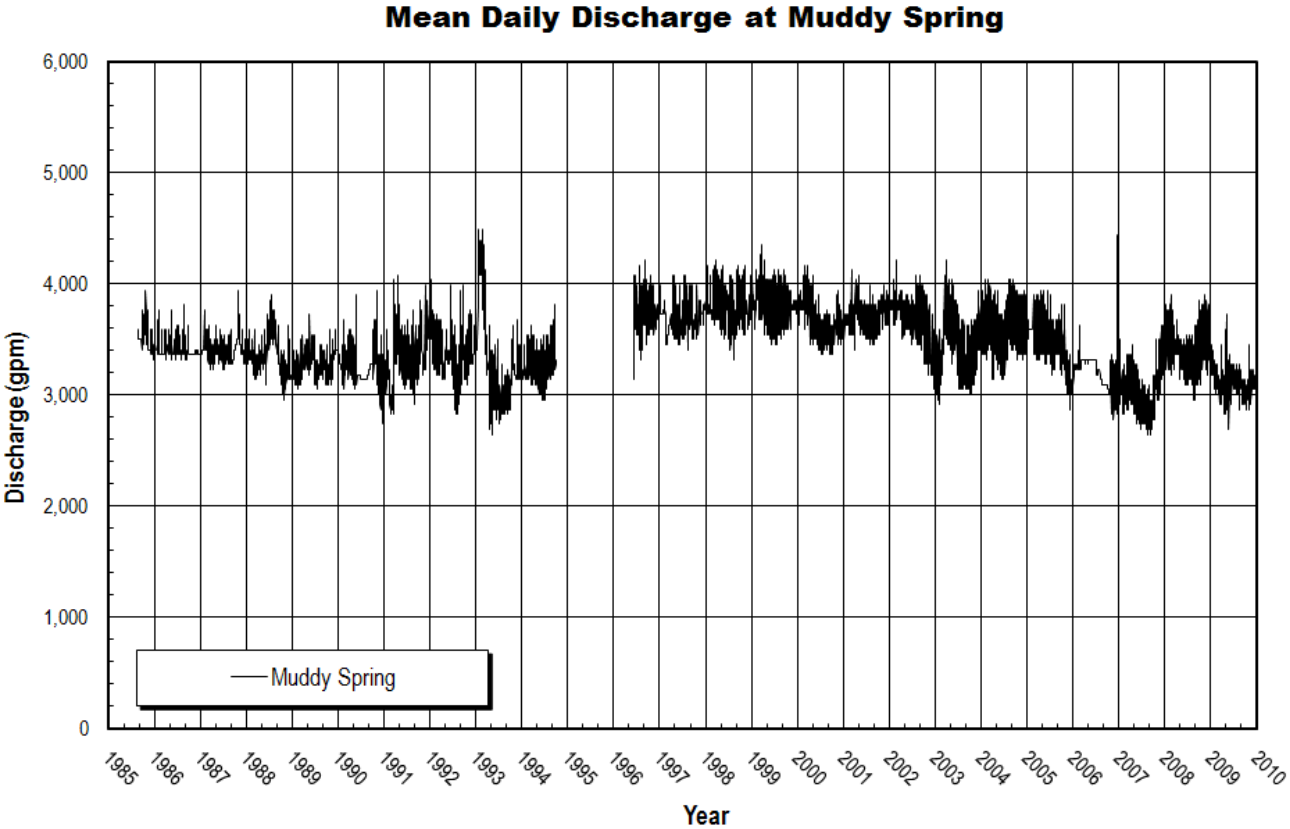


Figure 7: *Average daily discharge of Muddy Spring located on LDS Farm near LDS East and Central production wells, between 1985 and December of 2009. Notice that while discharge has varied somewhat seasonally, observations at the Muddy Spring have not reflected a sustained reduction in flow as a result of production from the LDS well field. (Data provided by the USGS). Note, no data available 10-1-94 thru 6-11-96.*

levels have shown a slight drop in elevation for the 2009 season when compared to the stabilization trend since 2001. Comparison of the water level data shown on Figures B-5, C-5, and C-6 with the pumpage differences shown on Figure 2 indicates that this may be due to slightly higher than average groundwater withdrawals in this area in the first half of the year then increasingly higher than average withdrawals in mid-Fall and early-Winter of 2009.

Meadow Valley and Weiser Wash

Water levels in Meadow Valley and Weiser Wash areas, where the only current year-round groundwater production is local domestic and agricultural users, continued to follow established seasonal and long-term trends through 2009. As shown on Figure C-7, carbonate water levels as observed in EH-3 and EH-7 followed established seasonal trends. Water levels in the Meadow Valley Wash, as shown on Figures C-8 through C-10, are similar to observed conditions during 2008, indicating an end of the upward trend that began during the 1988 pumping season and possibly marking the continuation of groundwater level stabilization.

Dry Lake Valley

As shown on Figure C-11, water levels at the old Harvey Well in Dry Lake Valley indicated that levels at this location had been slowly declining from 1997 to 2001. This decrease was likely due to well deterioration and the subsequent loss of artesian groundwater pressure to the overlying Muddy Creek Formation. However, the Harvey Well was replaced in 2001 and relocated a few hundred feet away. Water level measurements at the new well, RW-1, indicates that groundwater levels in this well have fluctuated by as much as ~9 feet since initial construction. This is most likely due to pumping at RW-1 to provide water for the Crystal Substation. Water levels in RW-1 have been increasing since the end of 2004 and continued to do so through 2009 with water levels exceeding their highest point since December of 2001 during June of 2009. Note that no data was collected between March 2008 to March of 2009 from RW-1 due to equipment malfunction and well maintenance. However, once RW-1 was fully operational again, groundwater levels in 2009 were measured to be 1.2 feet higher than the previous year (2008). Groundwater levels observed in Dry Lake Valley as measured in the Crystal Wells (Nos. 1 & 2) were on average 0.3 feet lower than levels observed last year. Overall, water levels measured at the Crystal wells (Nos. 1 & 2) as depicted in Figures B-13, B-14 and C-12 have remained relatively stable since 2000.

Water Quality In 2009

Field water quality measurements were collected on wells and springs within the NV Energy Monitoring Network. Electrical conductivity and temperature data were collected to evaluate seasonal and long-term trends related to groundwater production from the alluvial and carbonate aquifers. Beginning in June of 2006, pH and salinity data has also been collected from all wells and springs. All water quality data collected during 2009 are tabulated in Appendix E while temperature and electrical conductivity are shown graphically in Figures 8 through 12.

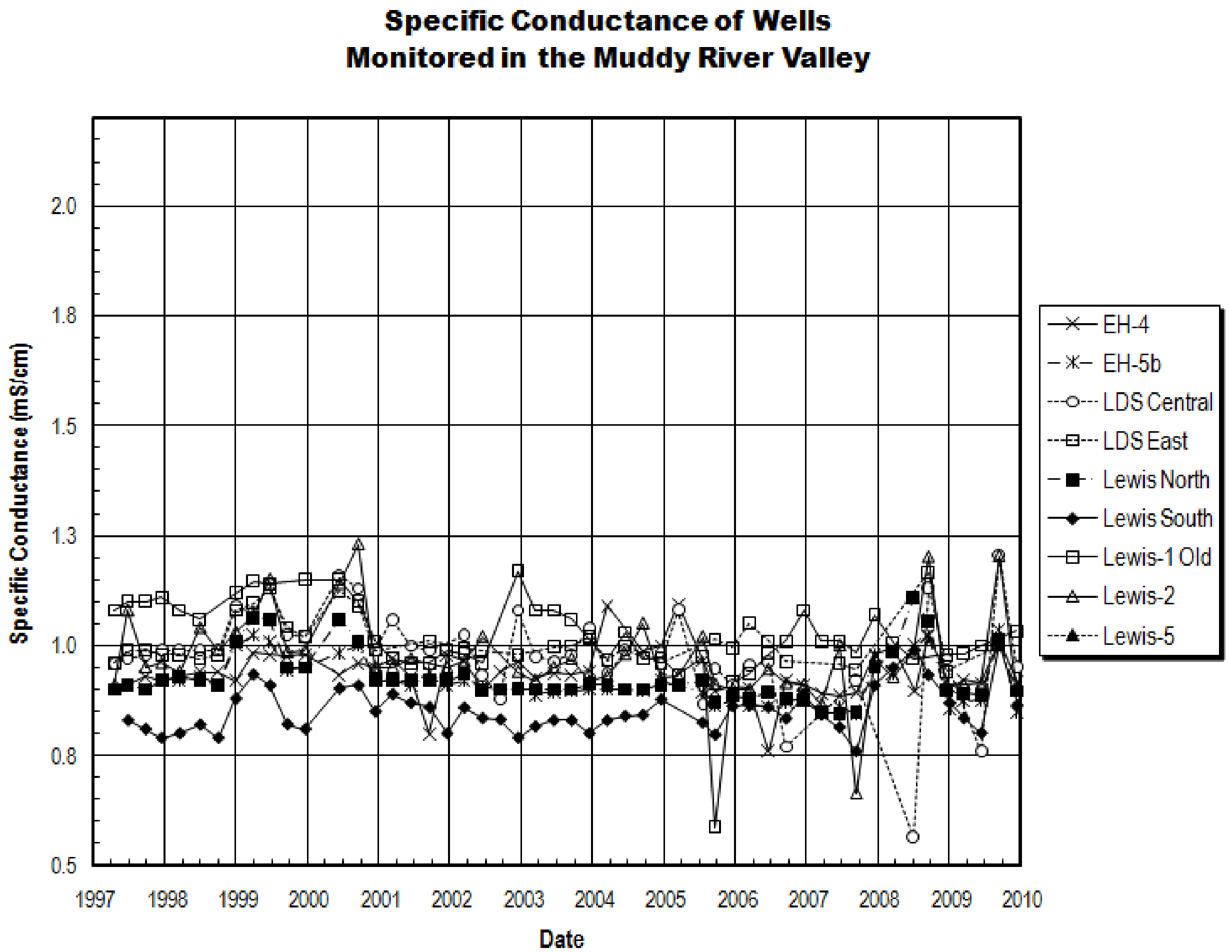


Figure 8: *Specific conductance for selected monitoring wells located in the western half of the Upper Muddy River Valley near Moapa, Nevada. Notice that while seasonal variations are present, the specific conductance is relatively low and stable through time compared to the specific conductance for the monitoring wells located in the eastern half of the Valley (see Figure 10).*

Upper Muddy River Valley

Field water quality measurements collected on wells and springs in the upper Muddy River Valley generally revealed two distinct patterns when comparing data collected since 1996. First, wells or springs that are directly influenced by groundwater from the carbonate aquifer appear to have relatively lower electrical conductivities and higher temperatures, as shown on Figures 8 and 9.

In contrast, wells that are not directly influenced by the carbonate aquifer exhibit higher and more variable electrical conductivities in addition to lower, seasonal temperatures, as shown on Figures 10 and 11.

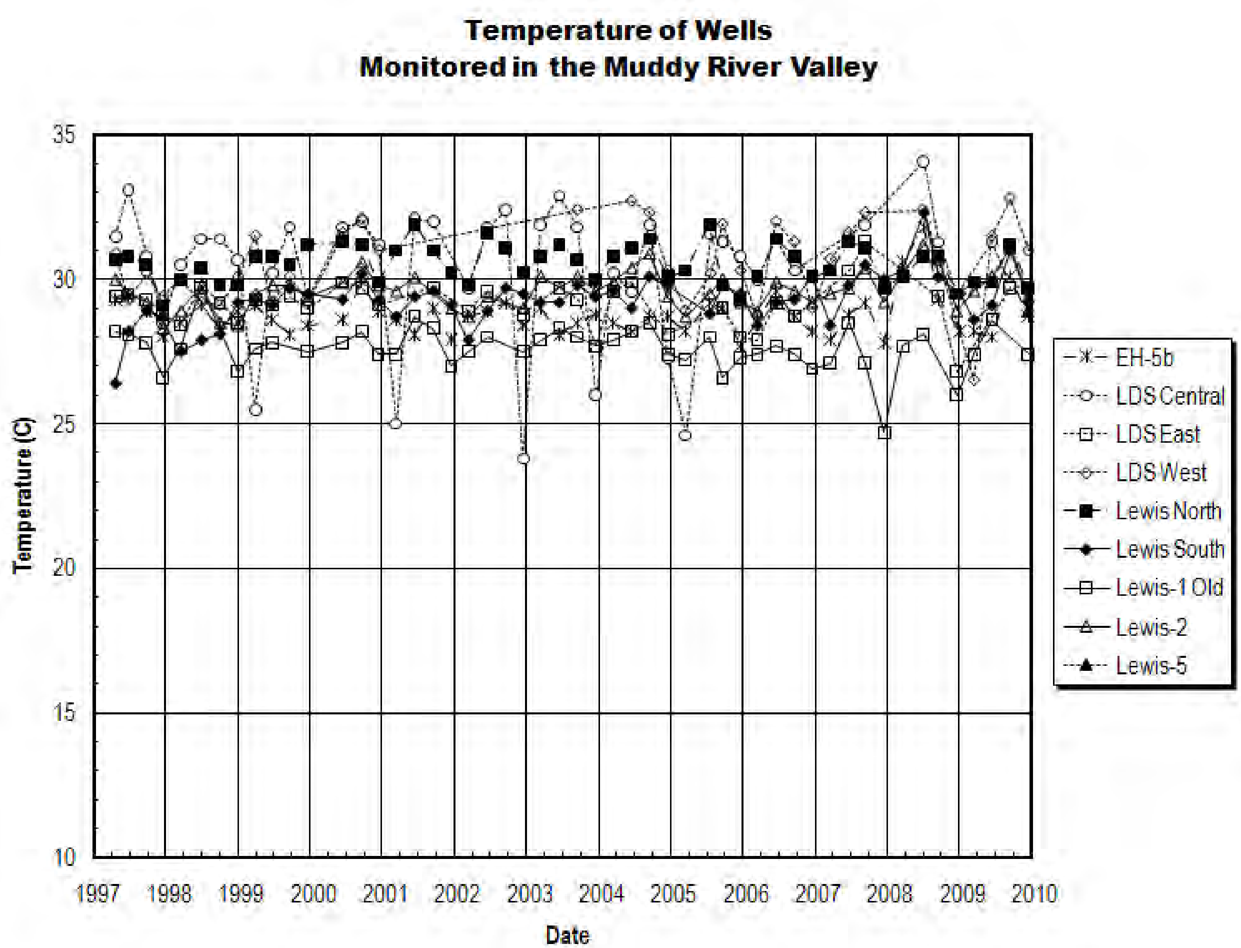


Figure 9: *Temperature of groundwater in selected monitoring wells in upper Muddy River Valley. Notice that although some seasonal variation is present, groundwater temperatures are generally and consistently warmer than those for wells shown on Figure 11. These consistent, warmer temperatures suggest these wells are closely tied to the carbonate aquifer.*

As shown on Figure 12, average electrical conductivities for springs and wells in the upper Muddy River Valley were plotted to identify the apparent boundary beyond which the carbonate aquifer is hydraulically disconnected from the alluvial aquifer. This boundary appears to coincide with the 1.0 mS/cm contour line, which is located near the LDS East well.

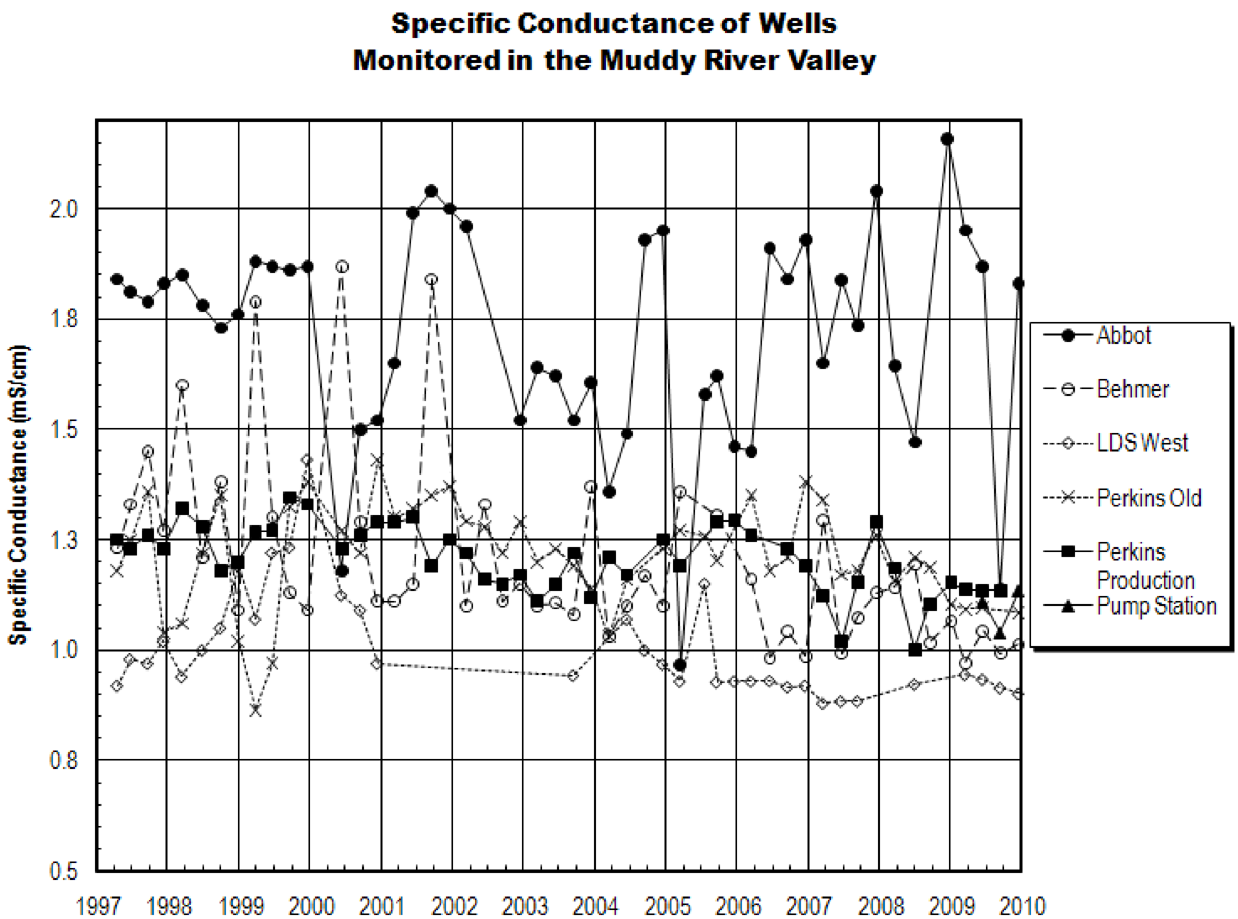


Figure 10: *Specific conductance of selected monitoring wells in the eastern half of the upper Muddy River Valley. Notice not only the large seasonal variations, but also the relatively higher conductivity values when compared with Figure 8. The higher, more volatile conductivity measurements suggest these wells are relatively poorly connected to the carbonate aquifer.*

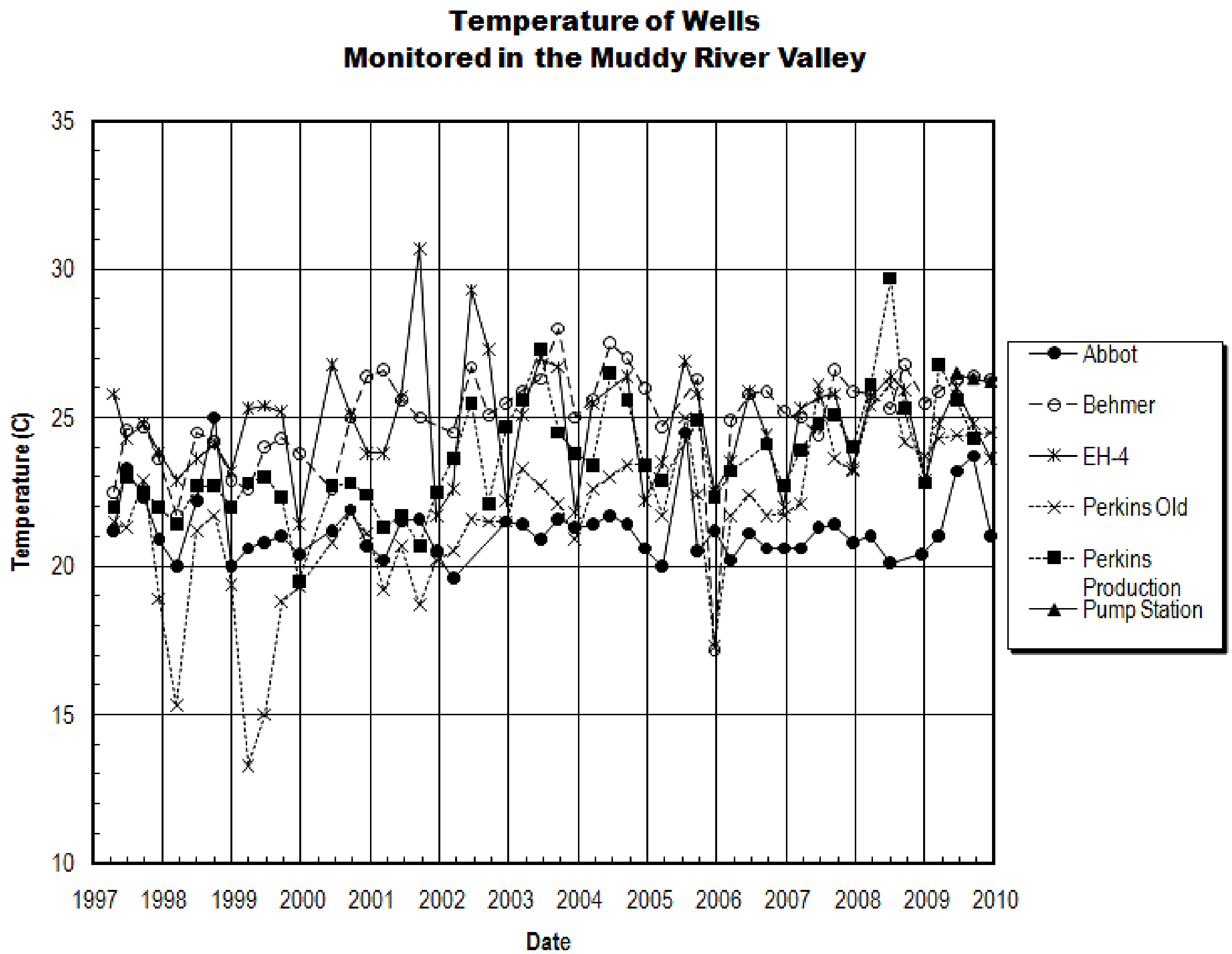
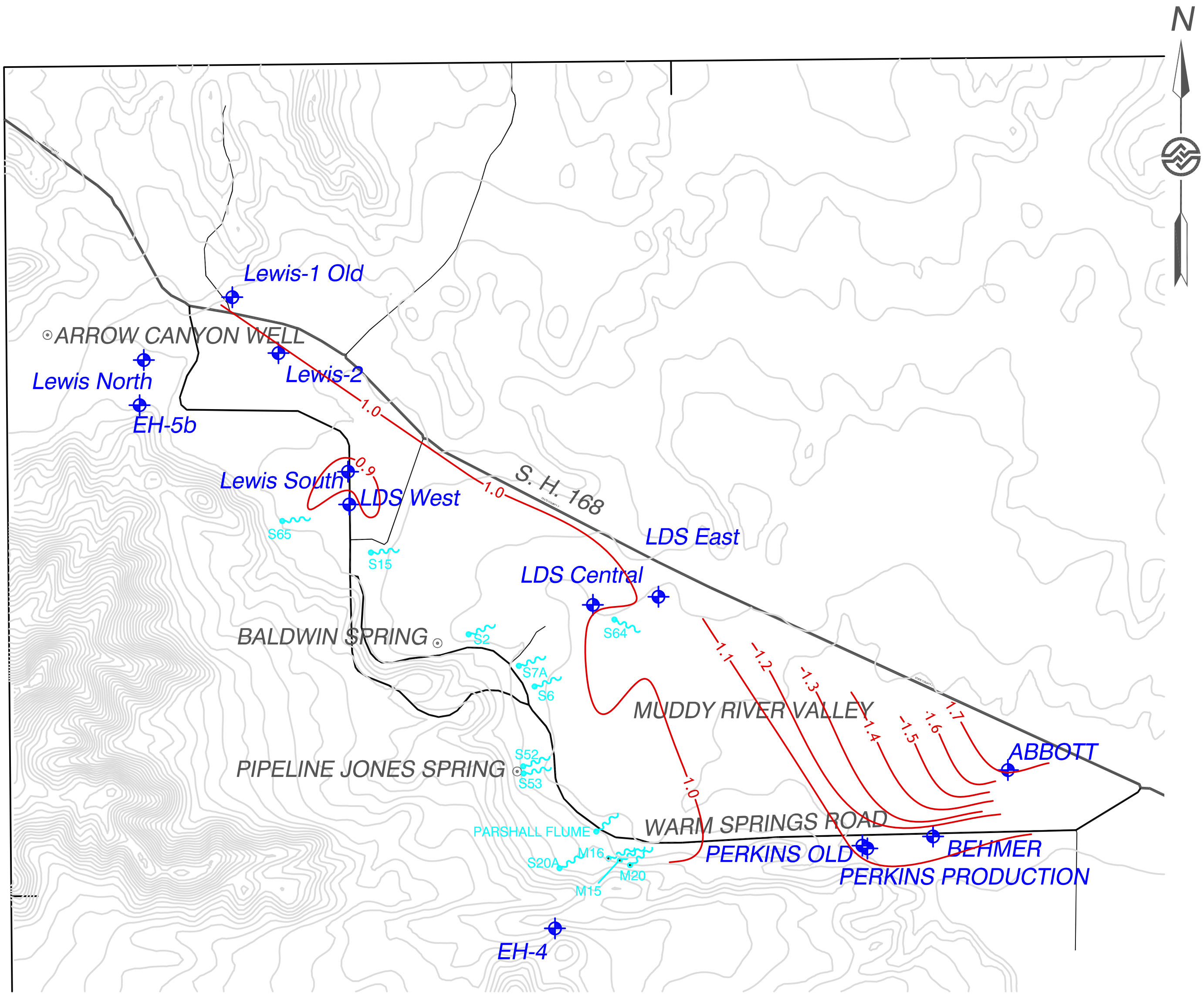


Figure 11: *Temperature data recorded for selected monitoring well s in the upper Muddy River Valley near Moapa, Nevada. Notice that groundwater temperatures are lower and more seasonal than for those wells shown on Figure 9.*

Meadow Valley and other areas

Field water quality measurements were also collected from monitoring wells in Meadow Valley and Weiser Wash. Observations made in these areas are tabulated in Appendix E.



LEGEND:

APPROXIMATE LOCATION OF NPC MONITORING WELL*

APPROXIMATE LOCATION OF SPRING OR SURFACE WATER*

APPROXIMATE LOCATION OF MVWD WELL OR SPRING

GRAPHIC SCALE

3000 0 3000 6000

(In Feet)

REF: Moapa quad base maps, 20' contour interval

AVERAGE ELECTRICAL CONDUCTANCE OF WELLS AND SPRINGS

NV ENERGY
Water Level Monitoring
Moapa, Nevada

Scale 1" = 3000'		File No. 14715002
Date 01/18/10		Project No. 97-35147-15
Drafted By REP/GRD		Figure No.
Checked By KJH		12
Approved By		

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Over 60 Years of Dedication in Engineering and Environmental Sciences

Conclusions

1. Of the 10.52 cfs that were produced in 2009, NV Energy pumped 5.65 cfs while MVWD pumped 4.87 cfs. Historically, groundwater production by NV Energy and MVWD averaged 11.13 cfs between 1988-2008 and 1992-2008, respectively. Overall, the combined 2009 production from both NV Energy and MVWD was 5.5% below the historic average, and 0.2% above the combined production for 2008. Production from NV Energy was 12.5% less than the 1988-2008 average and 4.7% less than the previous year 2008. Production from MVWD was 4.2% above the 1992-2008 average and 6.5% above the previous year. Of MVWD's total, Arrow Canyon Wells No.1 & 2 accounted for approximately 57.7% of production in 2009.

2. Maximum water levels in the eastern portion of the upper Muddy River Valley did not recover to the observed 2008 levels. However, minimum groundwater levels at Perkins, Abbott, and Behmer were higher than 2008 minimum levels by an average of 0.5 feet.

3. Generally, maximum water levels in 2009 for the alluvial aquifer within the western portion of the Upper Muddy River Valley recovered to levels similar to those observed in 2008. In spite of below average groundwater production for the LDS Well field, water levels in the vicinity of the LDS well field were observed to have similar annual fluctuations as seen in past years. Due to the LDS well field's proximity to Muddy Spring, this trend also suggests the lowermost springs in the valley have not been impacted by the additional groundwater withdrawals from the alluvial aquifer.

4. Despite the 36.6% decrease in production for the Lewis Well Field (when compared to the 1988-2008 average) overall water levels in the alluvial aquifer within the western portion of the Upper Muddy River Valley remained relatively similar to levels observed in 2008.

5. Water levels in the carbonate aquifer as measured in EH-4 and EH-5b were 0.4 and 0.5 feet, respectively, below maximum levels as compared to the previous year (2008). Similarly, groundwater levels in the Coyote Spring Valley as measured at RW-2 were 0.24 feet lower than the previous year (2008). In addition, groundwater levels observed in Dry Lake Valley as measured in Crystal Wells (Nos. 1 & 2) were on average 0.53 feet lower than levels observed last year. Overall, the continued declining trend in water levels is apparent throughout the carbonate aquifer since the wet year of 2004/2005. Water levels in the carbonate aquifer as measured in EH-3 and EH-7 (Weiser Wash) were observed to have an average maximum water level approximately 0.23 feet lower than levels observed last year however the overall trend has remained stable with relatively little fluctuation since the mid 1990's.

6. Water levels in Meadow Valley continue to recover from pumping during the late 1980's. Measured groundwater elevations in December of 2009 for the Meadow Valley well field are on average similar to levels observed in December of 2008. Overall water level observations in the Meadow Valley well field from 2008 through this quarter indicate the aquifer is no longer impacted by groundwater pumpage which ended in the 1980's. The groundwater table seems to have leveled off and stabilized as the local groundwater storage appears to have reached equilibrium with current local factors that influence flow into and out of the shallow unconfined aquifer.

7. Field water quality measurements collected on wells and springs in the upper Muddy River Valley generally indicate that wells and/or springs directly fed by groundwater from the carbonate aquifer have relatively lower electrical conductivities and higher temperatures. In contrast, wells that are not directly connected to the carbonate aquifer exhibit higher and more variable electrical conductivities in addition to lower, seasonal temperatures.

Closure

This report has been prepared solely for the use of NV Energy as it applies to the subject sites located in the Moapa Valley of Clark County, Nevada. Conclusions and recommendations of this report are based on the inspection and evaluation completed for the stated scope of work. Observed conditions may change with relation to time, on-site activities, and adjacent site activities. This report represents information pertaining to the specific time period in which it was collected.

Thank you for this opportunity to be of service. If you have any questions regarding this report, please contact the undersigned at your convenience.

Respectfully submitted,

CONVERSE CONSULTANTS

Kevin Howerton
Staff Geologist

Reviewed by:

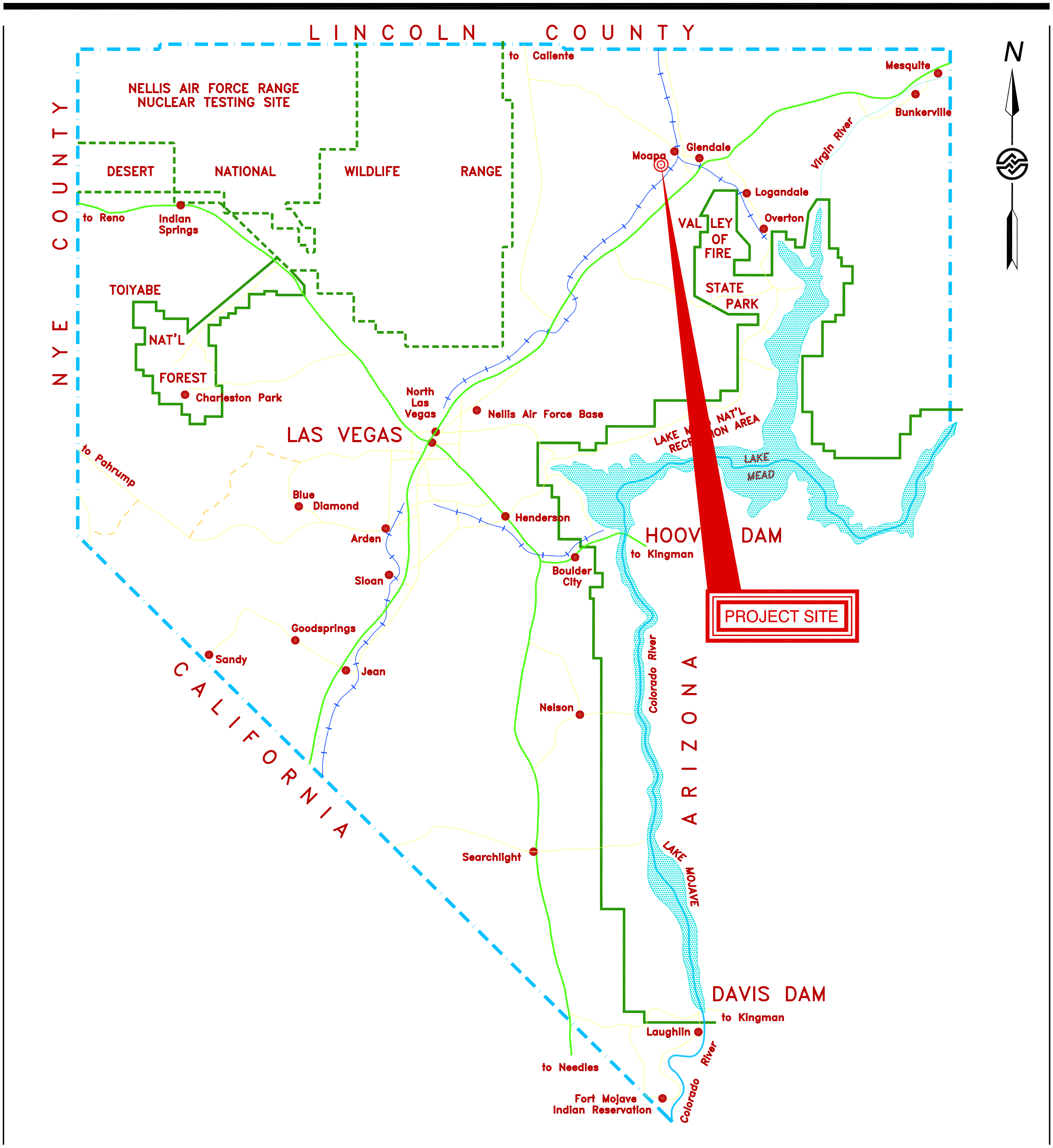
Jason M. Dixon, P.E., W.R.S.
Principal Engineer

KJH:JMD:ls

Encl: Appendices A through F

Dist: Robert (Bob) Ott E-mail - rott@nvenergy.com

Appendix A



CLARK COUNTY

NV ENERGY
Water Level Monitoring
Moapa, Nevada

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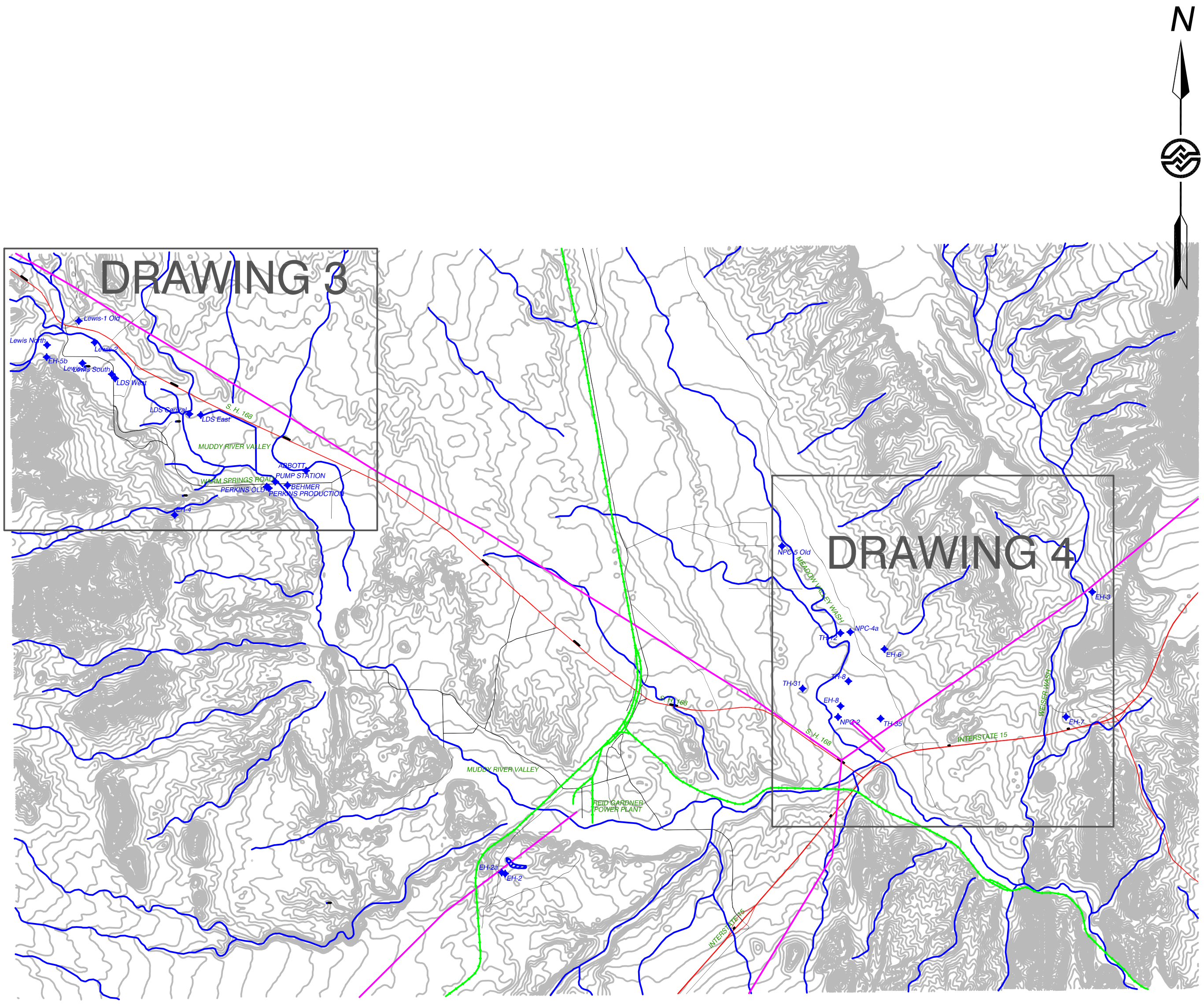
Scale: N.T.S.	File No.: 14715V01	
Date: 01/18/10	Project No.: 97-35147-15	
Drafted By: REP/GRD	Drawing No.: 1	
Checked By: KJH		
Approved By:		



GRAPHIC SCALE

10,000 0 10,000 20,000

(In Feet)

REF: Moapa quad base maps, 20' contour interval

MOAPA VALLEY MONITORING NETWORK INDEX MAP

NV ENERGY
Water Level Monitoring
Moapa, Nevada

Scale 1" = 10,000'	File No. 14714004
Date 01/18/10	Project No. 97-35147-15
Drafted By REP/GRD	Drawing No.
Checked By KJH	2
Approved By	

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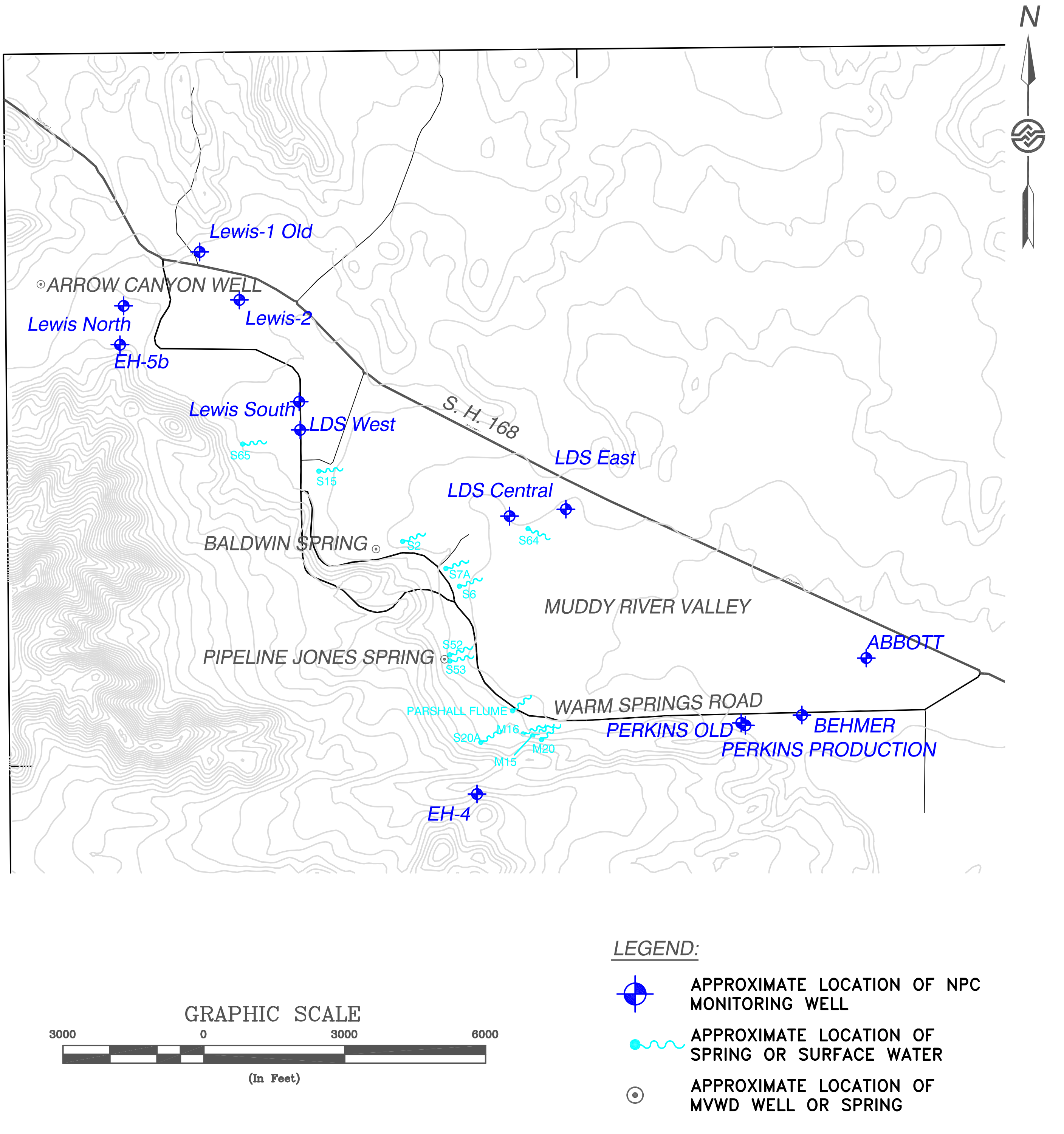

REF: Moapa quad base maps, 20' contour interval

UPPER MUDDY RIVER MONITORING WELLS

NV ENERGY
Water Level Monitoring
Moapa, Nevada

Scale 1" = 3000'	File No. 14715002	
Date 01/18/10	Project No. 97-35147-15	
Drafted By REP/GRD	Drawing No. 3	
Checked By KJH		
Approved By		

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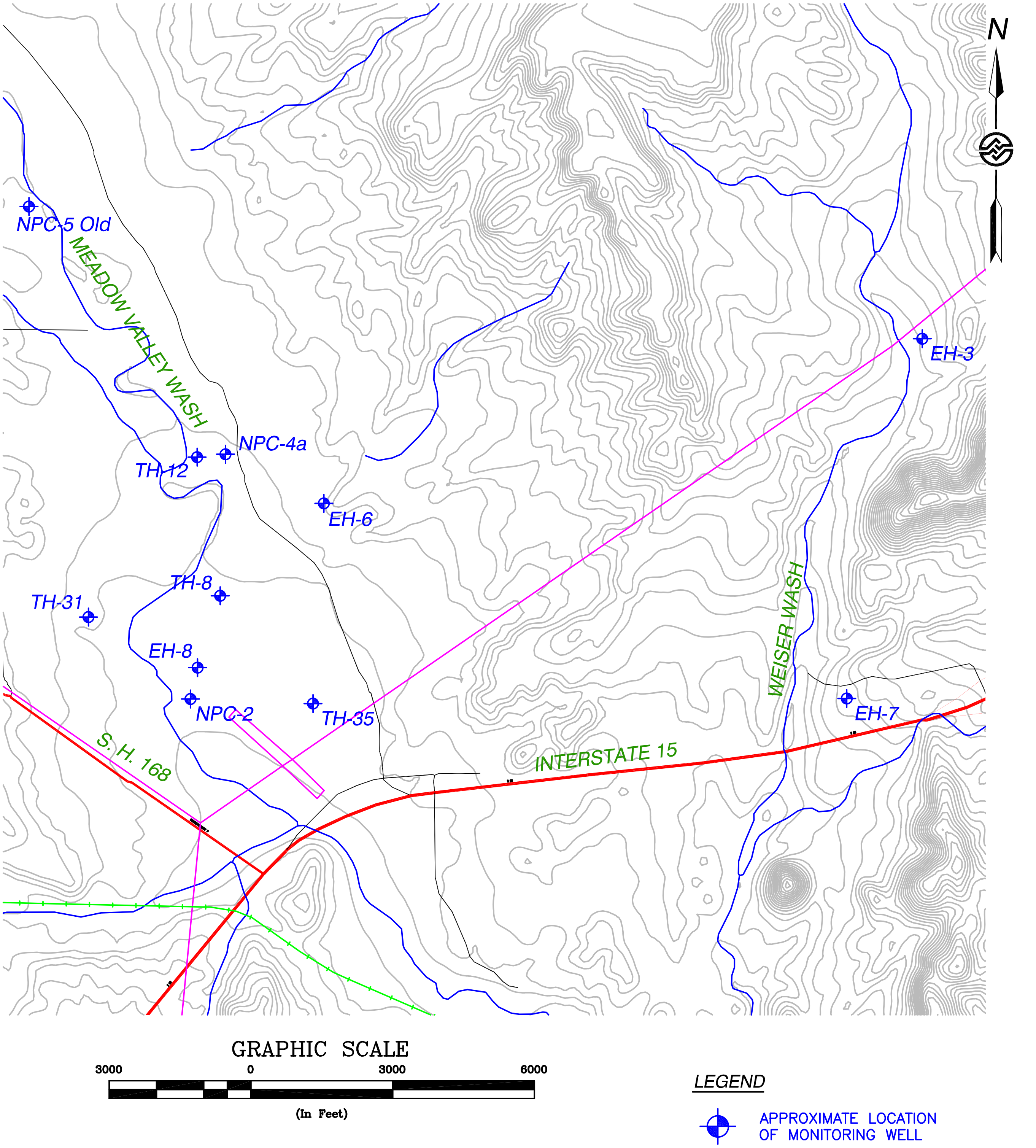


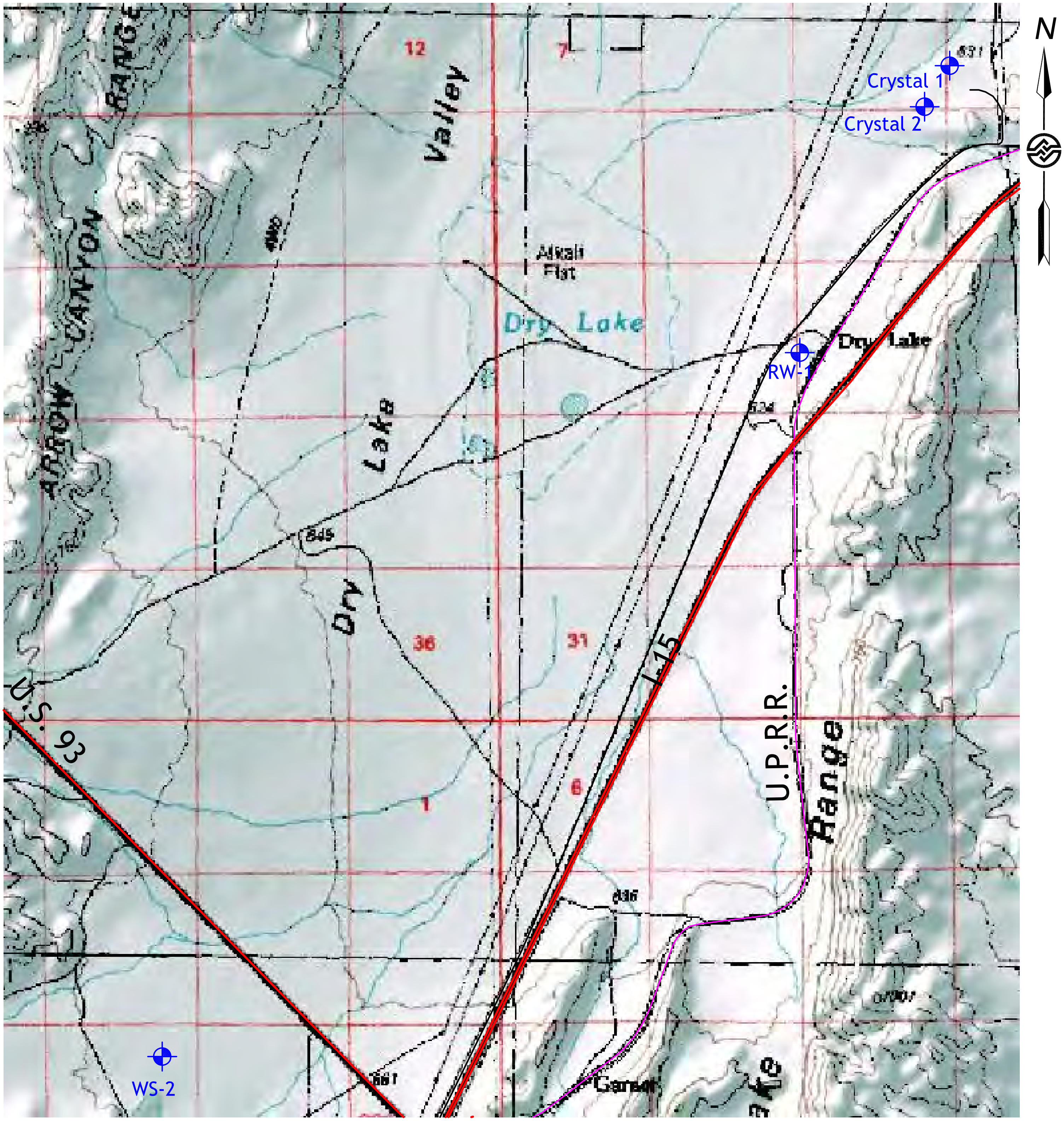
REF: Moapa quad base maps, 20' contour interval

MEADOW VALLEY AND WEISER WASH MONITORING WELLS

NV ENERGY
Water Level Monitoring
Moapa, Nevada

Over 60 Years of Dedication
in Engineering and
Environmental Sciences

Scale: 1" = 3000'
Date: 01/18/10
Drafted By: REP/GRD
Checked By: KJH
Approved By:
File No.: 14714004
Project No.: 97-35147-15
Drawing No.: 4



LEGEND

APPROXIMATE LOCATION OF MONITORING WELL

REF: GlobeXplorer USGS Topo, 2000

DRY LAKE VALLEY WELLS

NV ENERGY
Water Level Monitoring
Moapa, Nevada

Scale 1" = 5000'	File No. 14709003A
Date 01/18/10	Project No. 97-35147-15
Drafted By GRD	Drawing No.
Checked By KJH	5
Approved By	

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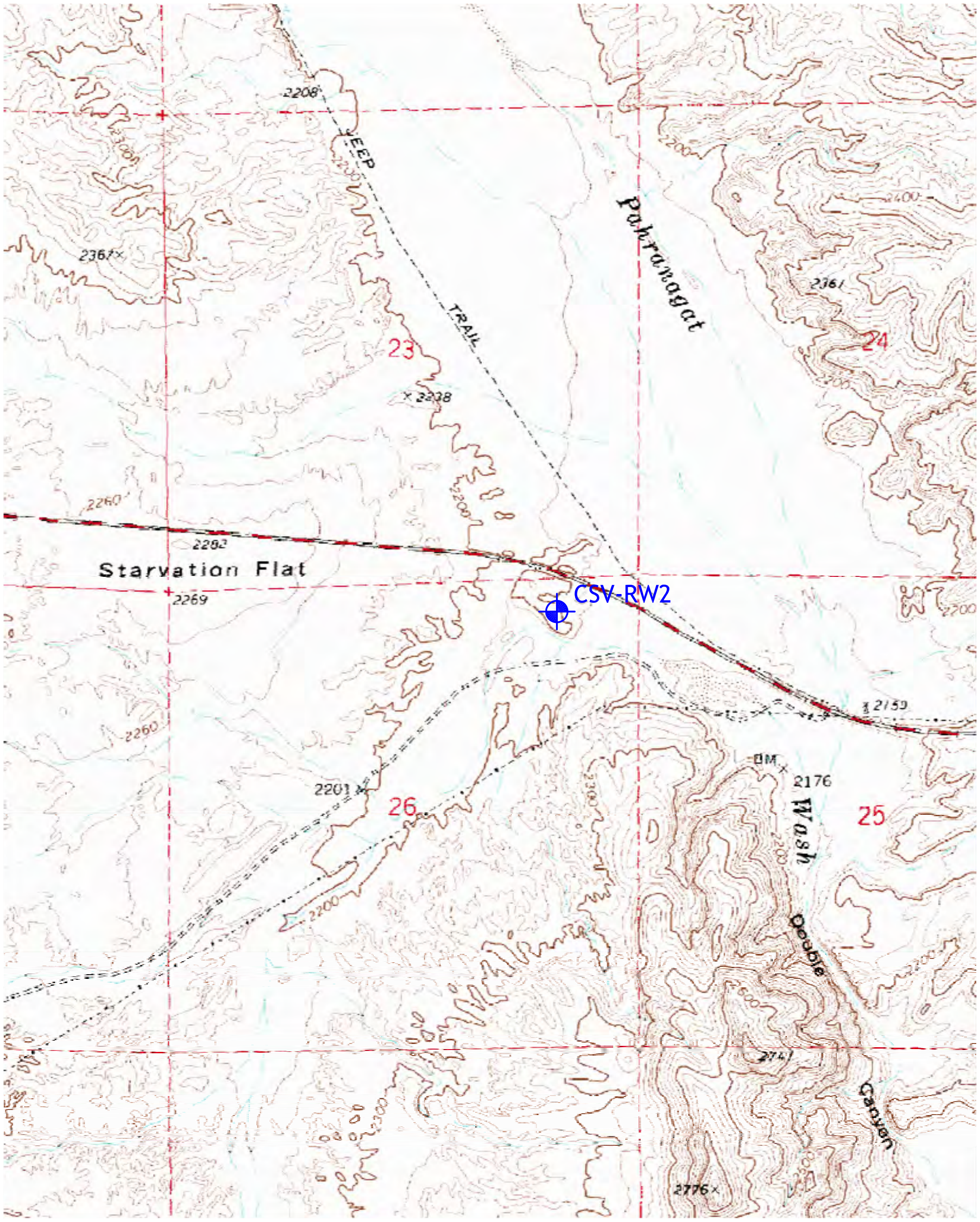
SE ROA 40000



LEGEND

APPROXIMATE LOCATION OF MONITORING WELL

REF: Farrier, Nevada 7.5' USGS Topo, 20" Contour Interval

COYOTE SPRING VALLEY WELL

NEVADA POWER COMPANY
Water Level Monitoring
Moapa, Nevada

Scale: 1" = 2000'	File No.: 14709003
Date: 01/18/10	Project No.: 97-35147-15
Drafted By: REP/GRD	Drawing No.: 6
Checked By: KJH	
Approved By:	

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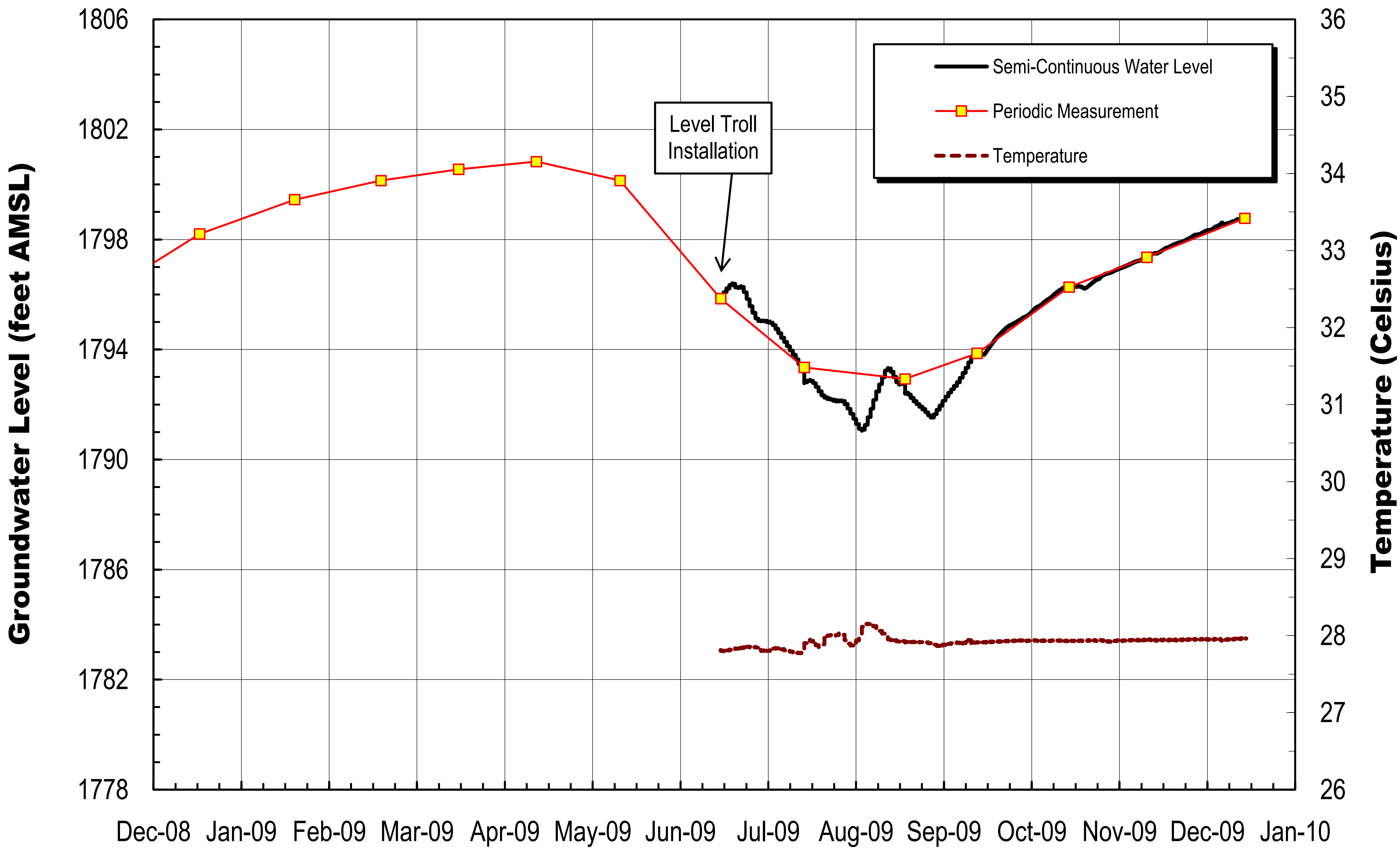
SE ROA 40001

Hydrographs of Continuously Monitored Wells

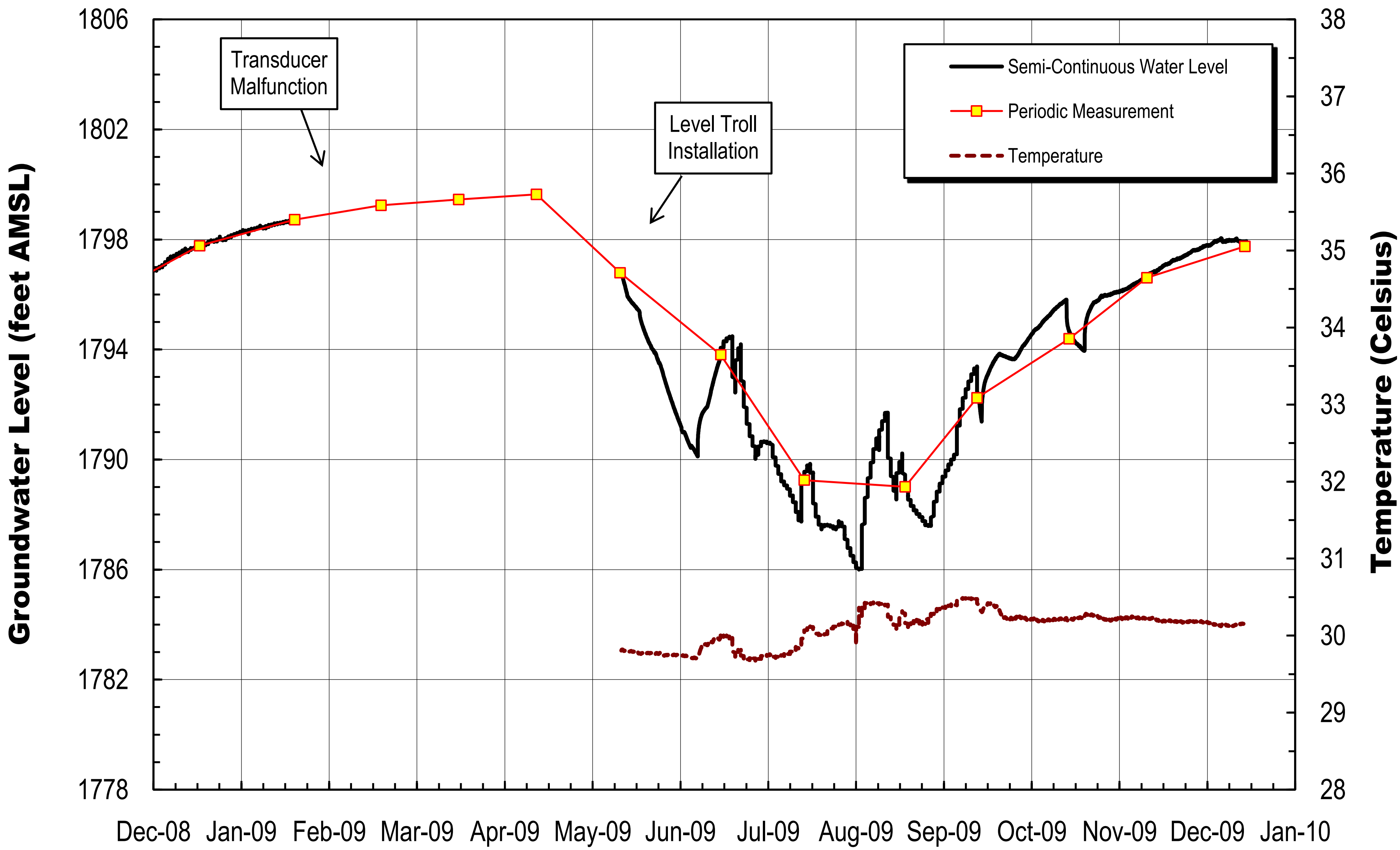
Appendix B



B-1. 2009 Hydrograph for Lewis-1 Old Well

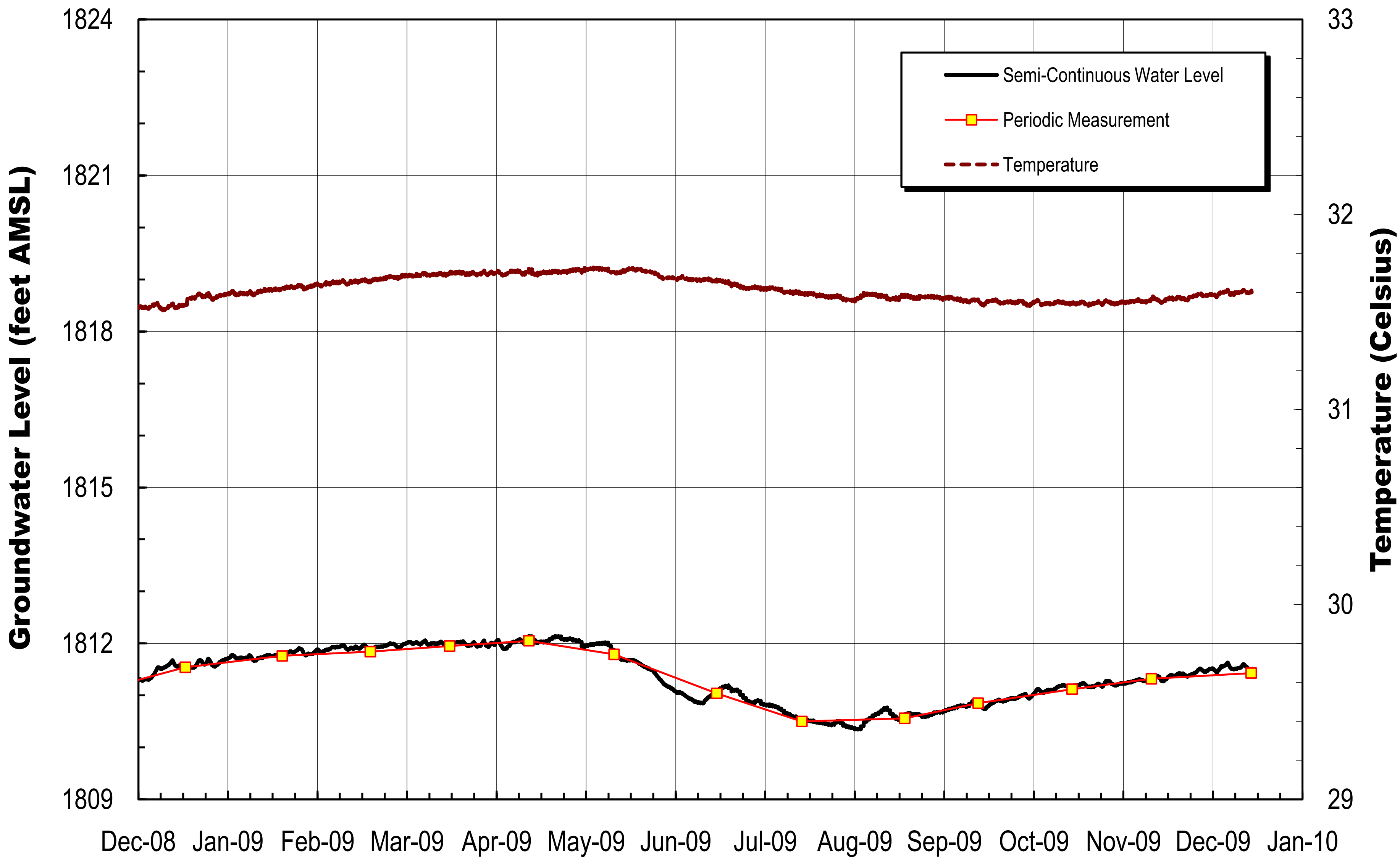
SE ROA 40003

JA_11146



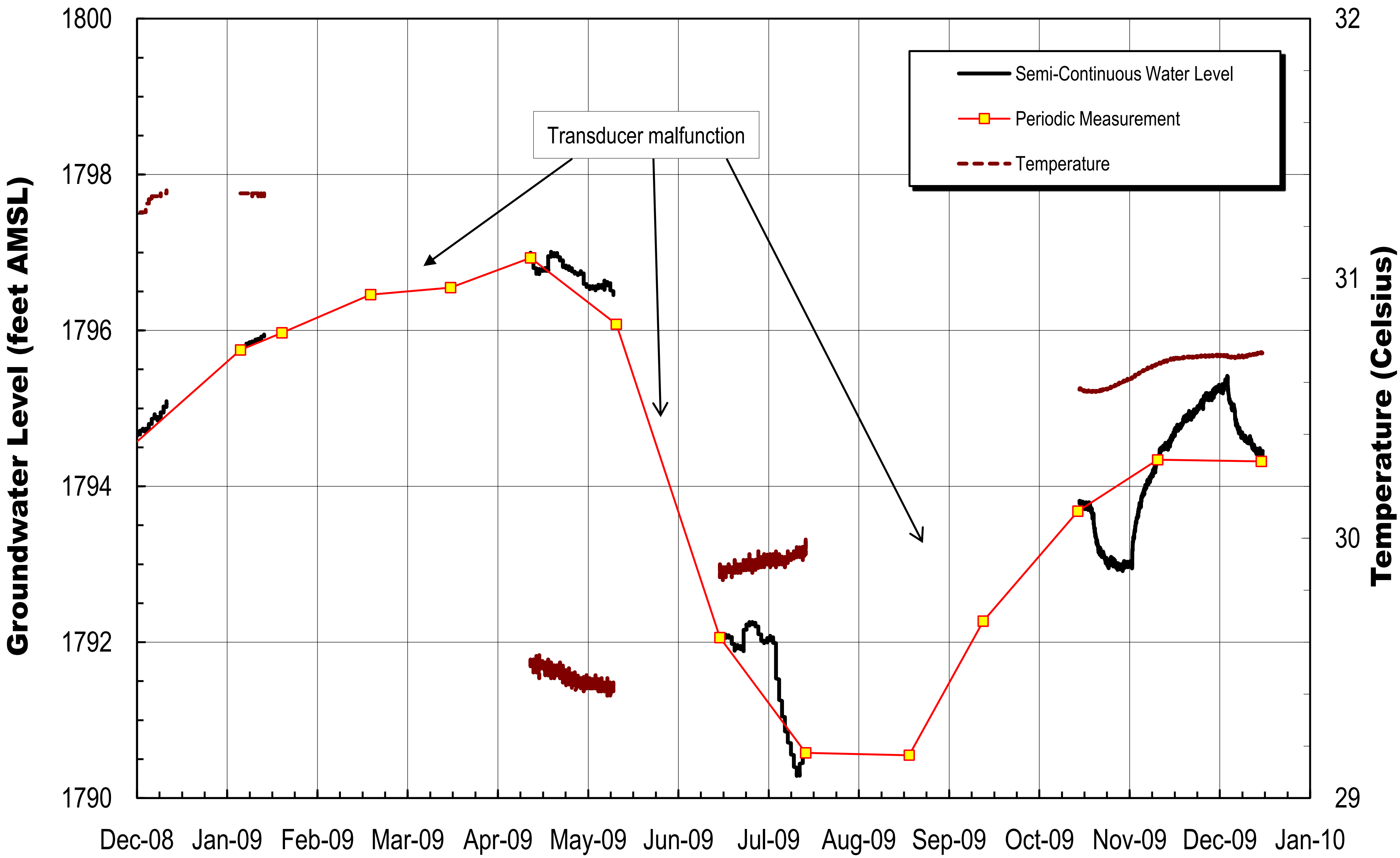
B-2. 2009 Hydrograph for Lewis-2 Well

SE ROA 40004



B-3. 2009 Hydrograph for Lewis North Well

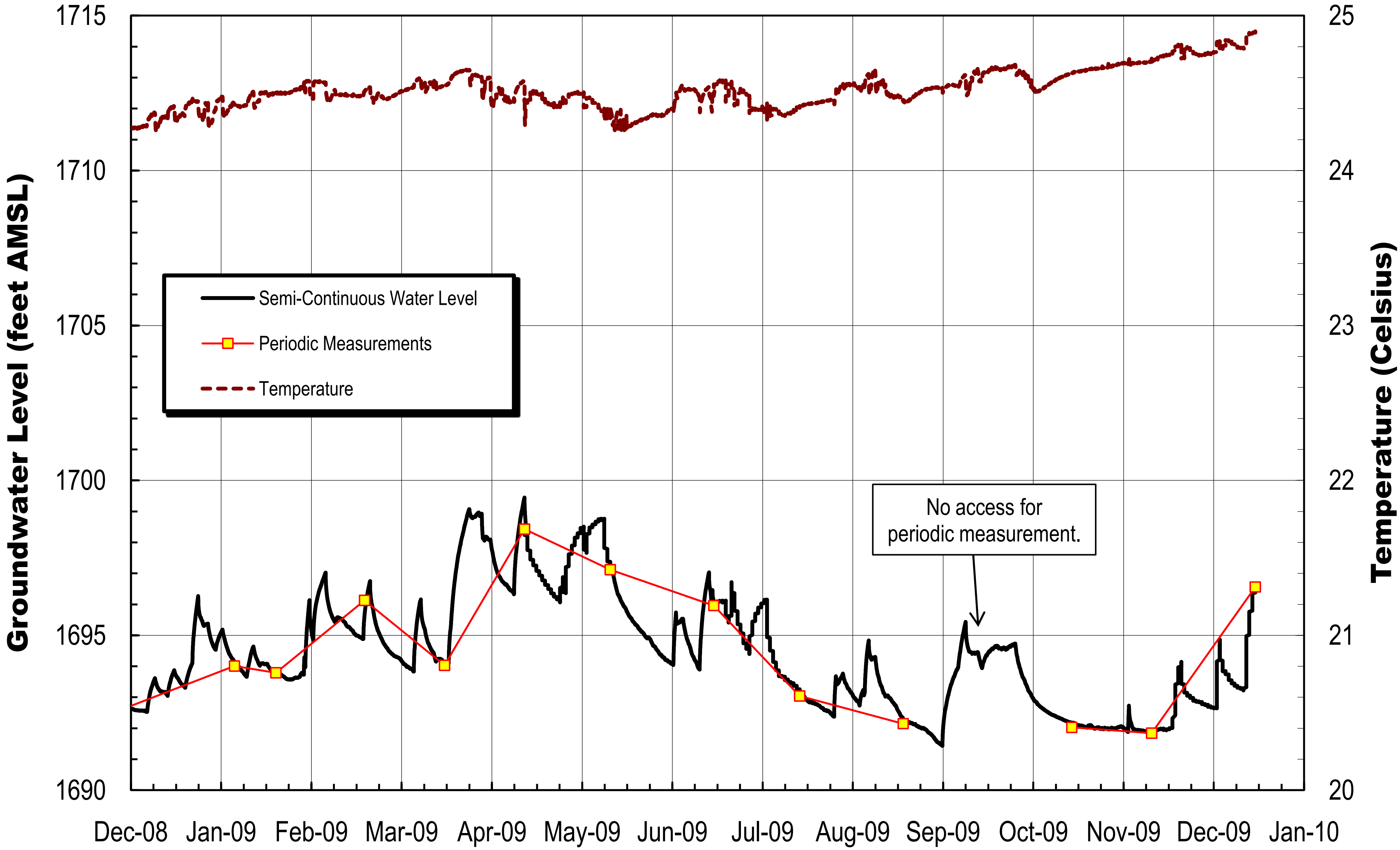
SE ROA 40005



B-4. 2009 Hydrograph for Lewis South Well

SE ROA 40006

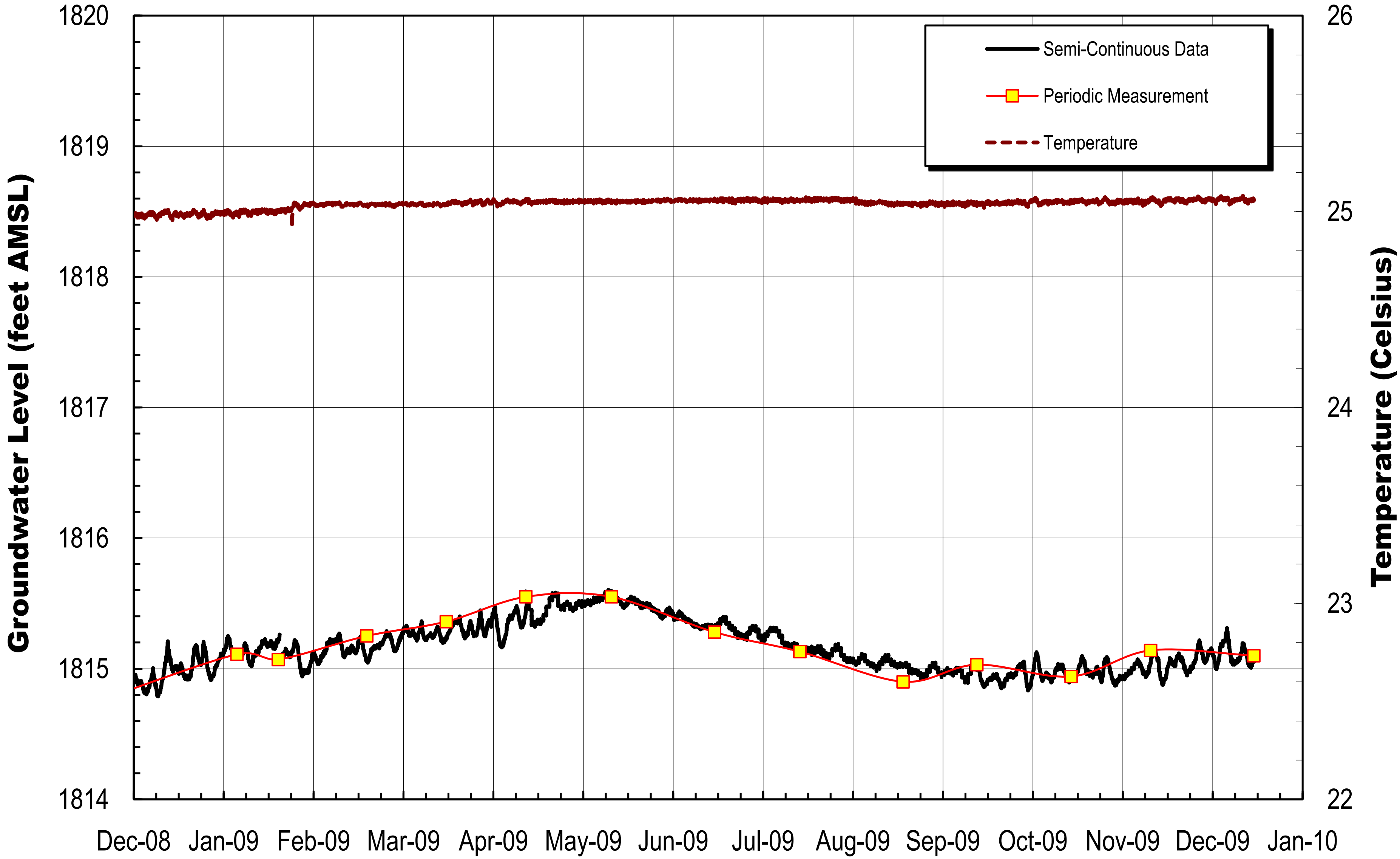
JA_11149



B-5. 2009 Hydrograph for the Perkins Old Well

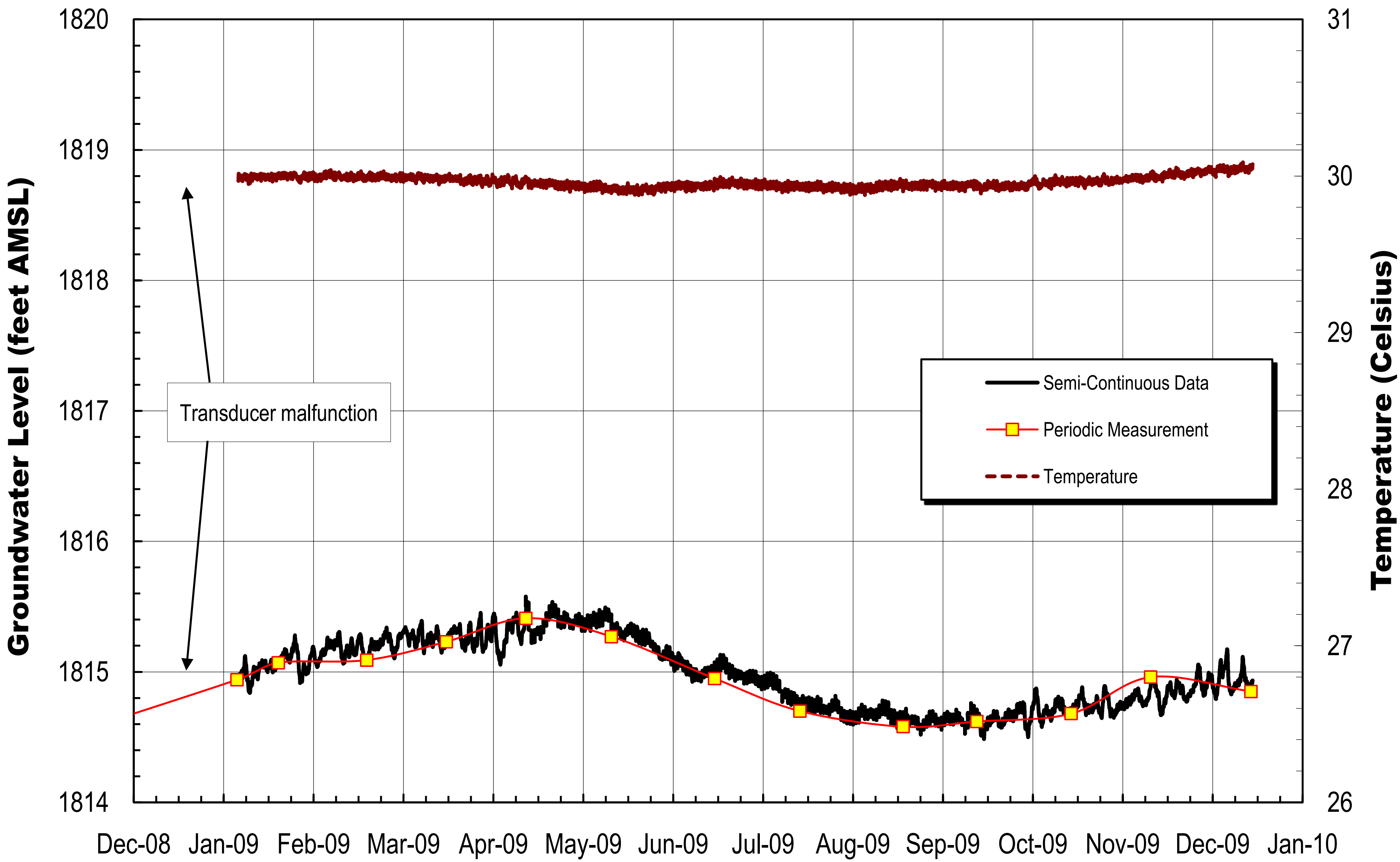
SE ROA 40007

JA_11150



B-6. 2009 Hydrograph for EH-4 Well

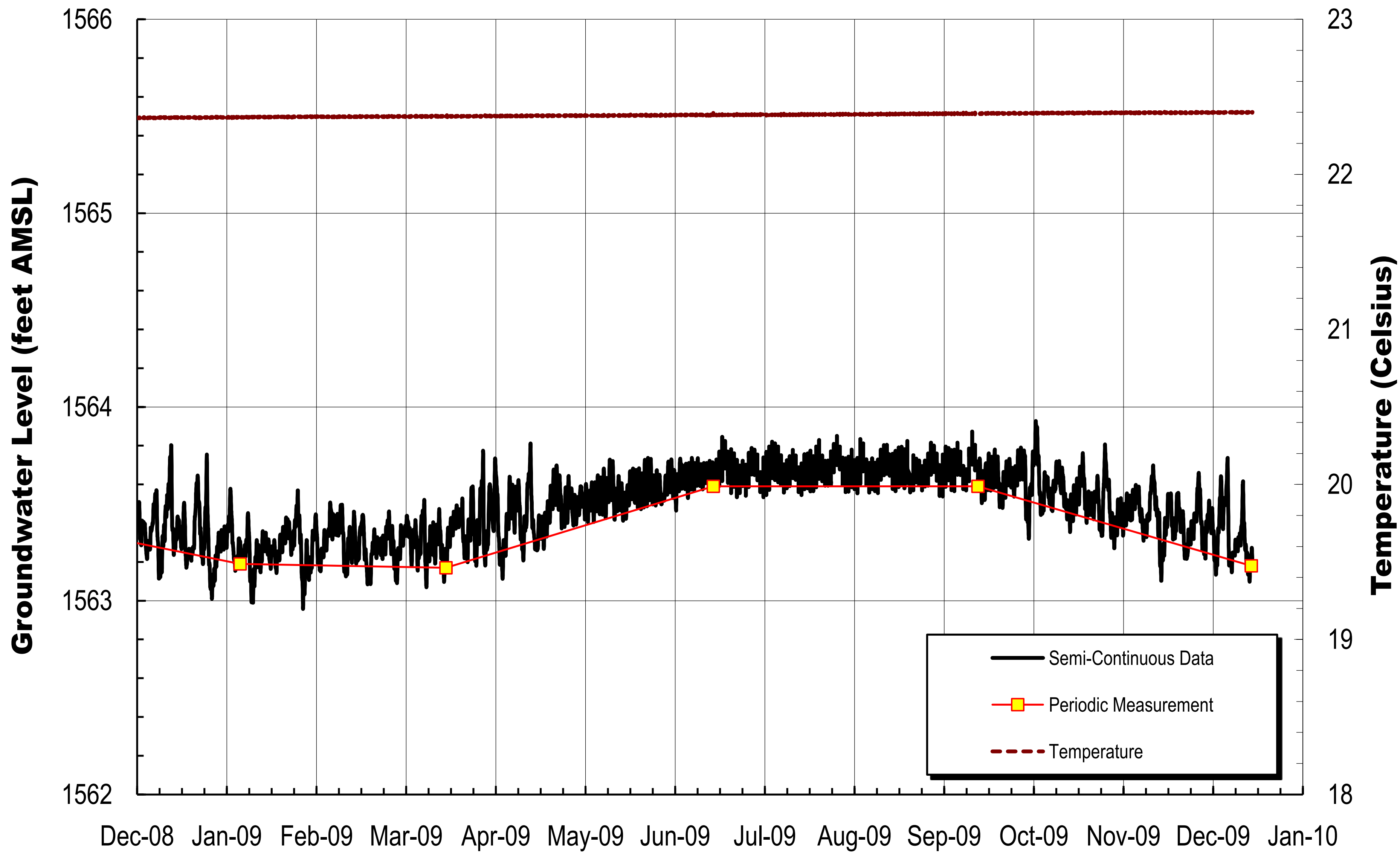
SE ROA 40008



B-7. 2009 Hydrograph for EH-5b Well

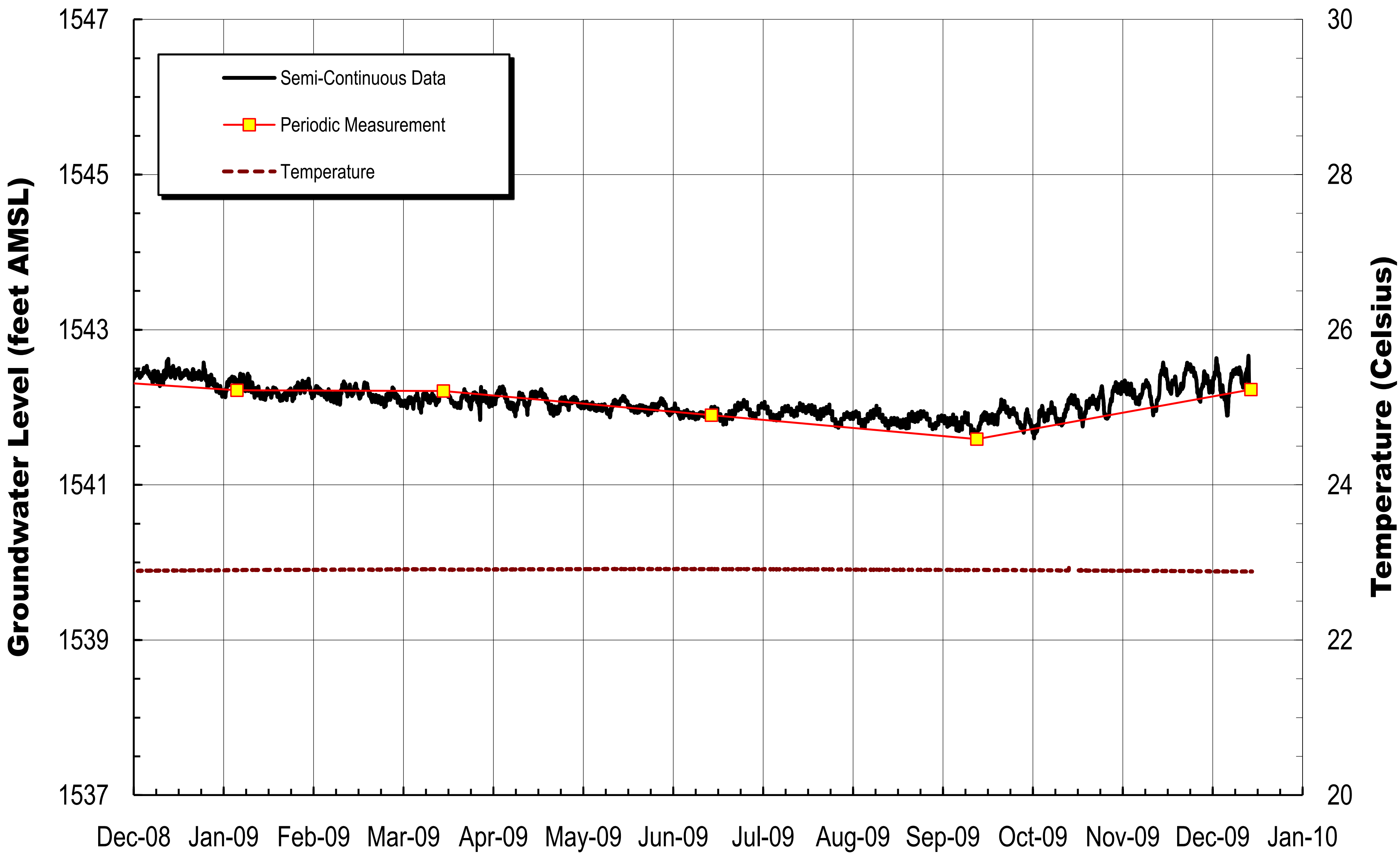
SE ROA 40009

JA_11152



B-8. 2009 Hydrograph for EH-7 Well

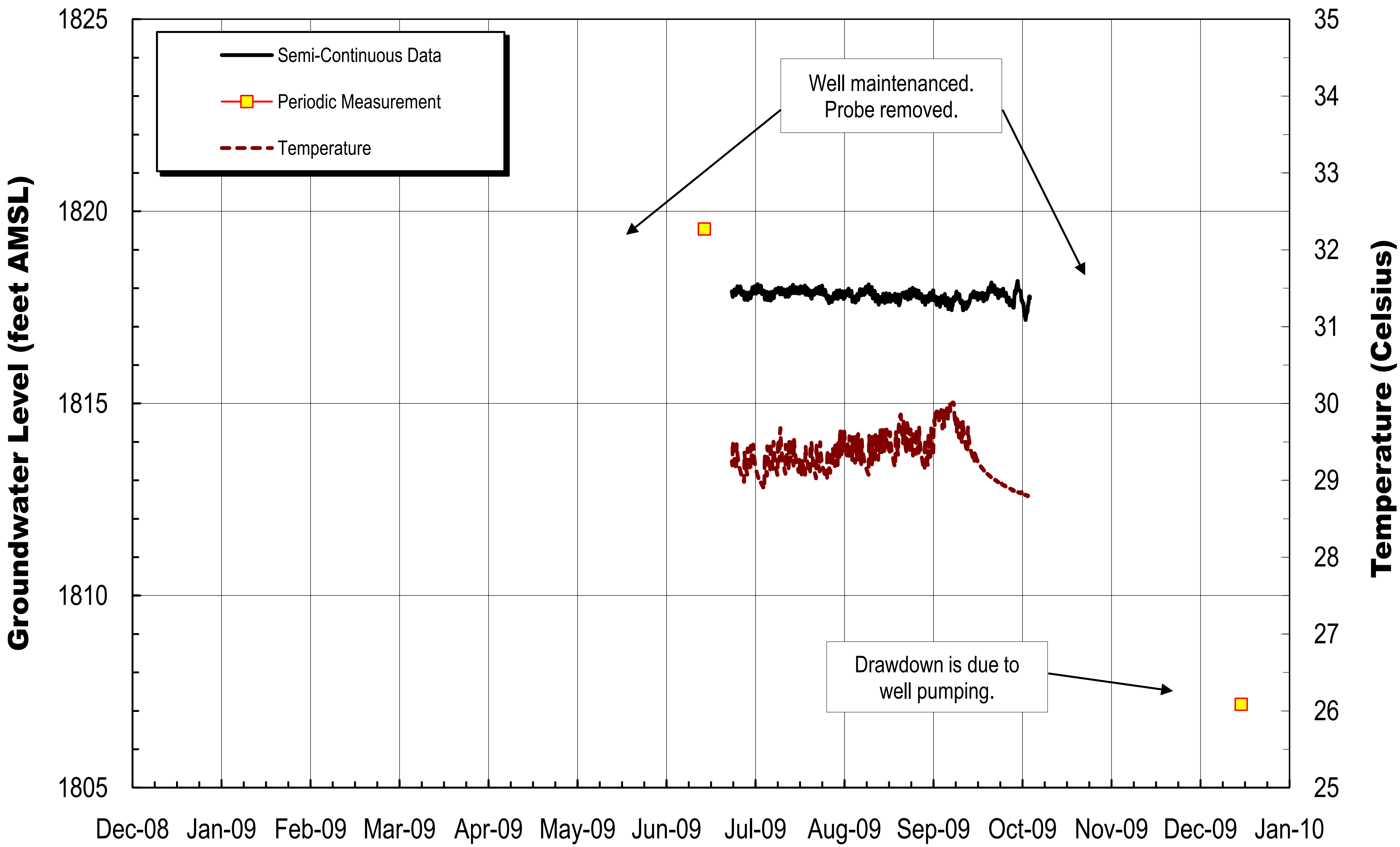
SE ROA 40010



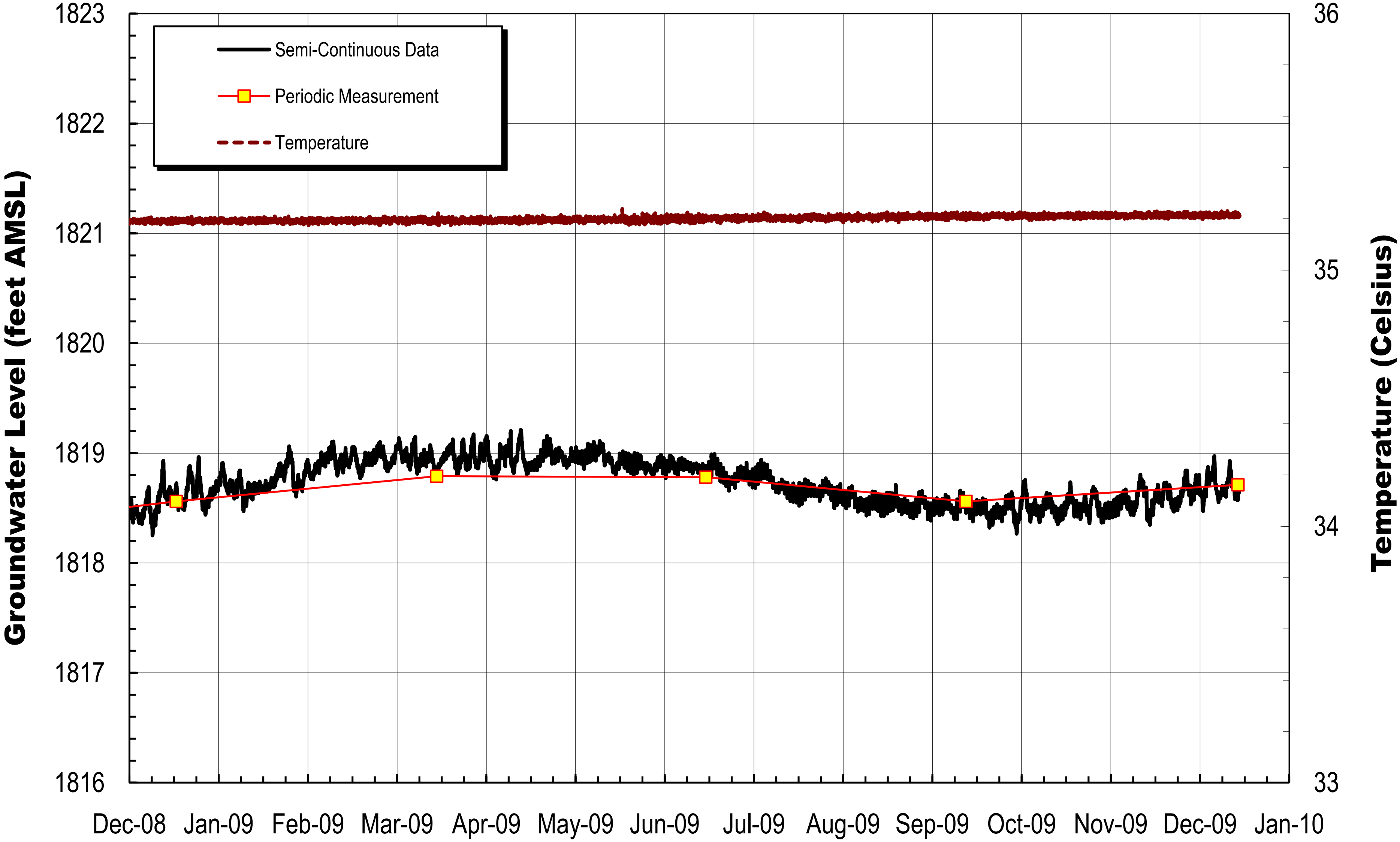
B-9. 2009 Hydrograph for EH-3 Well

SE ROA 40011

JA_11154



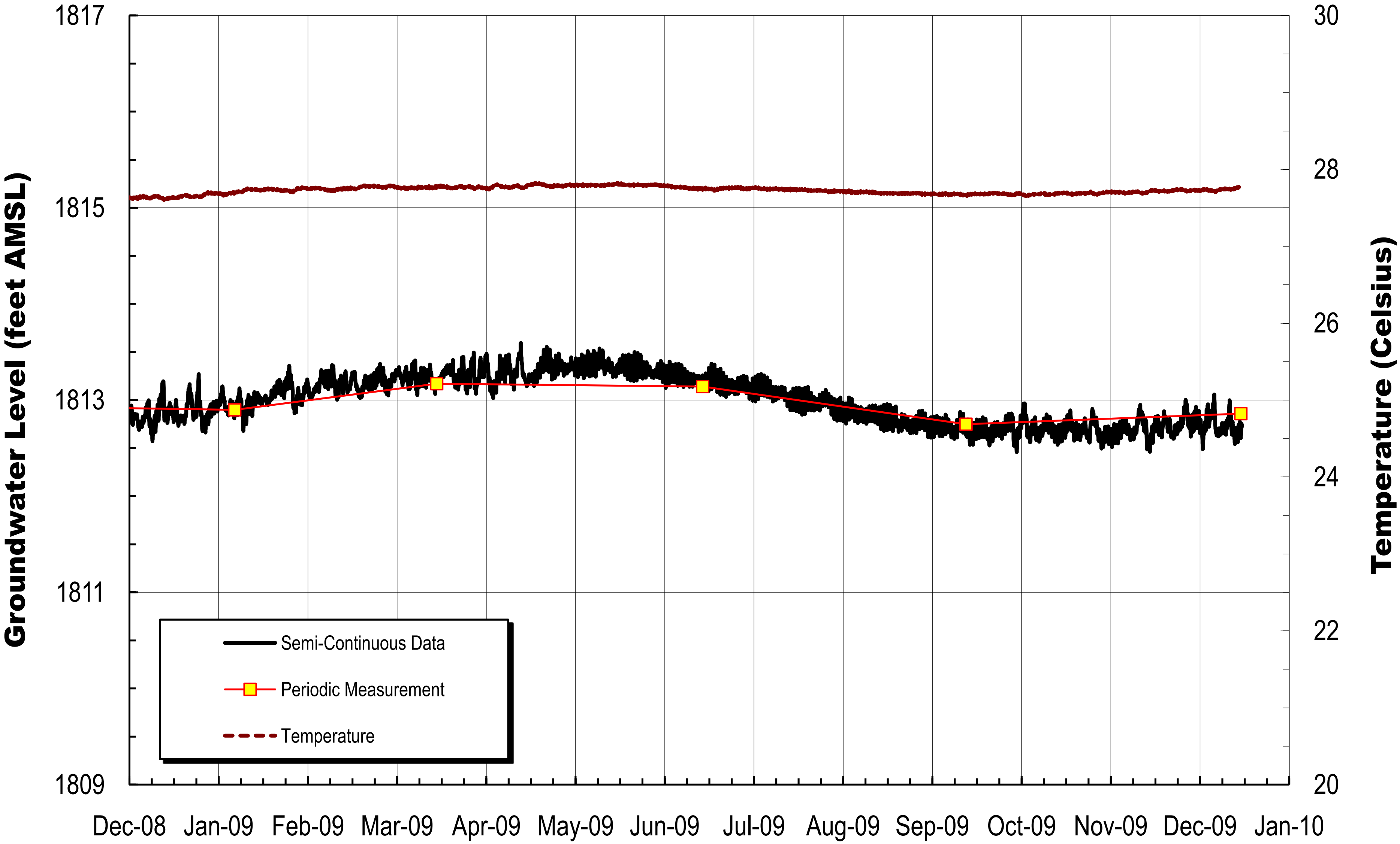
B-10. 2009 Hydrograph for RW-1 Well



B-11. 2009 Hydrograph for RW-2 Well (CSV)

SE ROA 40013

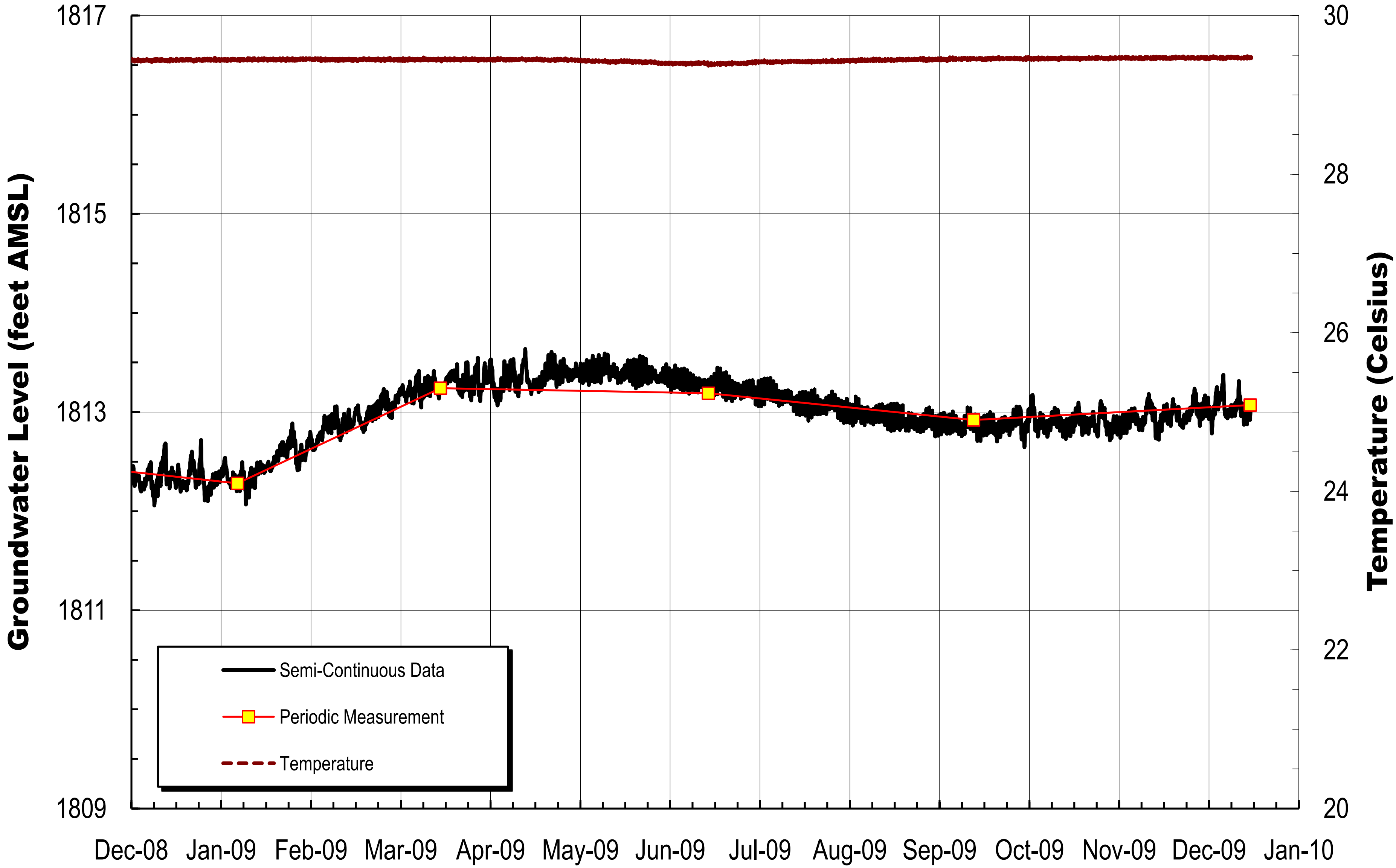
JA_11156



B-12. 2009 Hydrograph for Crystal 1 Well

SE ROA 40014

JA_11157



B-13. 2009 Hydrograph for Crystal 2 Well

SE ROA 40015

JA_11158

Appendix C

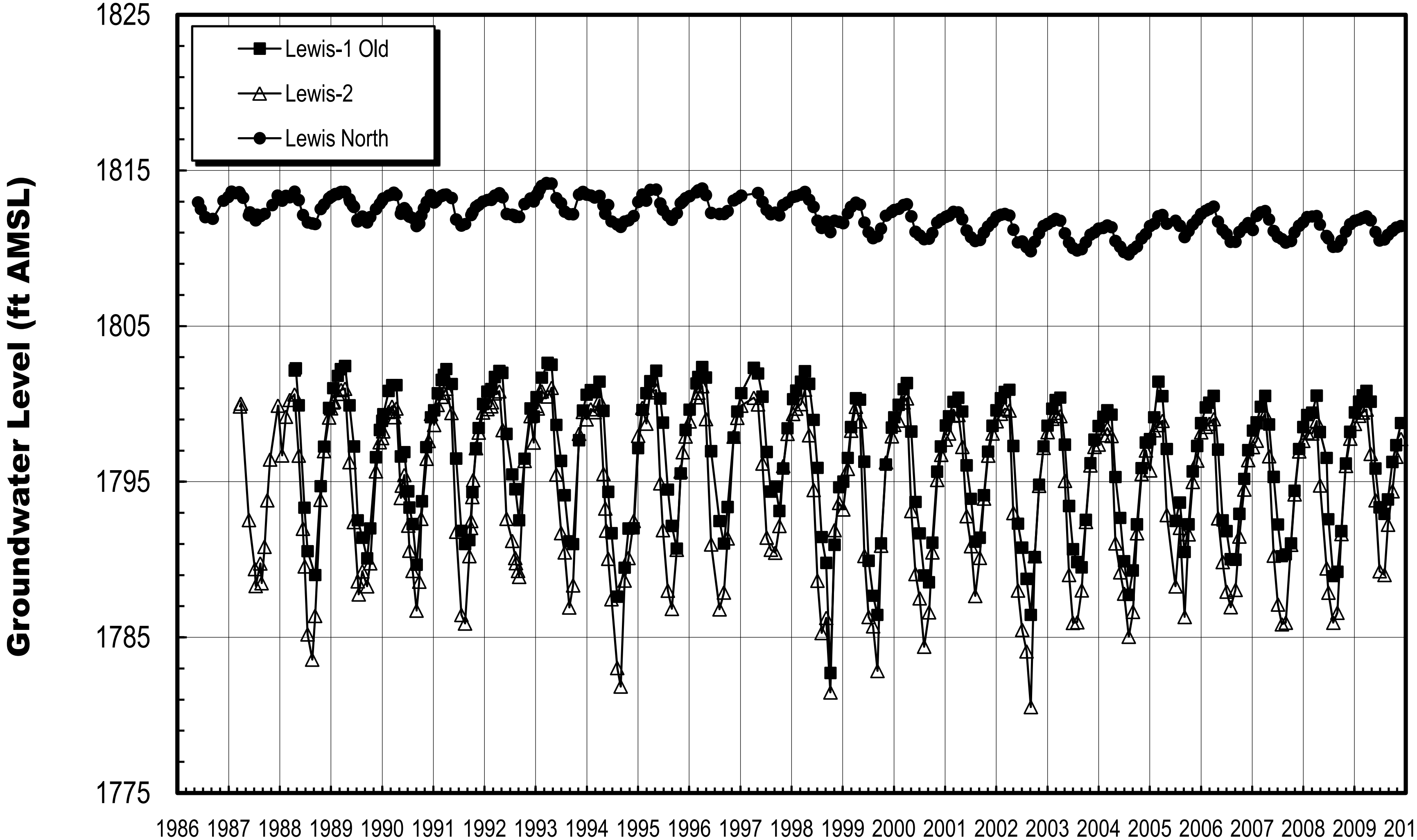


Figure C-1

SE ROA 40017

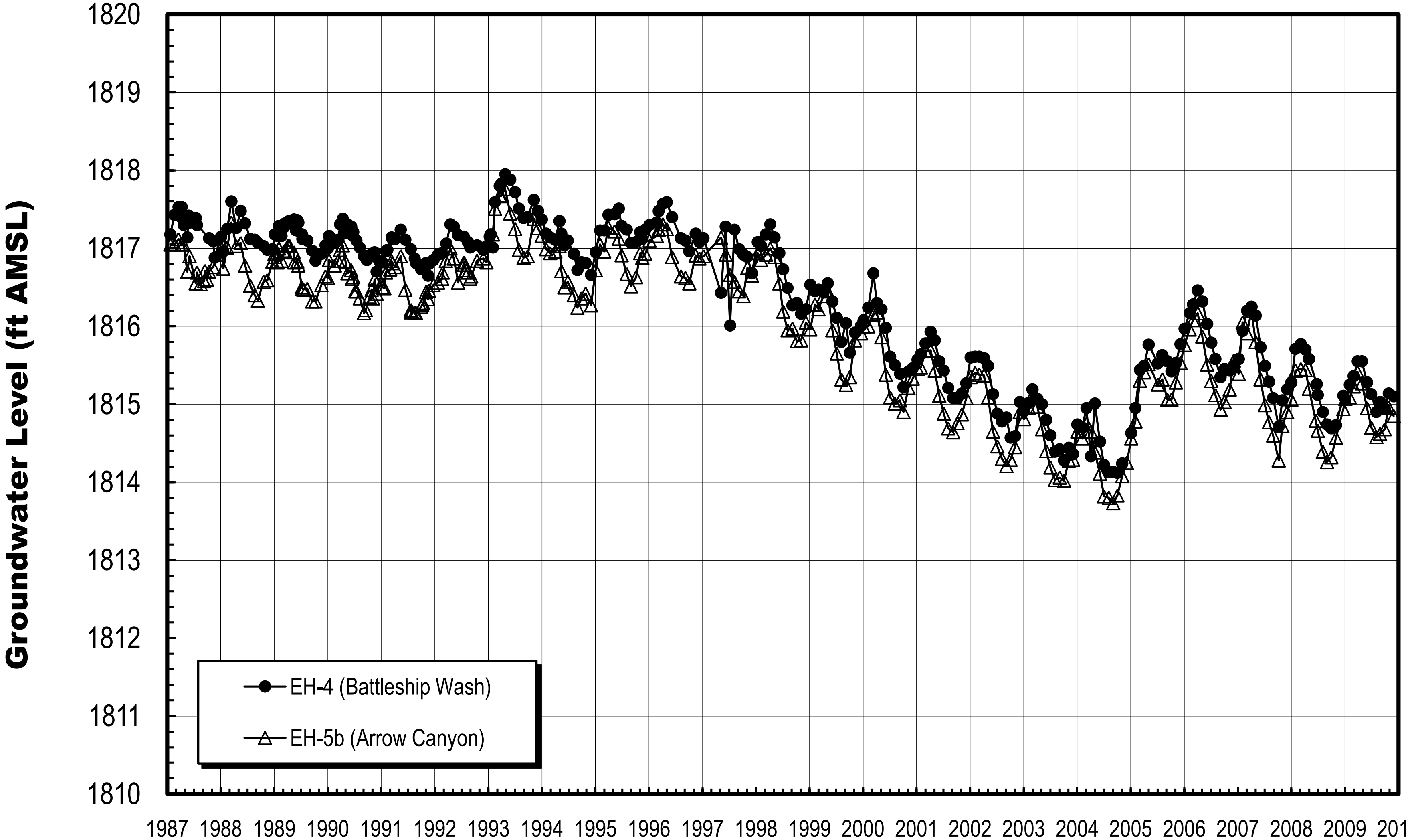


Figure C-2

SE ROA 40018

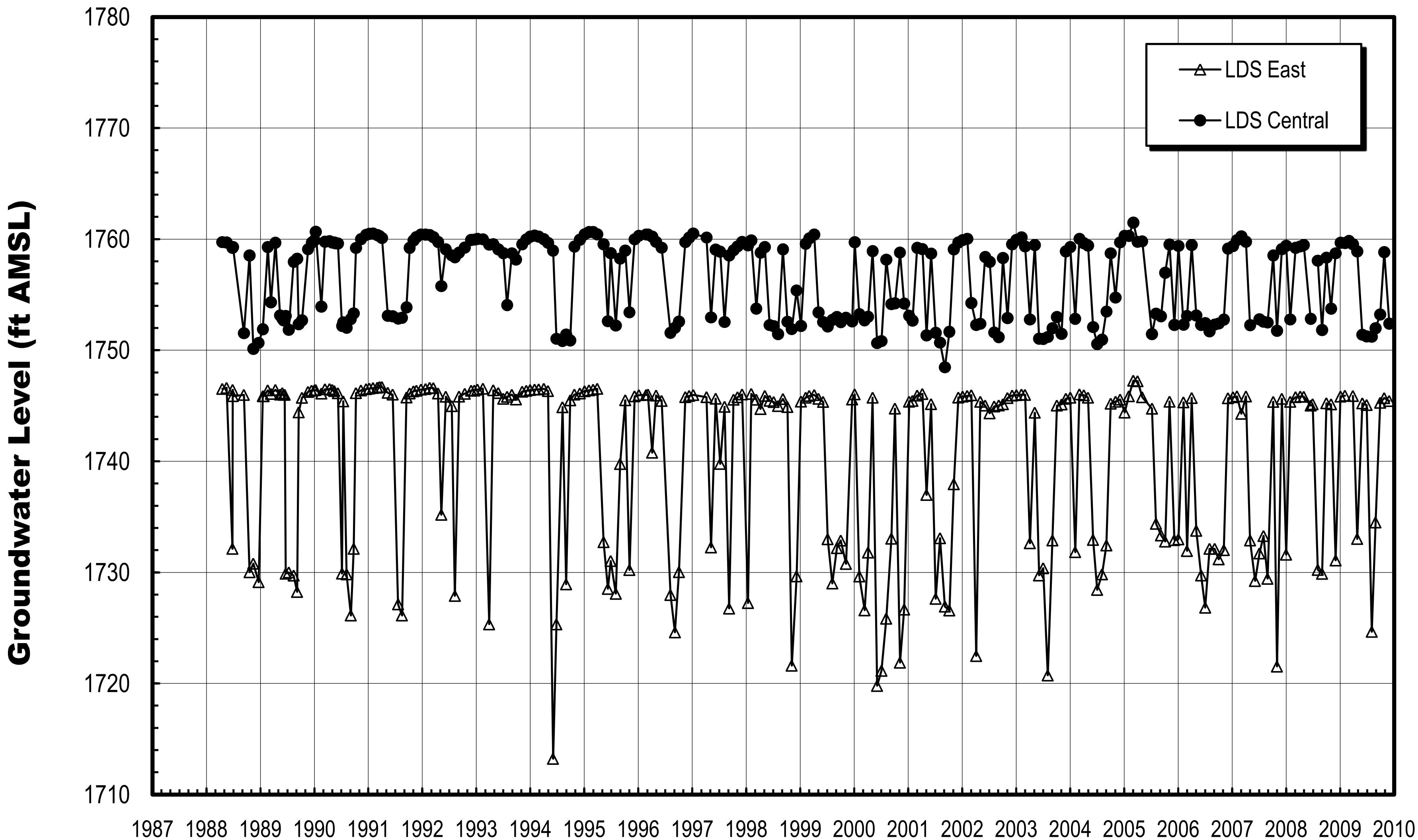
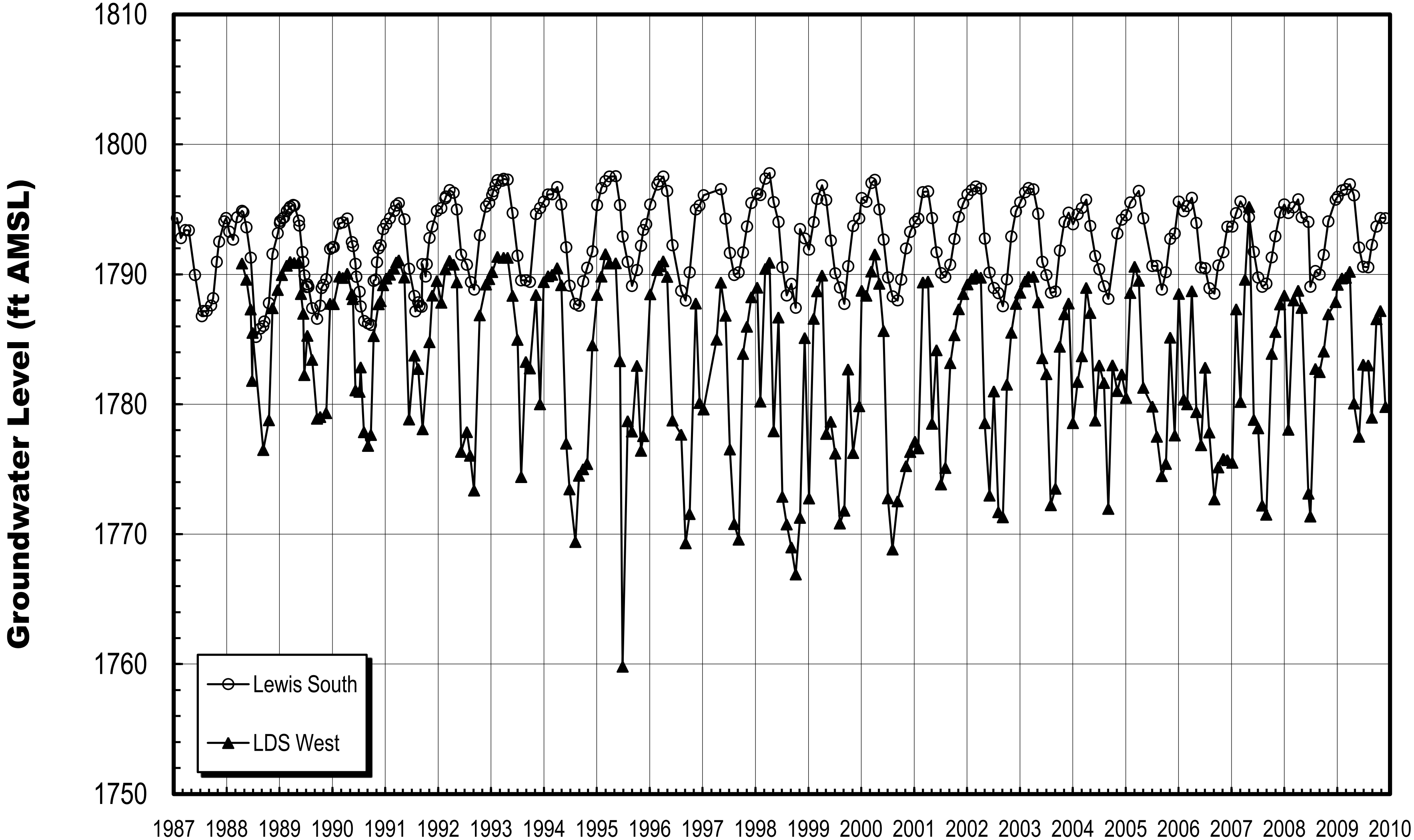


Figure C-3

SE ROA 40019

JA_11162



Groundwater Level (ft AMSL)
1810
1800
1790
1780
1770
1760
1750
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Lewis South
LDS West

Figure C-4

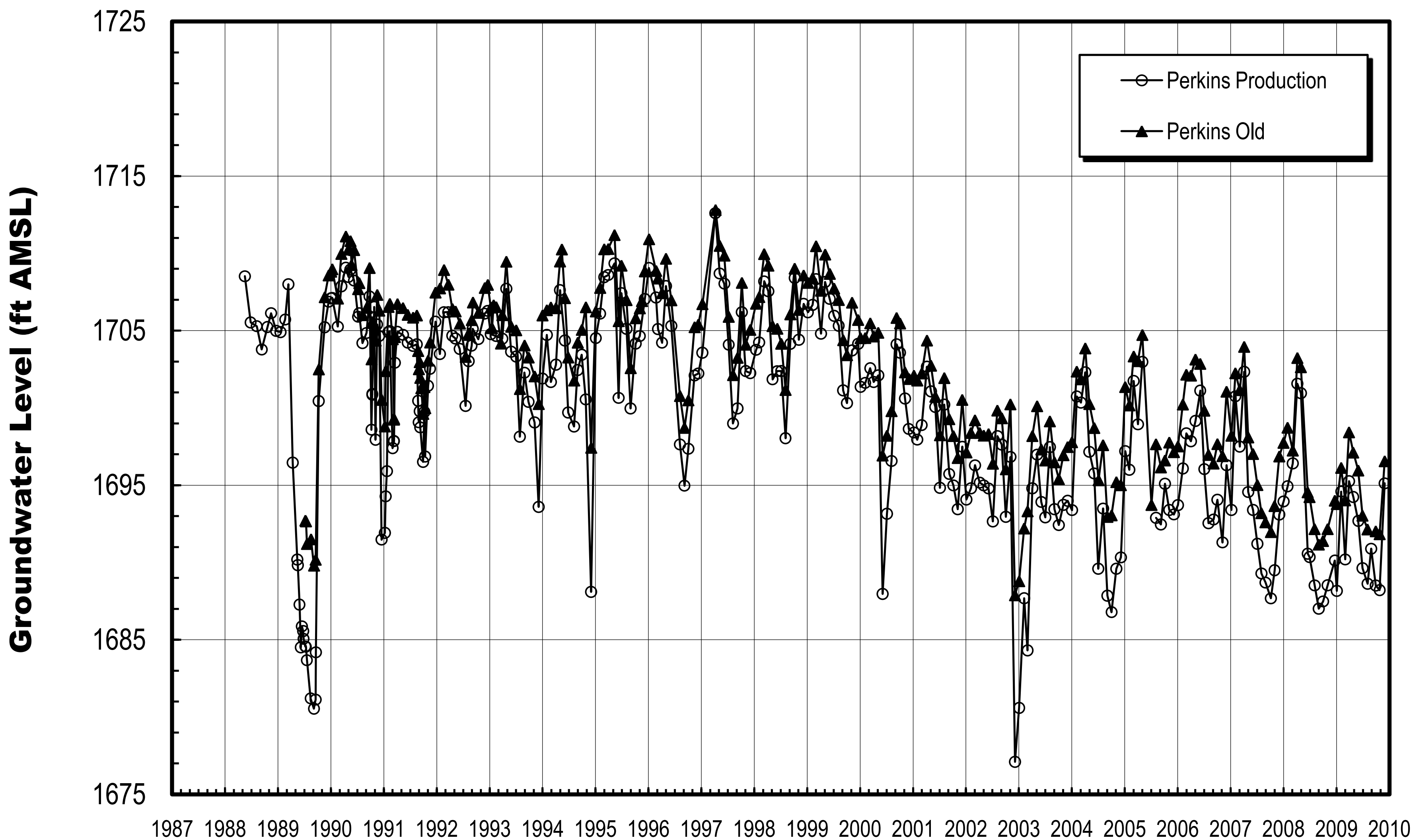


Figure C-5

SE ROA 40021

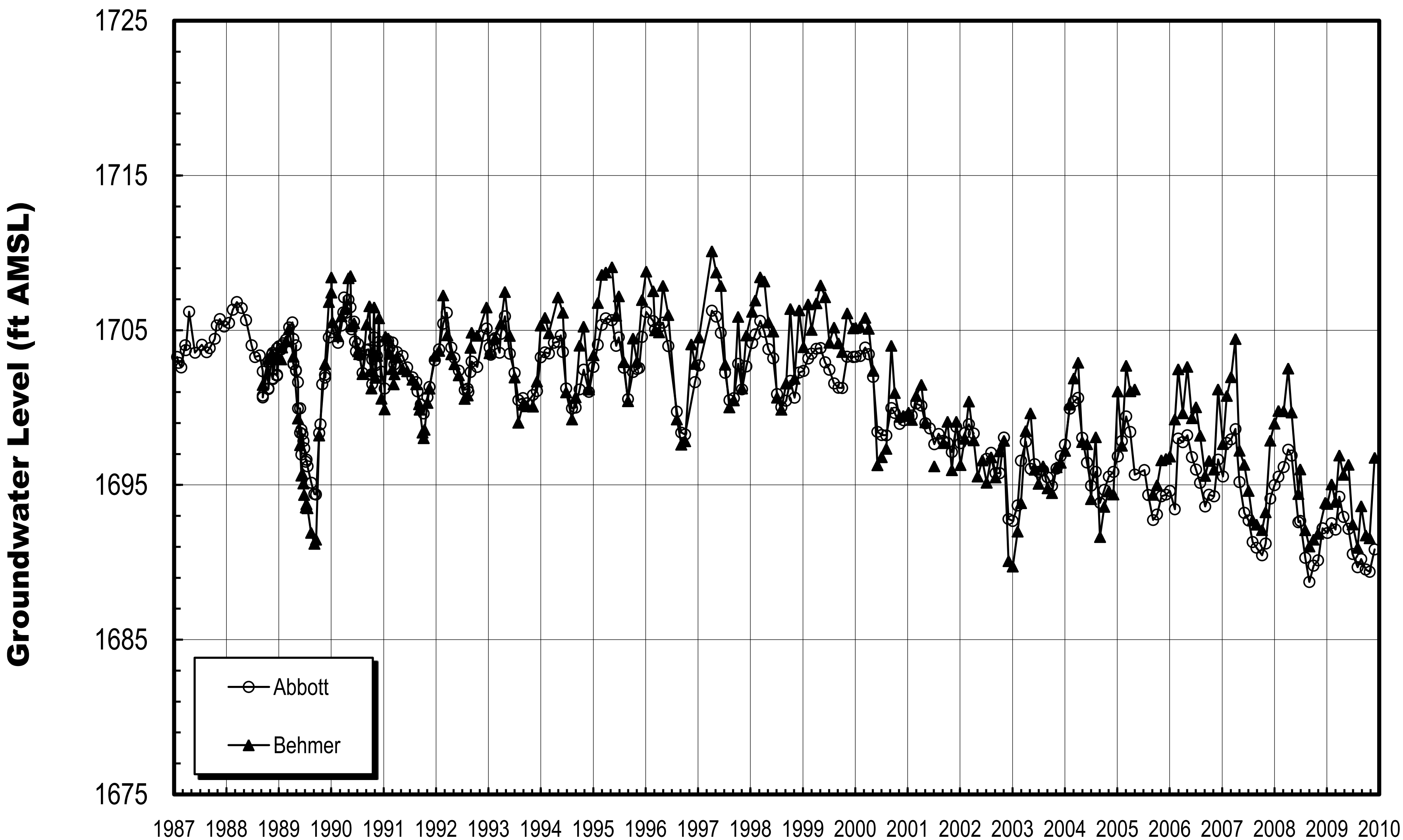


Figure C-6

SE ROA 40022

JA_11165

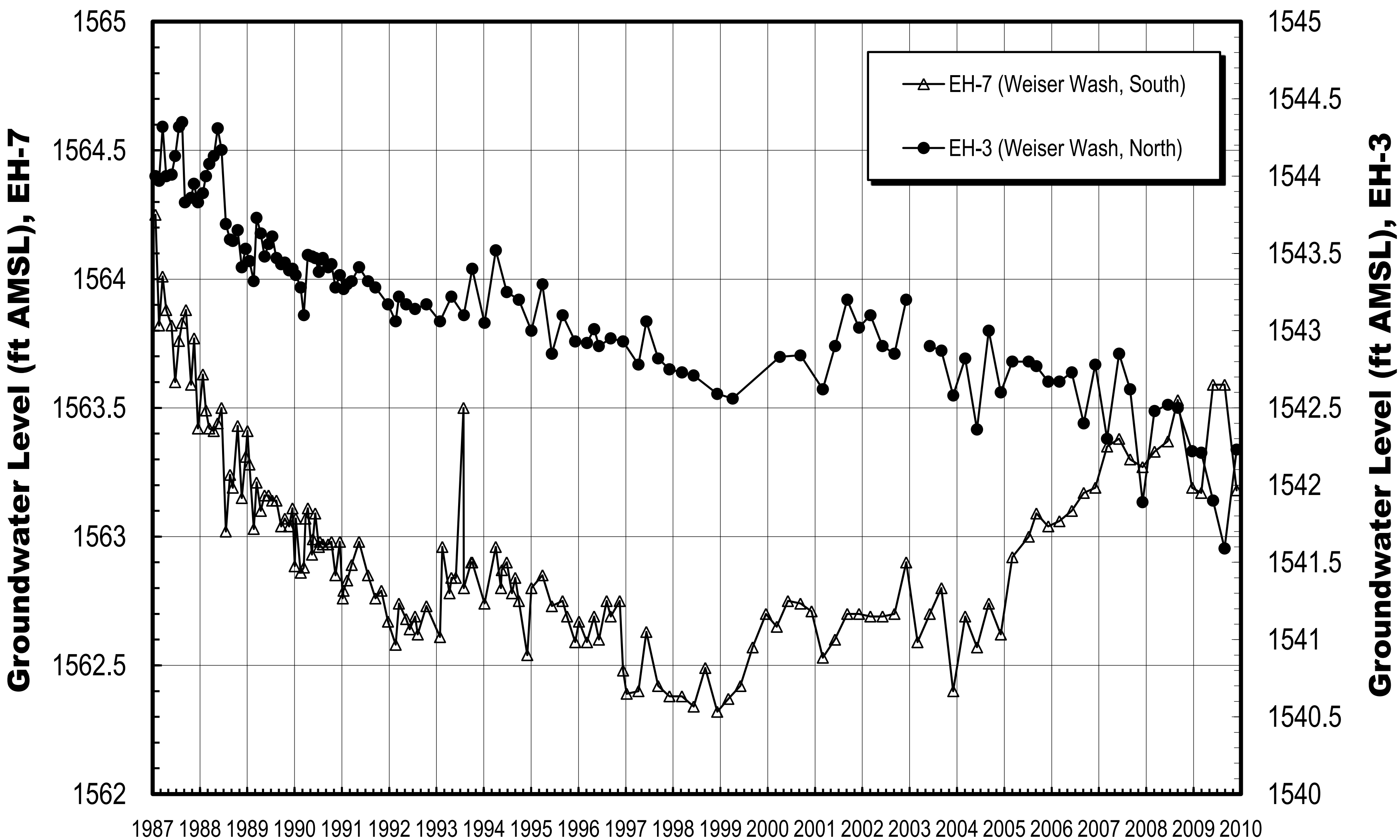


Figure C-7

SE ROA 40023

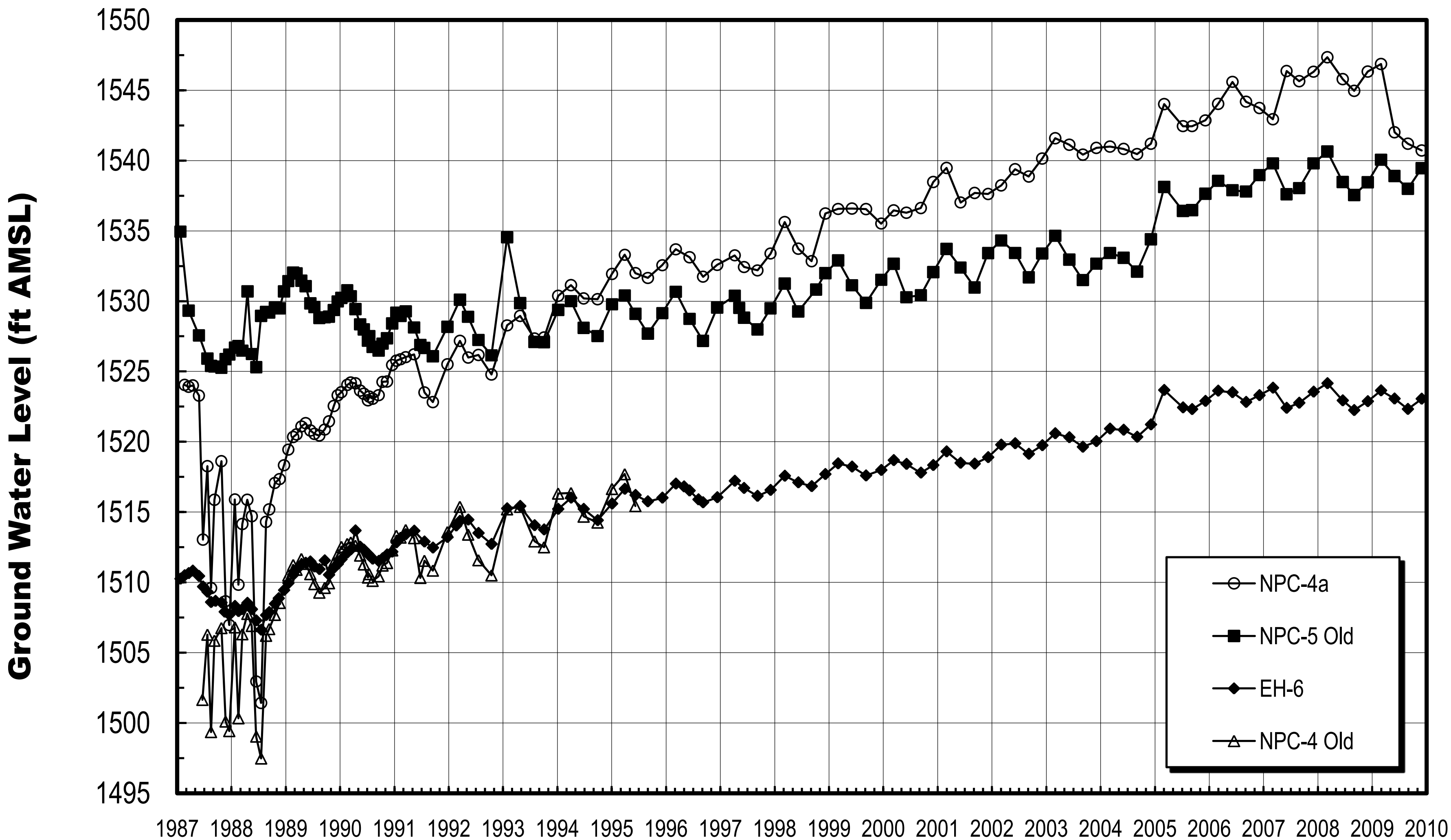


Figure C-8

SE ROA 40024

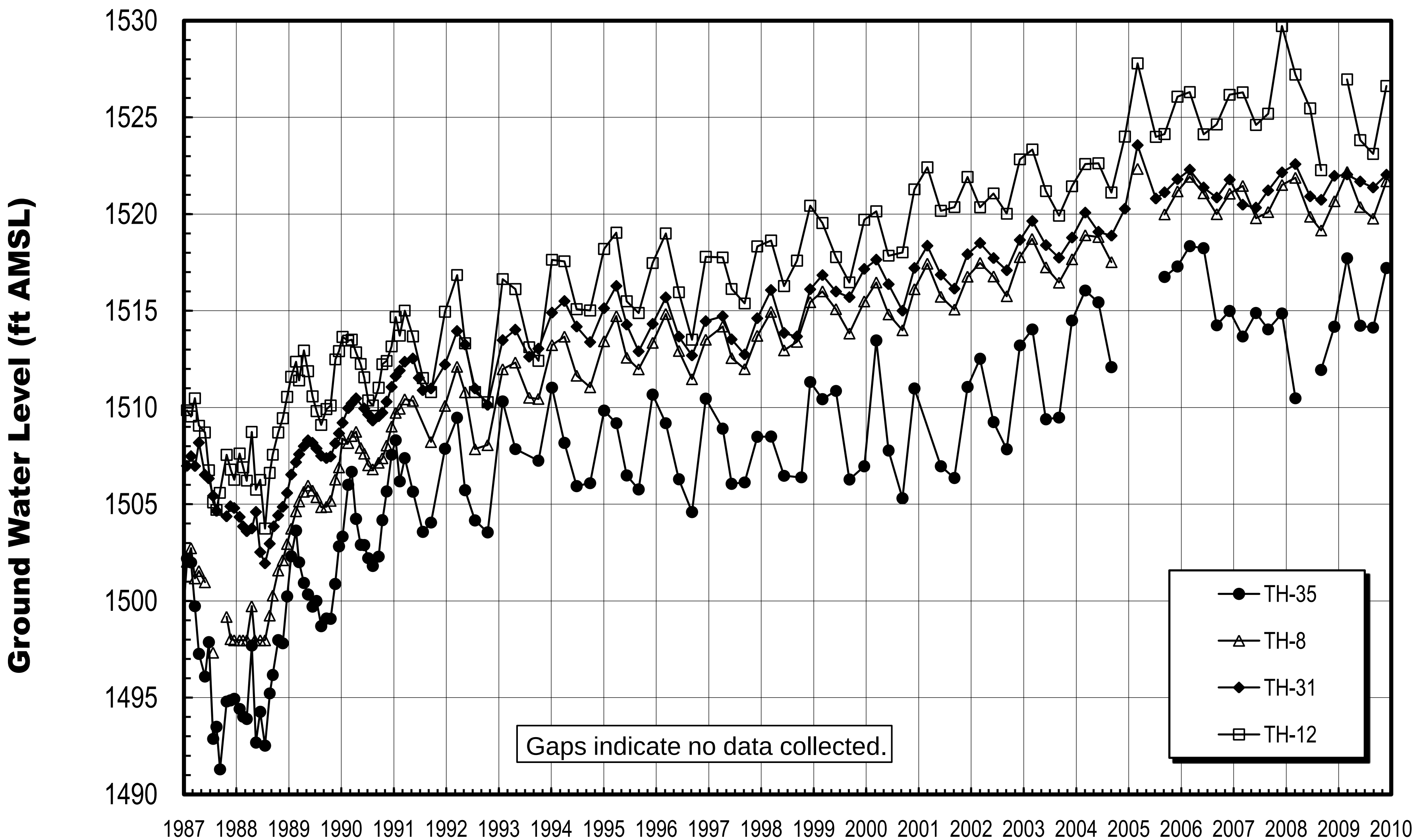
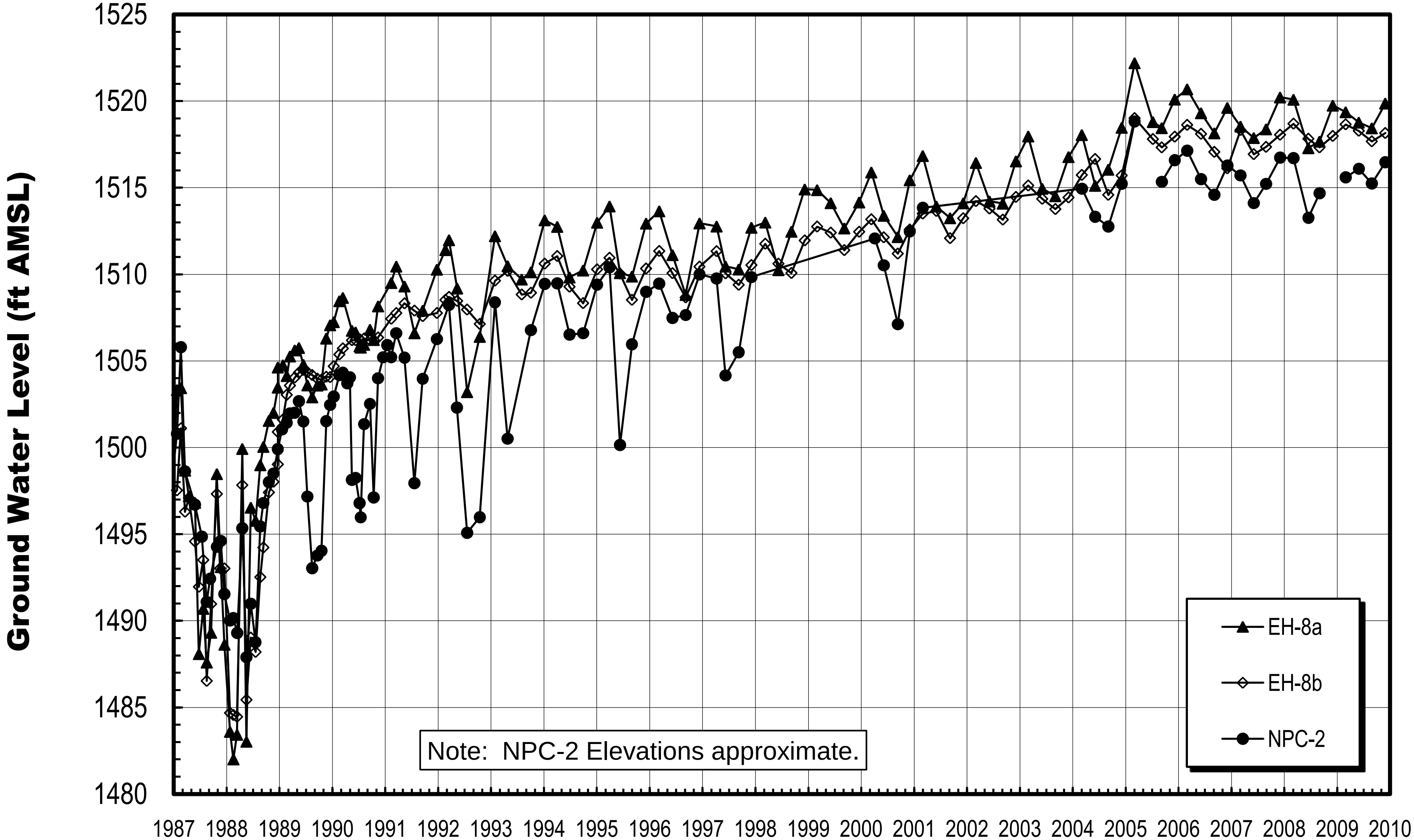


Figure C-9

SE ROA 40025

JA_11168



Ground Water Level (ft AMSL)
1525
1520
1515
1510
1505
1500
1495
1490
1485
1480
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Note: NPC-2 Elevations approximate.
EH-8a
EH-8b
NPC-2

Figure C-10

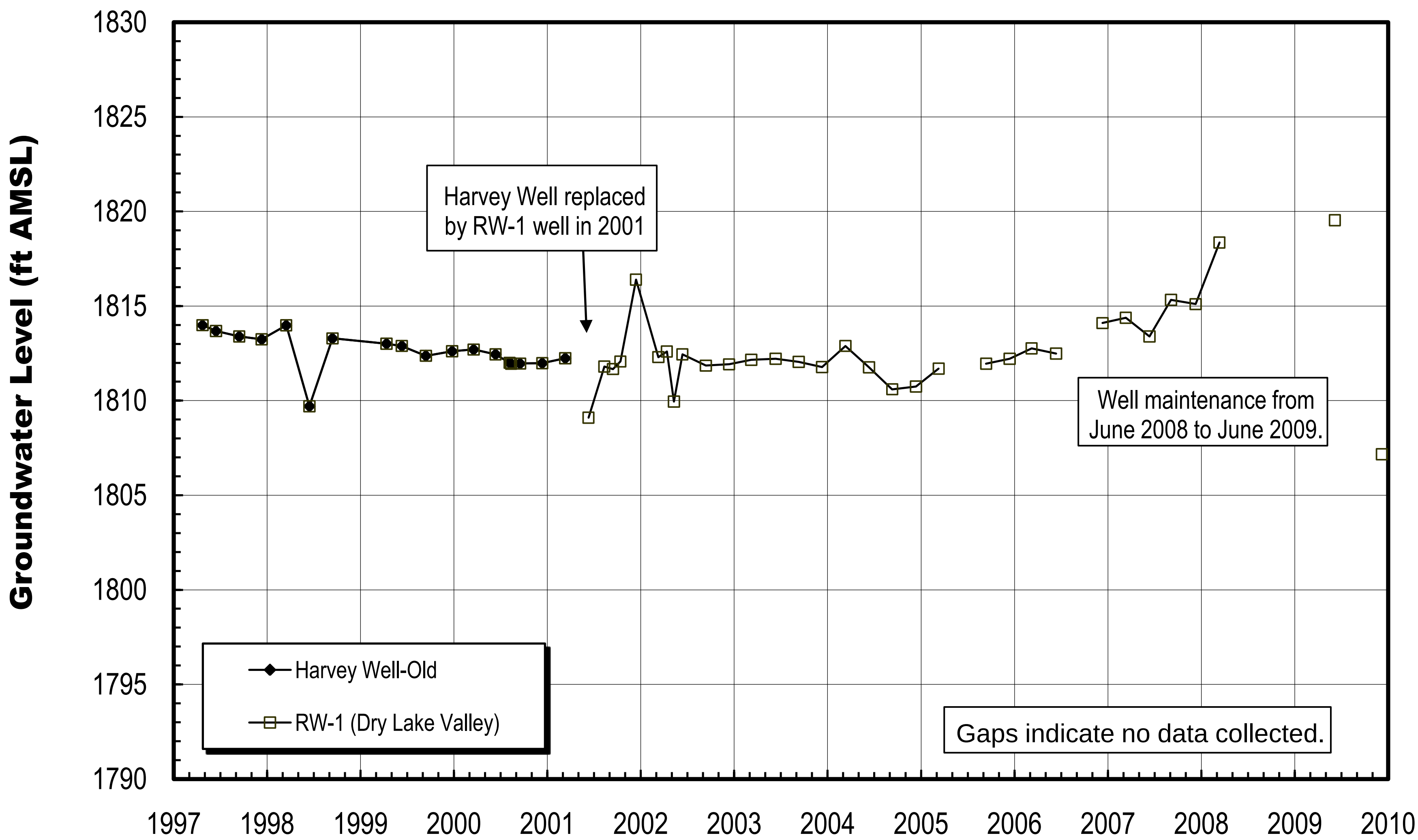


Figure C-11

SE ROA 40027

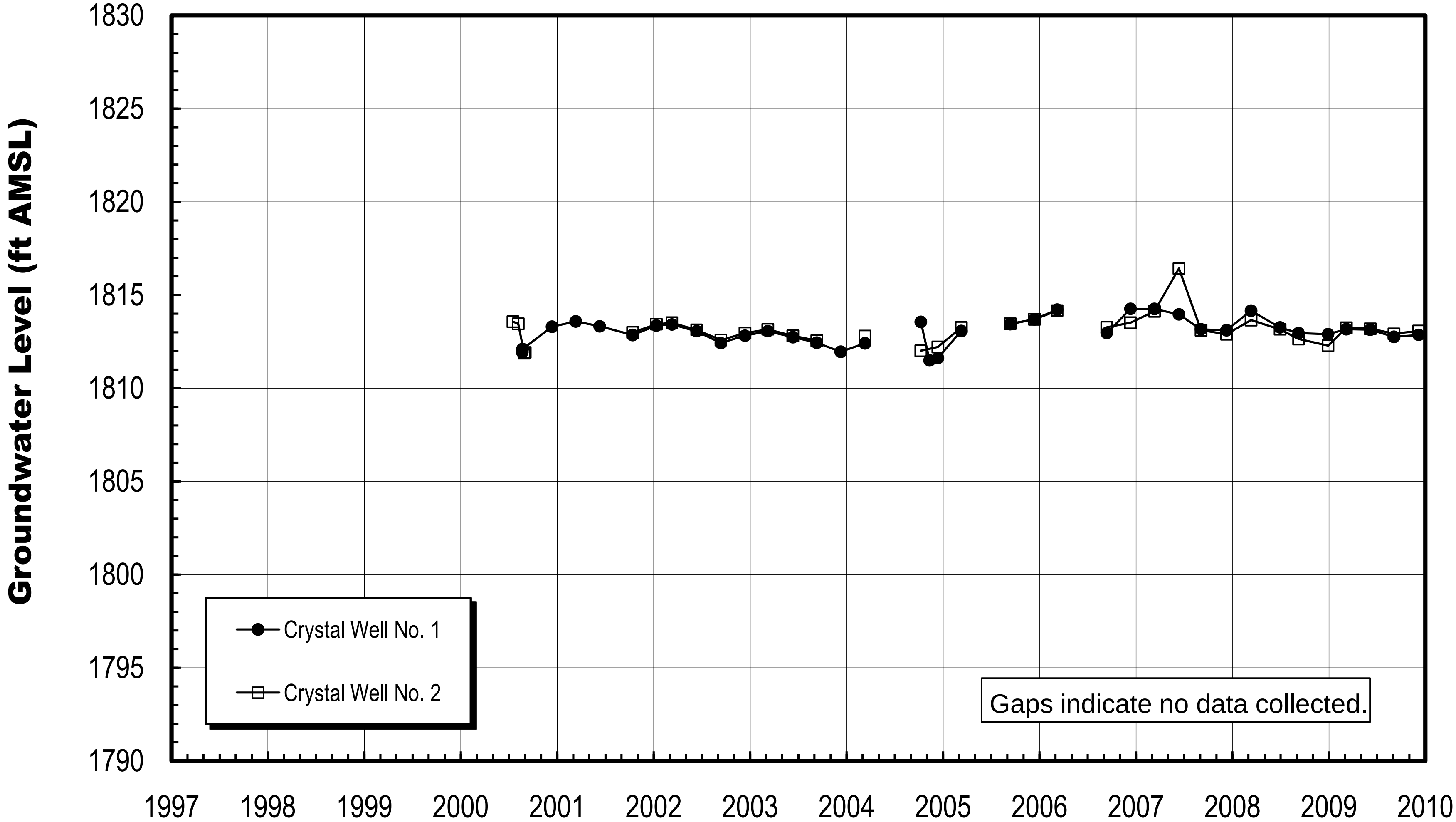
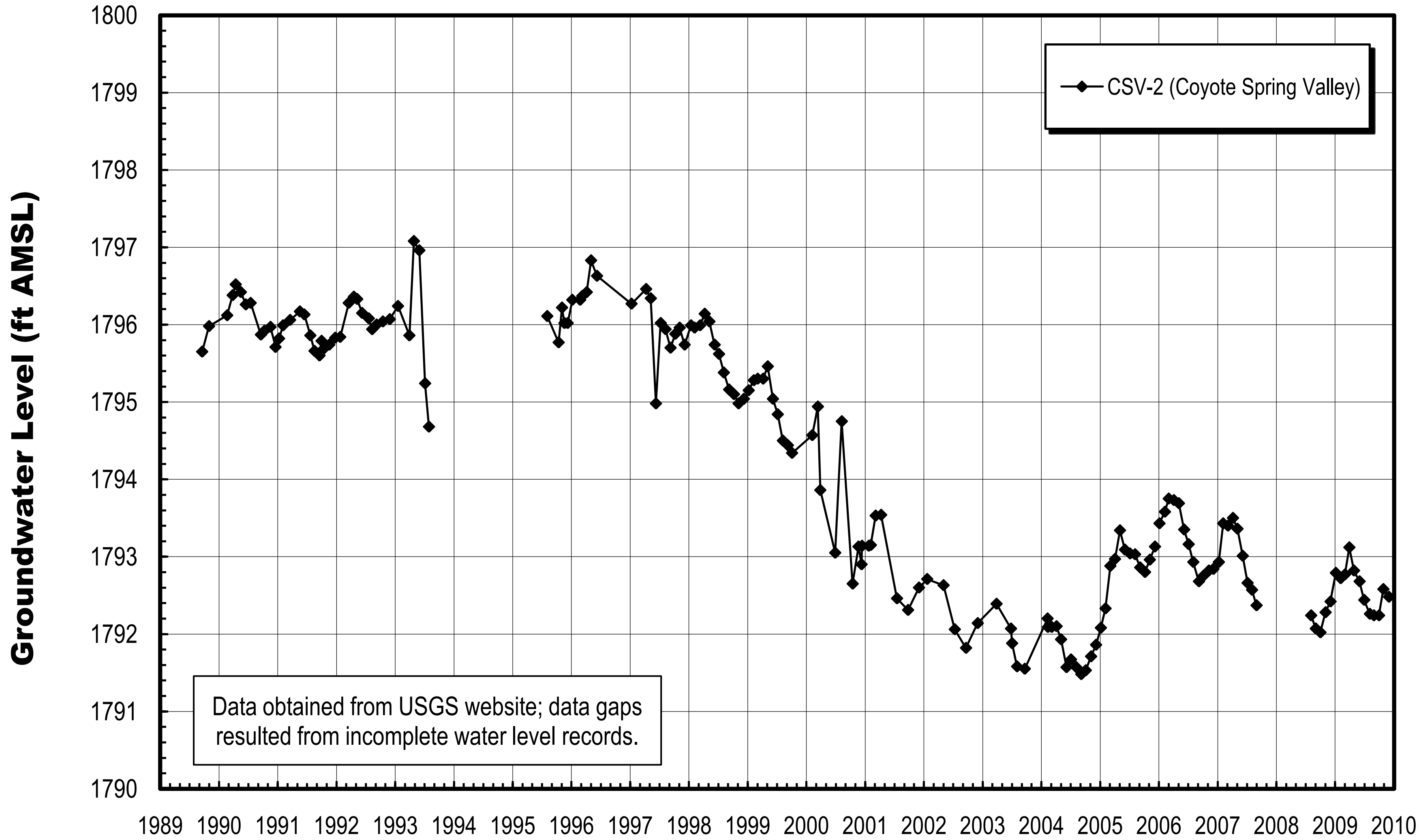


Figure C-12

SE ROA 40028


CSV-2 (Coyote Spring Valley)
Data obtained from USGS website; data gaps resulted from incomplete water level records.
Groundwater Level (ft AMSL)
1800
1799
1798
1797
1796
1795
1794
1793
1792
1791
1790
1989
1990
1991
1992
1993
1994
1995
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1998
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2001
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2007
2008
2009
2010

Figure C-13

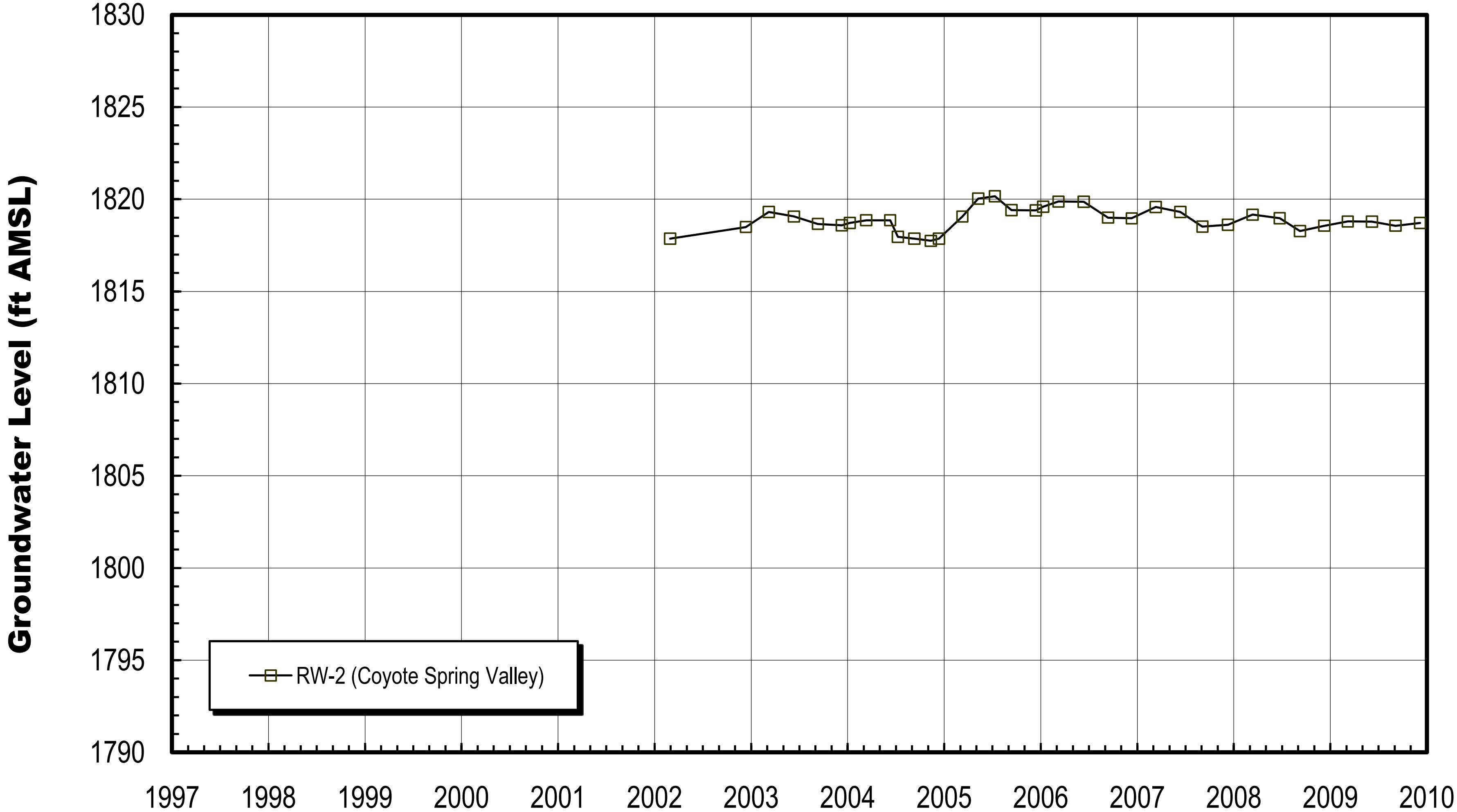

Figure C-14

SE ROA 40030

Appendix D

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
Abbott	1712.34	20-Jan-09	1100	20.45	1691.89
Abbott	1712.34	19-Feb-09	1251	19.81	1692.53
Abbott	1712.34	18-Mar-09	851	20.23	1692.11
Abbott	1712.34	14-Apr-09	1058	18.11	1694.23
Abbott	1712.34	13-May-09	953	19.41	1692.93
Abbott	1712.34	17-Jun-09	1015	20.18	1692.16
Abbott	1712.34	16-Jul-09	820	21.80	1690.54
Abbott	1712.34	20-Aug-09	1136	22.66	1689.68
Abbott	1712.34	14-Sep-09	1227	22.13	1690.21
Abbott	1712.34	16-Oct-09	1145	22.81	1689.53
Abbott	1712.34	12-Nov-09	1242	22.95	1689.39
Abbott	1712.34	16-Dec-09	1235	21.51	1690.83
Behmer	1717.89	20-Jan-09	1315	24.11	1693.78
Behmer	1717.89	19-Feb-09	1531	22.85	1695.04
Behmer	1717.89	18-Mar-09	1315	23.98	1693.91
Behmer	1717.89	14-Apr-09	1458	20.98	1696.91
Behmer	1717.89	13-May-09	1427	22.23	1695.66
Behmer	1717.89	17-Jun-09	1505	21.58	1696.31
Behmer	1717.89	16-Jul-09	1221	25.44	1692.45
Behmer	1717.89	20-Aug-09	1423	26.95	1690.94
Behmer	1717.89	14-Sep-09	1601	24.26	1693.63
Behmer	1717.89	16-Oct-09	1404	26.15	1691.74
Behmer	1717.89	12-Nov-09	1523	26.33	1691.56
Behmer	1717.89	17-Dec-09	1342	21.13	1696.76
CSV-2 (USGS)	2185.90	20-Jan-09	1200	393.11	1792.79
CSV-2 (USGS)	2185.90	19-Feb-09	1200	393.3	1792.6
CSV-2 (USGS)	2185.90	18-Mar-09	1200	393.13	1792.77
CSV-2 (USGS)	2185.90	14-Apr-09	1200	392.78	1793.12
CSV-2 (USGS)	2185.90	13-May-09	1200	393.08	1792.82
CSV-2 (USGS)	2185.90	17-Jun-09	1200	393.22	1792.68
CSV-2 (USGS)	2185.90	16-Jul-09	1200	393.46	1792.44
CSV-2 (USGS)	2185.90	20-Aug-09	1200	393.64	1792.26
CSV-2 (USGS)	2185.90	14-Sep-09	1200	393.66	1792.24
CSV-2 (USGS)	2185.90	16-Oct-09	1200	393.66	1792.24
CSV-2 (USGS)	2185.90	12-Nov-09	1200	393.32	1792.58
CSV-2 (USGS)	2185.90	17-Dec-09	1200	393.42	1792.48
EH-4	1933.93	20-Jan-09	1250	118.86	1815.07

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
EH-4	1933.93	19-Feb-09	1501	118.68	1815.25
EH-4	1933.93	18-Mar-09	1210	118.57	1815.36
EH-4	1933.93	14-Apr-09	1354	118.38	1815.55
EH-4	1933.93	13-May-09	1300	118.38	1815.55
EH-4	1933.93	17-Jun-09	1415	118.65	1815.28
EH-4	1933.93	16-Jul-09	1109	118.8	1815.13
EH-4	1933.93	20-Aug-09	1335	119.03	1814.9
EH-4	1933.93	14-Sep-09	1520	118.9	1815.03
EH-4	1933.93	16-Oct-09	1337	118.99	1814.94
EH-4	1933.93	12-Nov-09	1434	118.79	1815.14
EH-4	1933.93	17-Dec-09	1249	118.83	1815.1
EH-5b	1844.80	20-Jan-09	1158	29.73	1815.07
EH-5b	1844.80	19-Feb-09	1407	29.71	1815.09
EH-5b	1844.80	18-Mar-09	1009	29.57	1815.23
EH-5b	1844.80	14-Apr-09	1226	29.39	1815.41
EH-5b	1844.80	13-May-09	1107	29.53	1815.27
EH-5b	1844.80	17-Jun-09	1230	29.85	1814.95
EH-5b	1844.80	16-Jul-09	1011	30.1	1814.7
EH-5b	1844.80	20-Aug-09	1255	30.22	1814.58
EH-5b	1844.80	14-Sep-09	1357	30.18	1814.62
EH-5b	1844.80	16-Oct-09	1233	30.12	1814.68
EH-5b	1844.80	12-Nov-09	1349	29.84	1814.96
EH-5b	1844.80	16-Dec-09	1355	29.95	1814.85
EH-6	1553.99	17-Mar-09	1142	30.35	1523.64
EH-6	1553.99	16-Jun-09	1200	30.93	1523.06
EH-6	1553.99	14-Sep-09	1055	31.67	1522.32
EH-6	1553.99	16-Dec-09	1115	30.94	1523.05
EH-7	1680	17-Mar-09	950	116.83	1563.17
EH-7	1680	16-Jun-09	1100	116.41	1563.59
EH-7	1680	14-Sep-09	927	116.41	1563.59
EH-7	1680	16-Dec-09	938	116.82	1563.18
EH-8a	1534.03	17-Mar-09	1214	14.66	1519.37
EH-8a	1534.03	16-Jun-09	1220	15.26	1518.77
EH-8a	1534.03	14-Sep-09	1120	15.59	1518.44
EH-8a	1534.03	16-Dec-09	1133	14.16	1519.87
EH-8b	1534.03	17-Mar-09	1214	15.38	1518.65
EH-8b	1534.03	16-Jun-09	1221	15.75	1518.28

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
EH-8b	1534.03	14-Sep-09	1125	16.36	1517.67
EH-8b	1534.03	16-Dec-09	1135	15.88	1518.15
LDS Central	1762.78	20-Jan-09	1112	3.1	1759.68
LDS Central	1762.78	19-Feb-09	1315	3.13	1759.65
LDS Central	1762.78	18-Mar-09	910	2.94	1759.84
LDS Central	1762.78	14-Apr-09	1124	3.25	1759.53
LDS Central	1762.78	13-May-09	1021	3.89	1758.89
LDS Central	1762.78	17-Jun-09	1030	11.39	1751.39
LDS Central	1762.78	16-Jul-09	853	11.54	1751.24
LDS Central	1762.78	20-Aug-09	1158	11.57	1751.21
LDS Central	1762.78	14-Sep-09	1238	10.81	1751.97
LDS Central	1762.78	16-Oct-09	1156	9.56	1753.22
LDS Central	1762.78	12-Nov-09	1303	3.95	1758.83
LDS Central	1762.78	16-Dec-09	1308	10.39	1752.39
LDS East	1753.13	20-Jan-09	1108	7.3	1745.83
LDS East	1753.13	19-Feb-09	1305	7.22	1745.91
LDS East	1753.13	[A]18-Mar-09	903	No data	No data
LDS East	1753.13	14-Apr-09	1112	7.25	1745.88
LDS East	1753.13	13-May-09	1004	20.11	1733.02
LDS East	1753.13	17-Jun-09	1025	7.91	1745.22
LDS East	1753.13	16-Jul-09	838	8.06	1745.07
LDS East	1753.13	20-Aug-09	1150	28.47	1724.66
LDS East	1753.13	14-Sep-09	1246	18.63	1734.5
LDS East	1753.13	16-Oct-09	1201	7.86	1745.27
LDS East	1753.13	12-Nov-09	1255	7.44	1745.69
LDS East	1753.13	16-Dec-09	1255	7.7	1745.43
LDS West	1807.80	20-Jan-09	1215	18.6	1789.20
LDS West	1807.80	19-Feb-09	1430	18.11	1789.69
LDS West	1807.80	18-Mar-09	1045	18.06	1789.74
LDS West	1807.80	14-Apr-09	1333	17.6	1790.20
LDS West	1807.80	13-May-09	1157	27.74	1780.06
LDS West	1807.80	17-Jun-09	1306	30.3	1777.50
LDS West	1807.80	16-Jul-09	1042	24.75	1783.05
LDS West	1807.80	20-Aug-09	1326	24.81	1782.99
LDS West	1807.80	14-Sep-09	1415	28.83	1778.97
LDS West	1807.80	16-Oct-09	1310	21.25	1786.55
LDS West	1807.80	12-Nov-09	1422	20.62	1787.18

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
LDS West	1807.80	17-Dec-09	1126	28.01	1779.79
Lewis-1 Old	1828.71	20-Jan-09	1117	29.26	1799.45
Lewis-1 Old	1828.71	19-Feb-09	1327	28.57	1800.14
Lewis-1 Old	1828.71	18-Mar-09	930	28.16	1800.55
Lewis-1 Old	1828.71	14-Apr-09	1141	27.88	1800.83
Lewis-1 Old	1828.71	13-May-09	1032	28.57	1800.14
Lewis-1 Old	1828.71	17-Jun-09	1154	32.86	1795.85
Lewis-1 Old	1828.71	16-Jul-09	918	35.36	1793.35
Lewis-1 Old	1828.71	20-Aug-09	1209	35.78	1792.93
Lewis-1 Old	1828.71	14-Sep-09	1315	34.85	1793.86
Lewis-1 Old	1828.71	16-Oct-09	1209	32.44	1796.27
Lewis-1 Old	1828.71	12-Nov-09	1312	31.36	1797.35
Lewis-1 Old	1828.71	16-Dec-09	1319	29.94	1798.77
Lewis-2	1826.04	20-Jan-09	1132	27.32	1798.72
Lewis-2	1826.04	19-Feb-09	1335	26.8	1799.24
Lewis-2	1826.04	18-Mar-09	942	26.59	1799.45
Lewis-2	1826.04	14-Apr-09	1155	26.4	1799.64
Lewis-2	1826.04	13-May-09	1040	29.25	1796.79
Lewis-2	1826.04	17-Jun-09	1215	32.23	1793.81
Lewis-2	1826.04	16-Jul-09	1000	36.79	1789.25
Lewis-2	1826.04	20-Aug-09	1238	37.03	1789.01
Lewis-2	1826.04	14-Sep-09	1330	33.8	1792.24
Lewis-2	1826.04	16-Oct-09	1220	31.65	1794.39
Lewis-2	1826.04	12-Nov-09	1328	29.43	1796.61
Lewis-2	1826.04	16-Dec-09	1334	28.29	1797.75
Lewis North	1844.71	20-Jan-09	1150	32.95	1811.76
Lewis North	1844.71	19-Feb-09	1345	32.87	1811.84
Lewis North	1844.71	18-Mar-09	955	32.76	1811.95
Lewis North	1844.71	14-Apr-09	1209	32.66	1812.05
Lewis North	1844.71	13-May-09	1059	32.92	1811.79
Lewis North	1844.71	17-Jun-09	1225	33.67	1811.04
Lewis North	1844.71	16-Jul-09	952	34.21	1810.5
Lewis North	1844.71	20-Aug-09	1248	34.15	1810.56
Lewis North	1844.71	14-Sep-09	1344	33.86	1810.85
Lewis North	1844.71	16-Oct-09	1229	33.59	1811.12
Lewis North	1844.71	12-Nov-09	1339	33.39	1811.32
Lewis North	1844.71	16-Dec-09	1345	33.28	1811.43

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
Lewis South	1809.61	20-Jan-09	1210	13.64	1795.97
Lewis South	1809.61	19-Feb-09	1420	13.15	1796.46
Lewis South	1809.61	18-Mar-09	1026	13.06	1796.55
Lewis South	1809.61	14-Apr-09	1249	12.68	1796.93
Lewis South	1809.61	13-May-09	1120	13.53	1796.08
Lewis South	1809.61	17-Jun-09	1245	17.55	1792.06
Lewis South	1809.61	16-Jul-09	1033	19.03	1790.58
Lewis South	1809.61	20-Aug-09	1316	19.06	1790.55
Lewis South	1809.61	14-Sep-09	1408	17.34	1792.27
Lewis South	1809.61	16-Oct-09	1248	15.93	1793.68
Lewis South	1809.61	12-Nov-09	1406	15.27	1794.34
Lewis South	1809.61	17-Dec-09	1111	15.29	1794.32
NPC-4a	1548.30	17-Mar-09	1107	1.43	1546.87
NPC-4a	1548.30	16-Jun-09	1143	6.28	1542.02
NPC-4a	1548.30	14-Sep-09	1042	7.1	1541.2
NPC-4a	1548.30	16-Dec-09	1054	7.58	1540.72
NPC-5 Old	1567.20	17-Mar-09	1052	27.14	1540.06
NPC-5 Old	1567.20	16-Jun-09	1135	28.3	1538.9
NPC-5 Old	1567.20	14-Sep-09	1029	29.21	1537.99
NPC-5 Old	1567.20	16-Dec-09	1041	27.74	1539.46
Perkins Old	1728.51	20-Jan-09	1308	34.72	1693.79
Perkins Old	1728.51	19-Feb-09	1521	32.38	1696.13
Perkins Old	1728.51	18-Mar-09	1300	34.48	1694.03
Perkins Old	1728.51	14-Apr-09	1435	30.08	1698.43
Perkins Old	1728.51	13-May-09	1354	31.39	1697.12
Perkins Old	1728.51	17-Jun-09	1430	32.55	1695.96
Perkins Old	1728.51	16-Jul-09	1150	35.47	1693.04
Perkins Old	1728.51	20-Aug-09	1409	36.36	1692.15
Perkins Old	1728.51	[B]14-Sep-09	No data	No data	No data
Perkins Old	1728.51	16-Oct-09	1344	36.48	1692.03
Perkins Old	1728.51	12-Nov-09	1455	36.67	1691.84
Perkins Old	1728.51	17-Dec-09	1317	31.95	1696.56
Perkins Production	1727.9	20-Jan-09	1300	39.74	1688.16
Perkins Production	1727.9	19-Feb-09	1515	33.31	1694.59
Perkins Production	1727.9	18-Mar-09	1250	37.7	1690.2
Perkins Production	1727.9	14-Apr-09	1430	32.64	1695.26
Perkins Production	1727.9	13-May-09	1343	33.66	1694.24

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
Perkins Production	1727.9	17-Jun-09	1425	35.21	1692.69
Perkins Production	1727.9	16-Jul-09	1131	38.27	1689.63
Perkins Production	1727.9	20-Aug-09	1404	39.27	1688.63
Perkins Production	1727.9	14-Sep-09	1533	37.01	1690.89
Perkins Production	1727.9	16-Oct-09	1352	39.39	1688.51
Perkins Production	1727.9	12-Nov-09	1450	39.69	1688.21
Perkins Production	1727.9	17-Dec-09	1311	32.78	1695.12
TH-8	1541.53	17-Mar-09	1202	19.35	1522.18
TH-8	1541.53	16-Jun-09	1210	21.16	1520.37
TH-8	1541.53	14-Sep-09	1110	21.76	1519.77
TH-8	1541.53	16-Dec-09	1127	19.83	1521.7
TH-12	1550.94	17-Mar-09	1115	23.98	1526.96
TH-12	1550.94	16-Jun-09	1147	27.12	1523.82
TH-12	1550.94	14-Sep-09	1049	27.83	1523.11
TH-12	1550.94	16-Dec-09	1100	24.32	1526.62
TH-31	1548.18	17-Mar-09	1317	26.14	1522.04
TH-31	1548.18	16-Jun-09	1300	26.5	1521.68
TH-31	1548.18	14-Sep-09	1156	26.81	1521.37
TH-31	1548.18	16-Dec-09	1213	26.15	1522.03
TH-35	1530.49	17-Mar-09	1245	12.77	1517.72
TH-35	1530.49	16-Jun-09	1245	16.26	1514.23
TH-35	1530.49	14-Sep-09	1136	16.36	1514.13
TH-35	1530.49	16-Dec-09	1148	13.28	1517.21
RW-1	2069.10	[C]17-Mar-09	650	No data	No data
RW-1	2069.10	16-Jun-09	800	249.56	1819.54
RW-1	2069.10	[D]14-Sep-09	No data	No data	No data
RW-1	2069.10	17-Dec-09	943	261.93	1807.17
Crystal Well No. 1	2072.46	17-Mar-09	716	259.29	1813.17
Crystal Well No. 1	2072.46	16-Jun-09	820	259.32	1813.14
Crystal Well No. 1	2072.46	14-Sep-09	801	259.71	1812.75
Crystal Well No. 1	2072.46	17-Dec-09	838	259.6	1812.86
Crystal Well No. 2	2069.91	17-Mar-09	737	256.67	1813.24
Crystal Well No. 2	2069.91	16-Jun-09	835	256.72	1813.19
Crystal Well No. 2	2069.91	14-Sep-09	828	256.99	1812.92
Crystal Well No. 2	2069.91	17-Dec-09	854	256.84	1813.07
RW-2	2200.06	17-Mar-09	1356	381.27	1818.79

Well Name	Measurement Point Elevation (ft AMSL*)	Date	Time	Depth to Water (ft)	Water Level Altitude (ft AMSL*)
RW-2	2200.06	17-Jun-09	1000	381.28	1818.78
RW-2	2200.06	14-Sep-09	1712	381.5	1818.56
RW-2	2200.06	16-Dec-09	1419	381.35	1818.71

**AMSL = Above Mean Sea Level*

[A] No access to well. Combination lock on fence.

[B] No access. Tools needed to remove well covering.

[C] LevelTroll transducer probe stuck in well, thus no data collected.

[D] No access to well. Key required.

Appendix E

Well or Spring Name	Date	Temperature (°C)	pH	Salinity (ppt)	Specific Conductance at 25°C (mS/cm)
Wells					
Abbott	17-Mar-09	21	7.65	1	1.95
Abbott	17-Jun-09	23.2	7.5	0.9	1.87
Abbott	14-Sep-09	23.7	7.41	1	1.137
Abbott	16-Dec-09	21	7.72	0.9	1.829
LDS East	18-Mar-09	No Data			
LDS East	17-Jun-09	No Data			
LDS East	14-Sep-09	29.7	7.61	0.5	1.001
LDS East	16-Dec-09	No Data			
LDS Central	18-Mar-09	No Data			
LDS Central	17-Jun-09	31.3	7.8	0.4	0.76
LDS Central	14-Sep-09	29.8	7.79	0.5	1.206
LDS Central	16-Dec-09	29.7	7.9	0.5	0.953
Lewis-1 old	18-Mar-09	27.4	8.05	0.5	0.981
Lewis-1 old	17-Jun-09	28.6	7.9	0.5	1
Lewis-1 old	14-Sep-09	No Data			
Lewis-1 old	16-Dec-09	27.4	7.94	0.5	1.033
Lewis-2	18-Mar-09	29.6	7.71	0.5	0.911
Lewis-2	17-Jun-09	30.1	7.35	0.4	0.914
Lewis-2	14-Sep-09	31.1	7.18	0.5	1.203
Lewis-2	16-Dec-09	29.4	7.41	0.4	0.901
Lewis North	18-Mar-09	29.9	7.91	0.4	0.891
Lewis North	17-Jun-09	29.9	7.76	0.4	0.888
Lewis North	14-Sep-09	31.2	7.14	0.5	1.013
Lewis North	16-Dec-09	29.7	7.58	0.4	0.896
EH-5b	18-Mar-09	28.2	8.6	0.4	0.873
EH-5b	17-Jun-09	28	7.5	0.4	0.876
EH-5b	14-Sep-09	30.1	8.13	0.4	1.037
EH-5b	16-Dec-09	28.7	8.76	0.4	0.847
Lewis South	18-Mar-09	28.6	8.27	0.4	0.835
Lewis South	17-Jun-09	29.1	7.98	0.4	0.801
Lewis South	14-Sep-09	31	7.93	0.4	1.003
Lewis South	17-Dec-09	29.2	7.95	0.4	0.865
LDS West	18-Mar-09	26.5	8.13	0.5	0.945
LDS West	17-Jun-09	31.5	7.5	0.5	0.934
LDS West	14-Sep-09	32.8	7.91	0.5	0.915

Well or Spring Name	Date	Temperature (°C)	pH	Salinity (ppt)	Specific Conductance at 25°C (mS/cm)
LDS West	17-Dec-09	31	7.55	0.4	0.902
EH-4	18-Mar-09	24.8	7.94	0.5	0.922
EH-4	17-Jun-09	26	7.88	0.4	0.915
EH-4	14-Sep-09	24.8	7.79	0.5	1.01
EH-4	17-Dec-09	23.6	7.47	0.5	0.916
Perkins Production	18-Mar-09	26.8	8.01	0.6	1.137
Perkins Production	17-Jun-09	25.6	7.96	0.6	1.135
Perkins Production	14-Sep-09	24.3	7.67	0.6	1.134
Perkins Production	17-Dec-09	No Data			
Perkins Old	18-Mar-09	24.3	7.83	0.6	1.093
Perkins Old	17-Jun-09	24.4	7.47	0.5	1.095
Perkins Old	14-Sep-09	No Data			
Perkins Old	17-Dec-09	24.5	7.37	0.5	1.086
Behmer	18-Mar-09	25.9	7.89	0.5	0.971
Behmer	17-Jun-09	26.3	7.3	0.5	1.043
Behmer	14-Sep-09	26.4	7.2	0.5	0.993
Behmer	17-Dec-09	26.3	7.26	0.5	1.013
NPC-5 Old	17-Mar-09	20.4	8.79	1	2.009
NPC-5 Old	16-Jun-09	20.7	8.45	1.1	2.061
NPC-5 Old	14-Sep-09	21.3	8.08	1.1	2.211
NPC-5 Old	16-Dec-09	20.2	8.23	1.1	2.13
NPC-4a	17-Mar-09	17.3	9.29	1.2	2.361
NPC-4a	16-Jun-09	20	8.82	1.2	2.41
NPC-4a	14-Sep-09	No Data			
NPC-4a	16-Dec-09	19.8	8.58	1.3	2.434
TH-12	17-Mar-09	21	8.51	0.7	1.298
TH-12	16-Jun-09	20.5	8.27	0.6	1.296
TH-12	14-Sep-09	21.3	8.31	0.6	1.167
TH-12	16-Dec-09	20.2	8.63	0.7	1.3
EH-6	23.8	8.04	0.2	0.477	23.8
EH-6	22.7	7.7	0.2	0.483	22.7
EH-6	22.8	8.01	0.2	0.559	22.8
EH-6	16-Dec-09	21.9	7.53	0.2	0.488
TH-8	17-Mar-09	22	8.27	1	2.01
TH-8	16-Jun-09	21.2	7.72	1	2
TH-8	14-Sep-09	21.7	7.81	1.2	2.08

Well or Spring Name	Date	Temperature (°C)	pH	Salinity (ppt)	Specific Conductance at 25°C (mS/cm)
TH-8	16-Dec-09	21.5	8.1	1	1.99
EH-8a	17-Mar-09	20.4	8.06	1.3	2.488
EH-8a	16-Jun-09	20.2	7.98	1.3	2.511
EH-8a	14-Sep-09	No Data			
EH-8a	16-Dec-09	21.1	8.08	1.3	2.506
NPC-2	17-Mar-09	21.1	8.43	1	1.871
NPC-2	16-Jun-09	20.4	7.8	1	1.913
NPC-2	14-Sep-09	21.6	8.71	1	1.541
NPC-2	16-Dec-09	21	8.41	0.9	1.838
TH-35	17-Mar-09	20.3	7.9	1	1.895
TH-35	16-Jun-09	21.1	6.21	0.9	1.66
TH-35	14-Sep-09	20.9	7.86	1	1.877
TH-35	16-Dec-09	21.1	7.85	1	1.941
TH-31	17-Mar-09	23.1	8.6	0.7	1.426
TH-31	16-Jun-09	22.7	8.6	0.7	1.43
TH-31	14-Sep-09	23.1	8.32	0.6	1.531
TH-31	16-Dec-09	23.3	8.66	0.7	1.452
EH-7	17-Mar-09	22.1	9.73	0.6	1.189
EH-7	16-Jun-09	23.6	9.25	0.5	1.112
EH-7	14-Sep-09	24.1	8.8	0.54	1.283
EH-7	16-Dec-09	21.6	9.66	0.7	1.383
EH-3	17-Mar-09	No Data			
EH-3	16-Jun-09	No Data			
EH-3	14-Sep-09	No Data			
EH-3	16-Dec-09	No Data			
Crystal Well No. 1	17-Mar-09	24.6	8.47	0.6	1.178
Crystal Well No. 1	16-Jun-09	26.9	7.29	0.4	1.165
Crystal Well No. 1	14-Sep-09	25.9	7.52	0.1	1.495
Crystal Well No. 1	17-Dec-09	25.3	7.71	0.8	1.495
RW-2	18-Mar-09	32.7	8	0.4	0.759
RW-2	17-Jun-09	32.4	7.52	0.4	0.727
RW-2	14-Sep-09	31.7	7.64	0.4	1.009
RW-2	17-Dec-09	31.6	7.78	0.4	0.75
Springs					
S 52	18-Mar-09	29.8	0.5	7.84	0.93
S 52	17-Jun-09	No Data			

Well or Spring Name	Date	Temperature (°C)	pH	Salinity (ppt)	Specific Conductance at 25°C (mS/cm)
S 52	14-Sep-09	No Data			
S 52	17-Dec-09	31	0.5	7.31	0.931
S 53	18-Mar-09	31.2	0.4	7.78	0.902
S 53	17-Jun-09	No Data			
S 53	14-Sep-09	No Data			
S 53	17-Dec-09	31.3	0.4	7.51	0.926
S 65	18-Mar-09	18.4	0.5	8.2	0.921
S 65	17-Jun-09	24.2	0.4	7.57	0.842
S 65	14-Sep-09	24.4	0.5	8.06	0.932
S 65	17-Dec-09	15.5	0.5	7.6	0.923
M 15	18-Mar-09	No Data			
M 15	17-Jun-09	32	0.5	7.54	0.981
M 15	14-Sep-09	No Data			
M 15	17-Dec-09	29.8	0.5	7.81	0.976
M 16	18-Mar-09	No Data			
M 16	17-Jun-09	31.3	0.5	7.66	0.957
M 16	14-Sep-09	No Data			
M 16	17-Dec-09	31.1	0.5	7.49	0.986
M 20	18-Mar-09	No Data			
M 20	17-Jun-09	31.9	0.5	7.71	0.962
M 20	14-Sep-09	No Data			
M 20	17-Dec-09	31	0.5	7.64	0.96
Warm Springs East	18-Mar-09	No Data			
Warm Springs East	17-Jun-09	31.7	0.5	7.71	0.962
Warm Springs East	14-Sep-09	No Data			
Warm Springs East	17-Dec-09	30.6	0.5	7.8	0.971
Parshall Flume	21-Mar-08	31.3	0.4	8.12	0.91
Parshall Flume	2-Jul-08	32.1	0.3	8.32	0.9
Parshall Flume	17-Sep-08	31.68	0.49	7.84	1.14
Parshall Flume	6-Jan-09	29.8	0.5	8.19	0.95
Pedersen V-Weir (S20a)	18-Mar-09	No Data			
Pedersen V-Weir (S20a)	17-Jun-09	31.1	0.4	7.46	0.911
Pedersen V-Weir (S20a)	14-Sep-09	No Data			
Pedersen V-Weir (S20a)	17-Dec-09	30.7	0.4	7.56	0.907
S 2	18-Mar-09	30	0.5	7.94	0.968
S 2	17-Jun-09	31.8	0.5	7.6	0.934

Well or Spring Name	Date	Temperature (°C)	pH	Salinity (ppt)	Specific Conductance at 25°C (mS/cm)
S 2	14-Sep-09	27.3	0.5	8.2	0.927
S 2	17-Dec-09	28.4	0.5	7.82	0.948
S 6	18-Mar-09	24.1	0.5	8.29	0.913
S 6	17-Jun-09	27.7	0.4	7.15	0.925
S 6	14-Sep-09	30.5	0.5	8.21	0.914
S 6	17-Dec-09	22.5	0.5	7.75	0.925
S 7a	18-Mar-09	29.4	0.4	7.93	0.903
S 7a	17-Jun-09	30.1	0.4	7.63	0.922
S 7a	14-Sep-09	29.2	0.5	7.88	0.962
S 7a	17-Dec-09	28.1	0.5	7.48	0.937
S 15	18-Mar-09	No Data			
S 15	17-Jun-09	31.4	0.4	7.51	0.92
S 15	14-Sep-09	28.3	0.5	7.96	0.936
S 15	17-Dec-09	31.2	0.4	7.43	0.856
S 64	18-Mar-09	No Data			
S 64	17-Jun-09	26.4	0.5	7.23	1.052
S 64	14-Sep-09	27.9	0.5	7.78	1.028
S 64	16-Dec-09	23.9	0.5	7.61	0.996

Note: No Data indicates that production wells are not pumping or no access was available for data to be collected.

Appendix F

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ERRATA TO:

WATER RESOURCES AND GROUND-WATER MODELING IN THE WHITE RIVER AND MEADOW VALLEY FLOW SYSTEMS
CLARK, LINCOLN, NYE AND WHITE PINE COUNTIES, NEVADA

by
Las Vegas Valley Water District
June 2001

all errata sheets put in appropriate place

1) **Table of Contents**

Revision: Corrected table of contents to match body of document

2) **Figure 6-1.** Generalized ground-water recharge, evapotranspiration, and inter-basin flow of the White River and Meadow Valley Flow Systems, units in thousands of acre-feet per year.

Revision: Ground-water outflow from: Jakes Valley = 35,000 afy, Coyote Spring Valley to Upper Moapa Valley = 37,000 afy, and California Wash to Lower Moapa Valley = 41,000 afy

3) **Table 8-4.** Hydraulic properties assigned to hydrogeologic units and faults.

Revision: Corrected values for K_x and K_y for material 28 (Carbonate Rocks, Upper Moapa Subarea (South)). Correct values are $2.00 \times 10^{+1}$.

4) **Figures 8-26, 8-27, 8-28, 8-29, 8-30, 8-45, 8-46, 8-47, 8-48, 8-49, 8-54, 8-55, 8-56, 8-57, and 8-58.**

Revision: Charts revised to reflect minor changes in model output as a result of correcting the placement of two well locations used to pump existing permitted rights in Lower Meadow Valley Wash and Lower Moapa Valley. The revision does not change the relative differences between the compared variables or change the conclusions stated in the report.

5) **Appendix B** Added list of reference inadvertently excluded in report.

6) **Appendix C** Added list of reference inadvertently excluded in report.

COPY EX. 55

WATER RESOURCES AND GROUND-WATER MODELING IN THE WHITE RIVER AND MEADOW VALLEY FLOW SYSTEMS

CLARK, LINCOLN, NYE AND WHITE PINE COUNTIES, NEVADA

by

Las Vegas Valley Water District

June 2001

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Front cover picture insets from top left: Iverson Spring at Muddy Springs near Moapa (May 2001), discharge from MX-5 well after pump start-up (February 1998), spring flow below Pederson Spring at Muddy Springs near Moapa (May, 2001). Background picture of Coyote Spring Valley near MX-4 and MX-5 with pump rig in background.

List of Acronyms and Abbreviations

amsl	Average mean sea level
%	Percent
3-D	Three-dimensional
afy	Acre-feet per year
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
cfs	Cubic feet per second
CRBP	Colorado River Basin Province
CRBPN	Colorado River Basin Province of Nevada
CSI	Coyote Spring Investment LLC
DEM	Digital Elevation Model
DOI	U.S. Department of Interior
DRI	Desert Research Institute
DTW	Depth-to-water
ESA	Endangered Species Act
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
ft	Foot (feet)
ft/d	Foot (feet) per day
GIS	Geographic Information System
gal/min (gpm)	Gallon(s) per minute
gpd	Gallons per day
GWSI	Groundwater Site Inventory
in.	Inch(es)
K	Hydraulic conductivity
K_x, K_y	Horizontal hydraulic conductivity
K_z	Vertical hydraulic conductivity
LDS	Latter Day Saints
LVVWD	Las Vegas Valley Water District
ME	Maxey-Eakin
mi	Mile(s)
mi^2	Square mile(s)
MBPI	Moapa Band of Paiute Indians
MVWD	Moapa Valley Water District
MVIC	Moapa Valley Irrigation Company
NDOW	Nevada Department of Wildlife
NDWR	Nevada Department of Water Resources
NPC	Nevada Power Company
NPS	National Park Services
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
NV	Nevada
P	Precipitation

PRISM	Parameter-elevation Regressions on Independent Slopes Model
r_e	Natural recharge efficiency
SNWA	Southern Nevada Water Authority
S_s	Storage coefficient
S_y	Specific yield
T	Transmissivity
TNC	The Nature Conservancy
U.S.	United States
USAF	U.S. Air Force
USBR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WRCC	Western Regional Climate Center
yr	Year

TABLE OF CONTENTS

Section **Page**

Ex. 55
Errata

original

TABLES

FIGURES

PLATES

APPENDICES

Section **Page**

APPENDICES FIGURES

APPENDICES TABLES

APPENDIX A

APPENDIX B

APPENDIX C

WATER RESOURCES AND GROUND-WATER MODELING IN THE WHITE RIVER AND MEADOW VALLEY FLOW SYSTEMS, Clark, Lincoln, Nye and White Pine Counties, Nevada

EXECUTIVE SUMMARY

This Executive Summary is a synopsis of the report entitled, *Water Resources and Ground-water Modeling in the White River and Meadow Valley Flow Systems, Clark, Lincoln, Nye and White Pine Counties, Nevada*, prepared by the Las Vegas Valley Water District (LVVWD). This report has been prepared in support of the Las Vegas Valley Water District's ground-water applications (54055 through 54059 inclusive) in Coyote Spring Valley; applications have a total combined duty of 27,512 acre-feet per year.

Introduction

Urban development in southern Nevada is continuing and is now expanding to include the regions adjacent to Las Vegas Valley along the Interstate-15 corridor, including communities like Moapa Valley. In addition, numerous power-generating companies have expressed interest in building facilities in the same area. In Coyote Spring Valley, just north of Las Vegas and the "I-15 Corridor," there are over 16,000 acre-feet of ground-water permits owned by the Southern Nevada Water Authority (SNWA), Nevada Power Company (NPC), and Coyote Spring Investment Inc (CSI). In addition to the existing ground-water permits there are 27,512 acre-feet of ground-water applications filed in 1989 by the Las Vegas Valley Water District (LVVWD).

This report was prepared to define the regional hydrology and geology of the White River and Lower Meadow Valley Flow Systems, estimate their ground-water and surface water budgets, and simulate potential impacts on the regional ground-water and surface water resources from development of the LVVWD applications. However, due to the lack of hydrologic data and minimal ground-water development, the large-scale response of the aquifer system is poorly understood and prediction of future ground-water development is difficult to assess. For this reason ground-water development from the regional carbonate rock aquifer should be accompanied by monitoring to protect existing water right holders and environmental resources.

Hydrogeologic Setting

A regional hydrogeological evaluation was made of the entire White River and Meadow Valley Flow Systems. The geologic framework was defined and numerous cross-sections were constructed to help understand the movement of ground water through these two flow systems. New precipitation-altitude relationships were defined based on data collected over the last thirty years. Because of these additional data and revised methods, these relationships led to an estimate of more ground-water recharge than estimated by previous investigators. Ground-water discharge by evapotranspiration was also estimated at greater volumes than estimates by previous investigators.

The water-resources budget for the entire area shows ground-water recharge estimated at 324,000 acre-feet/year. Of this amount about 275,000 acre-feet/year is utilized by vegetation leaving a remainder of nearly 50,000 acre-feet/year to discharge from the two flow systems in the carbonate aquifer. About 10,000 to 20,000 acre-feet/year of this discharge is surface water in the Muddy River that actually flows into Lake Mead. The water-resources budget for the ground-water model area, a subset of valleys, including Coyote Spring Valley, at the southern end of these two flow systems, shows inflow from the regional carbonate aquifer plus local ground-water recharge to equal 117,000 acre-feet/year. Evapotranspiration consumes about 67,000 acre-feet/year leaving about 50,000 acre-feet/year of discharge out of the area.

The geochemical data base for the area was re-evaluated by the Desert Research Institute (University of Nevada System) and a deuterium-mass-balance model was developed. This geochemistry model, which has some commonality with the estimation of the water budget, is consistent with the hydrogeological model. The data from these two models were used to develop a numerical ground-water model.

Simulated Impacts

A three-dimensional ground-water flow model was developed to assist in understanding the response of the ground-water system from developing LVVWD ground-water applications in Coyote Spring Valley. The results based on the regional evaluation and model simulations are described below:

The ground-water flow model is calibrated based on predevelopment conditions and reasonably replicates responses to the hydrologic system from existing pumping through the year 2000. However, the model predicts a two cubic feet/second decline in the flow of the Muddy Springs that is not observed. Thus, the model tends to over estimate somewhat the response of the ground-water system.

Baseline for ground-water development is the pumping of the existing permits, about 44,000 acre-feet per year in the valleys (Coyote Spring Valley, Garnet Valley, California Wash, Lower Meadow Valley Wash, Muddy River Springs, and Black Mountain) where pumpage occurs in the model area. The simulated net response between pumping the permitted water rights, 18,000 acre-feet/year and the applications, 27,500 acre-feet/year, is 2.5 cubic feet/second decrease in the Muddy Springs.

Rogers and Blue Point Springs are not affected by the baseline (permitted) pumping or the addition of the proposed pumping as a result of the applications. The model predicts that the impact to the Muddy Springs in 61 years of pumping the permitted water rights will be a decrease of about four cubic feet per second. However, as stated above the model predicted a decline in spring flow of about two cubic feet per second in the year 2000, which has not been observed.

A model is only a tool dependent upon accurate hydrogeologic data. The availability of data in the model area is extremely limited. Therefore, the results from the model are very limited. The impacts of future ground-water development in the carbonate aquifer will remain largely unknown and speculative until there are opportunities to evaluate transient responses to significant, long-term ground-water pumping from the carbonate-rock aquifer. As data is collected from ground-water development the model will be continually refined and used for analysis of potential impacts.

1 INTRODUCTION

Urban development in southern Nevada is continuing and is now expanding to include the regions adjacent to Las Vegas Valley along the Interstate-15 corridor, including communities like Moapa Valley. In addition, numerous power-generating companies have expressed interest in building facilities in the same area.

Increased land development includes the need for additional water. In Coyote Spring Valley, just north of Las Vegas and the "I-15 Corridor," there are over 16,000 acre-feet of ground-water permits owned by the Southern Nevada Water Authority (SNWA), Nevada Power Company (NPC), and Coyote Spring Investment Inc (CSI). In addition to the existing ground-water permits there are 27,512 acre-feet of ground-water applications filed in 1989 by the Las Vegas Valley Water District (LVVWD). Also, there are over 100,000 acre-feet of ground-water applications more recently filed by CSI in 1997 and 1998, for a potential residential and golf course development in Coyote Spring Valley.

It is uncertain how many of the ground water applications in Coyote Spring Valley can be developed without impacting the down-gradient Muddy Springs in Upper Moapa Valley. The Muddy Springs are managed by the U.S. Fish and Wildlife Service (USFWS) and are the home of the Moapa dace (U.S. Fish and Wildlife Service, 1995), a protected species of fish listed as endangered under the Endangered Species Preservation Act of 1966 on March 11, 1967 (32 Federal Register 4001). Other aquatic species of concern that occur in the Muddy River ecosystem are three fish, two snails, and two insects. There are also springs in hydrologic basins near Coyote Spring Valley on lands managed by the U.S. Park Service (USPS) and Bureau of Land Management that are of concern to those agencies and the public who uses them.

Because there is need for development in the I-15 Corridor and Coyote Spring Valley and because impacts on nearby springs are unknown, LVVWD has carried out a detailed analysis in an attempt to understand the origin, movement, volume, and fate of ground-water in the general area. This report summarizes those findings. It is also a supporting document for the hearing scheduled before the Nevada State Engineer in July 2001 for water rights applications 54055 through 54059 (inclusive) held by LVVWD.

1.1 PURPOSE AND SCOPE

The purpose of this study is to further define the ground-water flow systems that are contributory to the Muddy Springs in Upper Moapa Valley and to determine if there is ground-water flow that bypasses the springs. The scope of the study is to estimate a water-resource budget for the White River Flow System, including the Meadow Valley Flow System component. This was done using additional precipitation data, the results of recent geologic investigations, geochemistry, and interpretive techniques that were not available to earlier investigators. Finally, a ground-water model was constructed to evaluate the hydrogeologic processes and to assess the future spring flow impacts of permitted and potential additional groundwater pumpage using various pumping simulations.

1.2 DEFINITION OF STUDY AREA OF THIS REPORT

The Muddy Springs and Muddy River represent a major discharge point in the White River and Meadow Valley Flow System that drains to the Colorado River. There are 27 hydrographic basins in eastern and southern Nevada that are part of the Colorado River Basin drainage (**Figure 1-1**). These basins form the White River and Meadow Valley Flow Systems; in this report, these basins are referred to collectively as the Colorado River Basin Province of Nevada. Much of the area is accessible by mule and rail. There are several other valleys in Nevada that are also tributaries to the Colorado River drainage, but are not within the study area.

The Muddy Springs and Muddy River, in part the focus of this study, are located in the eastern edge of Upper Moapa Valley (Eakin, 1964, Plate 1) and are the source of the Muddy River. There are 20-30 separate spring orifices that make up the Muddy Springs and these are located over an area of about three square miles (3 mi^2). Additionally there are undoubtedly diffuse seeps to the Muddy River and to the alluvial ground-water system within the Upper Moapa Valley that are undefined. The collective spring flow represents part of the discharge from the White River Flow system.

The study area includes all of the valleys that make up the White River Flow system as first defined by Eakin (1964) and we have included Hidden, Garnet, California Wash, Black Mountain Basin and Lower Moapa Valley. Also part of the study are all of the valleys that are tributary to, and including, Meadow Valley Wash as described by Rush and Eakin (1963), and Rush (1964). All valleys in the study area are listed in **Table 1-1** along with their appropriate references. The area modeled is much smaller and is shown on **Figure 1-1**. The detailed geologic interpretations are mostly confined to the area modeled.

Not all 27 basins are represented in the ground-water model constructed for this study, but their collective hydrologic resources are used. The net ground-water flow across the model boundary in both the alluvial aquifer system and the underlying, interconnected, regional carbonate aquifer system represents a valuable resource.

The study area encompasses about 7,734,000 acres (12,080 square miles) and covers significant parts of White Pine, Lincoln, and Clark Counties and a small part of Nye County. The highest points in the study area are Currant Mountain (11,513 feet) in the White Pine Range and Troy Peak (11,298 feet) in the Grant Range.

Most of the valleys within the study area have no surface outflow, yet all are tributaries to the Colorado River drainage through ground-water discharge. All of these valleys are in the classic Basin and Range physiographic region, as described by Fenneman (1931). The Basin and Range is a series of parallel to sub-parallel, north trending mountain ranges separated by elongated valley lowlands and are further classified by Heath (1984), as being in the Alluvial Basins Ground-Water Region. These basins are also part of the carbonate rock province of eastern-southern Nevada and western Utah as described by Plume and Carlton (1988). The carbonate rock province represents a regional aquifer system that underlies the entire area. The hydraulic

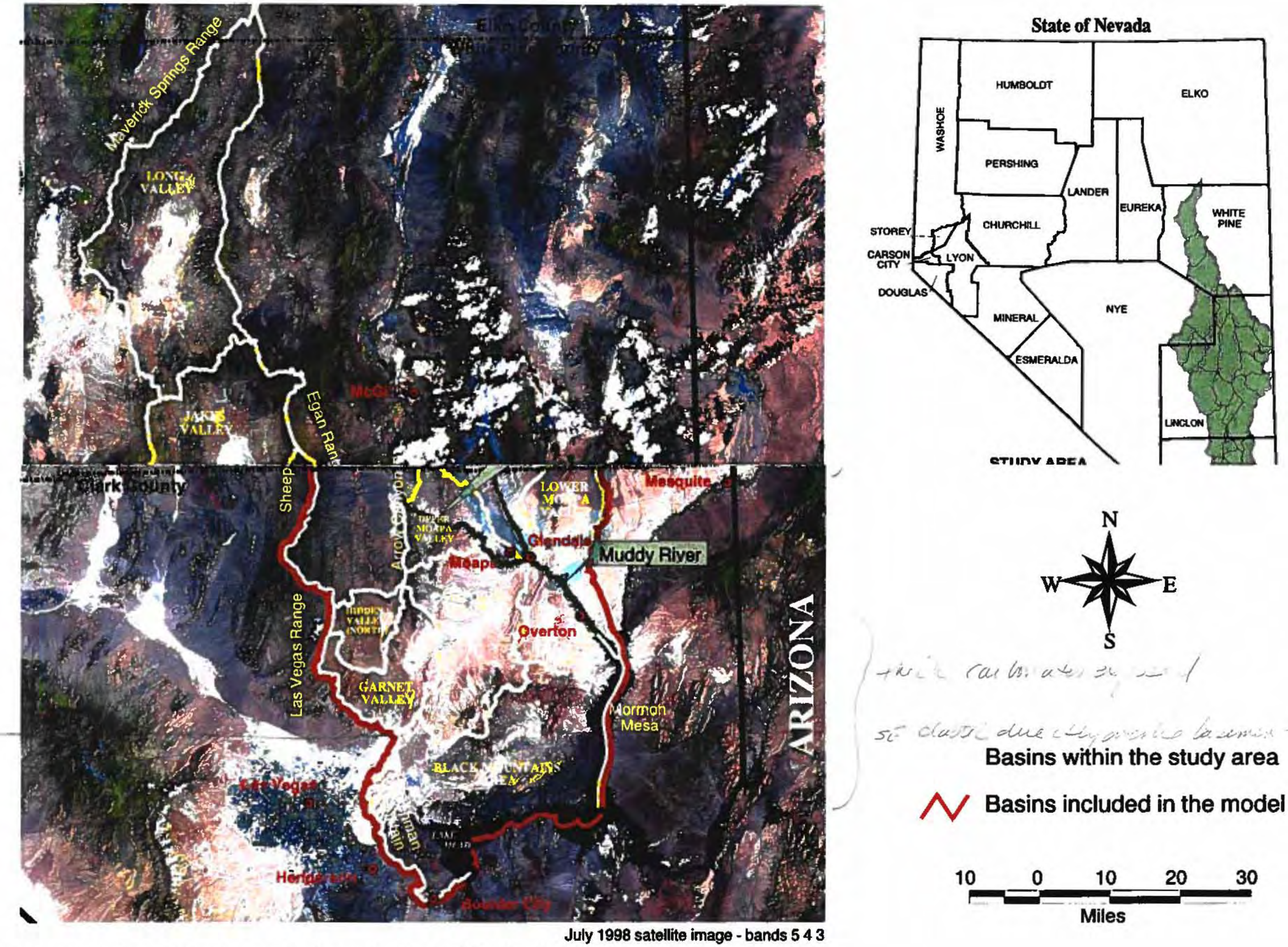

Figure 1-1. Location of Study area drainage basins and basins included within the model.

connectivity of this aquifer system is believed to be large, but there may be structural blocks that compartmentalize different parts of the flow system. Most of these valleys are part of the White River ground-water flow system first described by Eakin (1966). These 27 basins are collectively referred to here as the Colorado River Basin Province of Nevada (CRBPN).

The northwestern part of the study area is bounded by a long continuous northeasterly trending mountain range which includes the White Pine, Grant and Quinn Canyon Range. The northwestern part of the study is also bounded by parts of the northerly Egan Range. The southwestern part is bounded by the northerly trending Sheep Range and the smaller northwesterly trending Pahranagat Range. The extreme southwestern part is bounded by the Las Vegas Range and Frenchman Mountain.

The eastern part of the study area is bounded by the northwesterly trending Fortification Range, parts of the northwesterly Wilson Creek Range and parts of the basically east-west Clover Mountains. The southeastern boundary transects the Mormon Mountains and Mormon Mesa and the Overton arm of Lake Mead. The southern boundary is Lake Mead in Nevada and Arizona. All of the northeasterly trending Delamar, Meadow Valley and virtually all of the Clover Mountains are within the study as are numerous small ranges like the Fairview, Bristol, Highland Peak, Seaman, and North and South Pahroc Ranges.

The largest hydrographic basin in the study area is the White River Valley at about 1,017,000 acres, and the smallest, Rose Valley is about 8,000 acres. Most of the western side of the study area is composed of large valleys bounded by high mountain ranges. The eastern side is composed of smaller valleys nestled in amongst generally rugged terrain.

1.3 PREVIOUS INVESTIGATIONS

The U. S. Geological Survey (USGS) has evaluated the hydrology of the entire study area **(Figure 1-1)** through a series of building block studies that began in the early 1960s. Most of these were at a reconnaissance level in a cooperative program with the state of Nevada with a few additional in-depth studies. Scott and others (1971) summarized hydrologic data for many of the hydrographic basins in the state. Winograd and Thordarson (1975) in their investigation of the regional hydrogeologic framework for the Nevada Test site provided insights into the recharge and direction of ground-water flow from the Sheep Range.

As part of the MX Missile investigations numerous wells were drilled in many of the valleys and Ertec Western (1981) conducted an extensive aquifer test in Coyote Spring Valley in well No. CE-DT-5, commonly known as MX No. 5. This well pumped at least 3,400 gallons per minute (gpm) for a 30-day test with virtually no drawdown at the wellhead. According to Buqo and others (1992, p. 28) the 3,400 gpm was the capacity of the pump used to test the well so the aquifer system was not significantly stressed. This converts to 5474 afy MX-5

The USGS Regional Aquifer Systems Analyses (RASA) started in the 1980s and continued on into the 1990s. The RASA project was funded in total by the USGS and resulted in the development of a three-dimensional finite difference ground-water flow model that includes all of the entire carbonate-rock province of Nevada, Utah, and California and covers all of the valleys of interest for this study. According to Prudic et al. (1995, p. D 38) the model results are only conceptual. The Department of the Interior Agencies (DOI) funded the USGS to take this conceptual steady state ground-water model and run transient scenarios. These scenarios were based on proposed ground-water withdrawals by the Las Vegas Valley Water District through out much of the carbonate-rock province.

According to the authors of the modeling effort, Schaefer and Harrill (1995, p. 2 and 7) the results of this 200 year simulation need to be viewed with caution. Also in the mid 1980s the USGS initiated the Carbonate Aquifer program in cooperation with the LVVWD, City of North Las Vegas, Desert Research Institute (DRI) and the U. S. Bureau of Reclamation (USBR).

Other studies by the USGS, DRI, the LVVWD, and SNWA focused on specific disciplines or a combination of disciplines such as geochemistry, geophysics, geology, evapotranspiration (ET) and hydrology. Kirk and Campana (1990), as part of a regional, multi-agency study of the carbonate rock aquifer, developed a ground-water flow model for the White River Flow System based on geochemistry.

LVVWD developed ground-water models for many of the valleys as part of their regional investigations of ground-water basins in eastern and southern Nevada. Prudic and others (1993) developed a conceptual evaluation of regional flow in the carbonate rocks of eastern and southern Nevada through the use of a ground-water flow model. Dettinger and others (1995) studied the distribution of the carbonate-rock aquifers and their potential for development and have indicated the best way to develop ground water from the carbonate aquifer is a staged approach with adequate monitoring of related effects. Thomas (1996) synthesized ground-water flow in southern Nevada through the use of geochemistry and Plume (1996) described the hydrogeologic framework of the carbonate rock province in Nevada, Utah, and California. Katzer (1996) developed a conceptual model for the ground-water flow system in Coyote Spring Valley. Bredehoeft and Hall, (1996) developed a ground-water model for the Upper Muddy River Valley. They observed that pumping from the Arrow Canyon Well will ultimately reduce the flow of the river and springs by an equal amount.

In another study within the California Wash, Johnson and others, (2001) concluded that long-range impacts from proposed pumping (7000 AFY) on the Muddy Springs discharge is minimal. There are also studies referenced that include Master of Science thesis, consultant's reports, and reports by the U. S. Air Force (USAF) for the MX Missile-siting project. **Table 1-1** lists the various studies that have contributed to the understanding of the complex hydrogeology of this vast area. The geologic references are many and are referenced in the geology section of this report and are not included in **Table 1-1.**

All of these publications are referenced in the text and are listed alphabetically by senior author and chronologically by year in the Reference Section.

Table 1-1. Previous hydrologic investigations in the study area of the Colorado River Basin Province of Nevada.

VALLEY and Hydrologic Site No.		TYPE OF STUDY Valley	Regional	REFERENCE[1]
WHITE RIVER FLOW SYSTEM				
Long	175	X	X	R-3, B-33, W-1409,1475 L, P-1628, O-96-469
Jakes	174	-	X	B-33, W-1409, 1475 L, P-1628, O-96-469
White River	207	X	X	B-8, 33, W-365, 1409, 1475 L, O-96-469
Garden	172	X	X	R-18, B-33, W-365, 1409, 1475 L, L-8, O-96-469
Coal	171	X	X	R-18, B-33, W-365, 1409, 1475 L, L-8, O-96-469
Cave	180	X	X	R-13, B-33, W-365, 1409, 1475 L, L-11, O-96-469
Pahroc	208	X	X	R-21, B-33, W- 365, 1409, 1475 L, L-10
Dry Lake	181	X	X	R-16, B-33, W- 365, 1409, L-16, O-96-469
Delamar	182	X	X	R-16, B-33, W- 365, 1409, L-16, O-96-469
Pahranagat	209	X	X	R-21, B-33, W- 365, 1409, 1475 L, WRI- 91-4146
Kane Springs	206	X	X	R-25, B-33, W-365, 1409, WRI- 91-4146
Coyote Spring	210	X	X	R-25, B-33, W-224, 365, 1409, L-3, OP, O-96-469, WRI- 91-4146
Upper Moapa	219	X	X	R-50, B-33, W-224, 365, 1409, O-96-469, WRI-91-4146
Lower Moapa	220	X	X	R-50, W-224, 365, 1409, WRI- 91-4146
Hidden	217	X	X	R-50, W-224, 365, 1409, WRI- 91-4146
Garnet	216	X	X	R-50, W-224, 365, 1409, WRI- 91-4146
California Wash	218	X	X	R-50, W-224, 365, 1409, WRI- 91-4146
Black Mountains	215	X	X	R-50, W224, 365, 1409, P-295, 298, WRI- 91-4146
MEADOW VALLEY FLOW SYSTEM				
Lake	183	X	X	R-24, W-365, W-1409, 1475 L
Patterson	202	X	X	R-27, B-7, W-1409, 1475 L, O-96-469
Spring	201	X	X	R-27, B-7, W-365,1409, 1475 L, WRI- 91-4146
Eagle	200	X	X	R-27, B-7, W-365,1409, 1475 L, WRI- 91-4146
Rose	199	X	X	R-27, B-7, W-365,1409, 1475 L, WRI- 91-4146
Dry	198	X	X	R-27, B-7, W-365,1409, 1475 L, WRI- 91-4146
Clover	204	X	X	R-27, B-7, W-365,1409, 1475 L, WRI- 91-4146
Panaca	203	X	X	R-27, B-7, W-365,1409, 1475 L, WRI- 91-4146
Meadow Valley Wash	205	X	X	R-27, W-224, 365, 1409, 1475 L, WRI- 91-4146

1. USGS Publications: R - Reconnaissance Series Report; W- Water-Supply Paper; Professional Paper-P, Water-Resource Investigations Report-WRI, B - Nevada Water Resources Bulletin, and O - Open-File Report. DRI Publications- D. LVVWD Publications-L., and Other Publications-OP.

1.4 AVAILABILITY OF DATA

A variety of data and information from numerous sources were compiled for the purposes of this study and the construction of a ground-water flow model. Since much of the study area is located in remote and undeveloped areas, few data are available. However, significant data and information were acquired in the form of published and unpublished documents and data sets for the various parameters required for the development of a conceptual model of the study area and the construction of a flow model. To assist in the development of records, information was garnered from site reconnaissance and field investigations and from numerous interviews with local, state, and federal agencies and various ground-water consultants working within the boundary of the study area.

Historical records of (climatic) precipitation were acquired from the DRI Western Regional Climatic Center website, www.wrcc.dri.edu/summary/climsmnv.html. Additional precipitation station data were obtained from NDWR unpublished records. For the period 1984 to 2000, high-elevation precipitation data was compiled from Water Resources Data reports published annually by the USGS.

Well and spring data were compiled from numerous sources including data collected by SNWA and data obtained from the USGS Ground-water Site Inventory database (GWSI), NDWR Well Log Database and Water Rights Database, and published and unpublished reports, hydrogeologic investigations, and maps. A significant portion of the water-level and ground-water production data were compiled from MVWD and NPC hydrologic monitoring reports submitted to NDWR. Interviews conducted with representatives of MVIC, MVWD, NDWR, and various consultants working within the study area were used to assist in the development of the various historical records.

Surface-water data, including stream flow and spring discharges, were compiled from the USGS National Water Information System database and published USGS Water Resources Data reports for water years 1913 to 2000. Continuous records of stream-flow were compiled for water years 1944 to 2000 for the Moapa gaging station, and 1950 to 2000 for the Glendale gauging station. Data for water-year 2000 have not yet been fully published and is considered preliminary.

Selected coverages depicting spatial (vector) data were acquired from the USGS Eros Data Center and developed through site reconnaissance and field investigations by SNWA. USGS 30-meter seamless digital-elevation-model data were acquired from the USGS National Elevation Dataset. Satellite imagery for the years 1981 and 1998 was acquired from the USGS Eros Data Center. Aerial photography for 1953 was acquired from the USGS Eros Data Center, and for 1997-2000 from the private sector. Geologic data (geologic outcrop and fault maps) were acquired from the Nevada Bureau of Mines and Geology and the USGS.

Additional data acquired for the purposes of this study and ground-water modeling effort that are not discussed in this section are discussed in subsequent sections of this report.

2 HYDROLOGIC SETTING

The valleys that make up the White River and the Meadow Valley Flow Systems are in the Colorado River Basin Province of Nevada **(Figure 2-1)**. These two parallel flow systems are probably in hydraulic continuity with each other at depth and both discharge ground water from the deep seated carbonate aquifer. These valleys are part of the Basin and Range Province and are characterized as bounded by north- to northeast trending sub-parallel mountain ranges. The mountain ranges, depending on location, are made up of a mixture of marine sedimentary rocks from the Paleozoic and Mesozoic Eras and volcanic rocks of Tertiary age. The valleys' unconsolidated sediments reflect the erosion process from the mountain blocks and are filled with sediments that range in size from clay to boulders. Carbonate rocks, mostly of Paleozoic age underlie virtually all the valley aquifer systems, thus providing continuity of ground-water flow throughout the entire area. Ground-water storage and flow in the carbonate rocks are enhanced by dissolution and an extensive fracture system. In some valleys volcanic rocks are on top of carbonate rocks and underneath the valley unconsolidated aquifer system.

The dominant hydrologic features of the area are the several large springs scattered throughout the area that represent flow from the carbonate aquifer system. The largest of these are the Muddy Springs located near the central part of Upper Moapa Valley that collectively discharge about 37,000 acre-feet/year (adjusted for evapotranspiration). This spring flow is virtually unchanged since it was first estimated by Eakin (1966). The Muddy Springs are the headwaters of the Muddy River, which historically was a tributary to the Virgin River, but now flows to Lake Mead because of the construction of Hoover Dam.

The White River flows several thousand afy from its headwaters in the White Pine Range and is a continuous drainage to its junction with Lake Mead. The channel, once it leaves White River Valley is ephemeral and is a remnant of the wetter climate dating back to the late Pleistocene time (Eakin, 1966). The drainage is known as Pahranagat Wash once it reaches Pahranagat Valley and turns into the Muddy River in Upper Moapa Valley.

There are other perennial streams mostly in the higher mountain blocks in the northern parts of the area such as in the White Pine and Eagan Ranges in the White River Valley drainage and Clover Mountains that drain to Clover Valley. Meadow Valley Wash is perennial to intermittent for most of its length starting in Spring Valley (east side of the Wilson Creek Range) and flowing generally to a point about 10 miles north of Moapa.

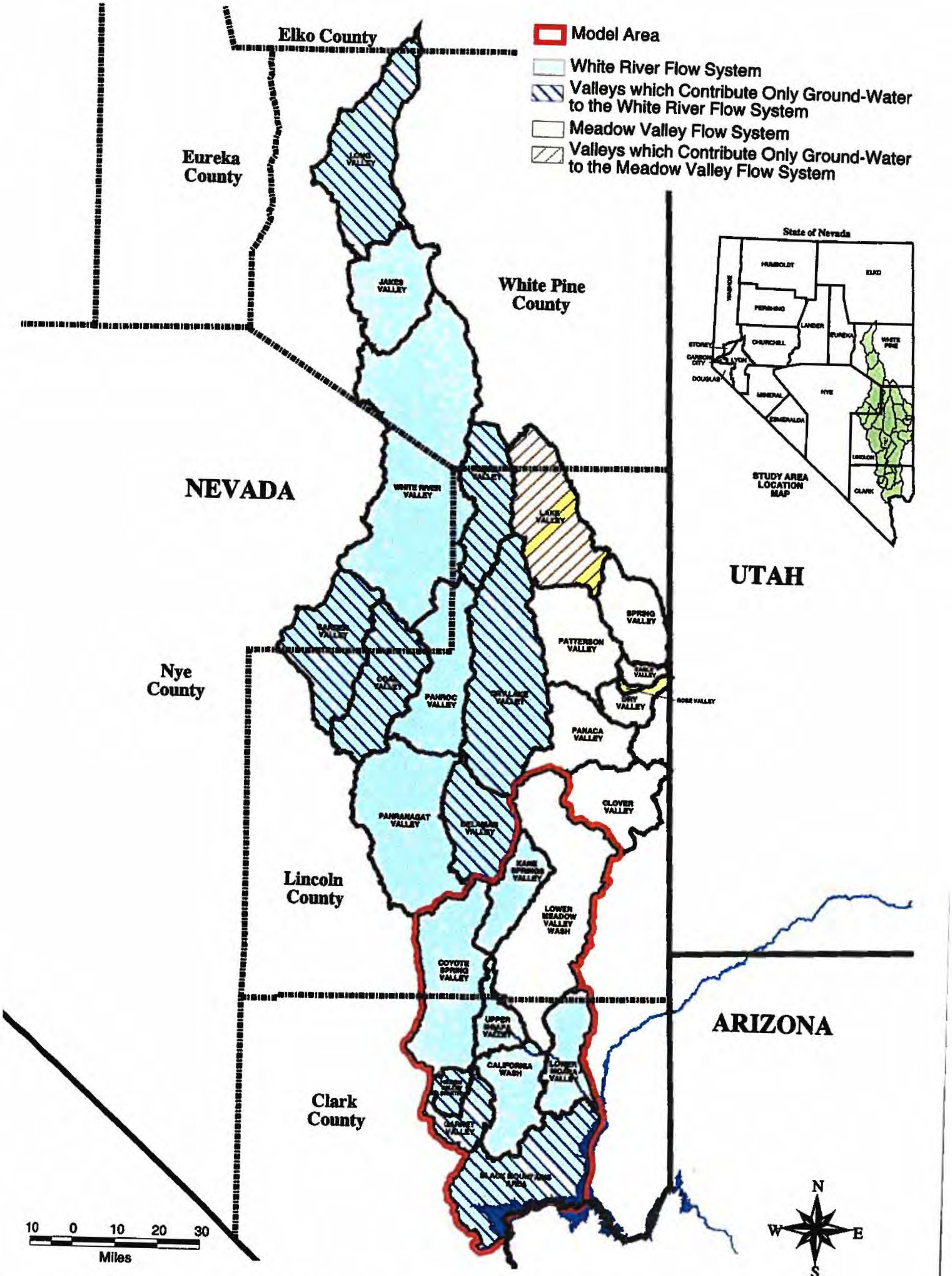

Figure 2-1. Location map for White River and Meadow Valley Flow Systems

3 GEOLOGY

3.1 GENERAL GEOLOGY

The exposed bedrock in the ranges in the northern part of the modeled area consists generally of fresh volcanic rocks, which continue to south of the Lincoln County-Clark County line. Most of these volcanic rocks are ash-flow tuffs, which form thin, widespread planar sheets of brittle rock. The area also contains two major eruptive centers, the Caliente caldera complex at and just south of Caliente, and further to the south, the Kane Springs Wash caldera complex. The volcanic centers are the source of most of the tuffs in the area. In the southern part of the study area, thick Paleozoic carbonate rocks are exposed and they form the carbonate-rock aquifer of eastern and southern Nevada. The valley-fill overlying these carbonate rocks are made up of poorly to moderately consolidated Quaternary to latest Tertiary clastic basin-fill deposits that are also aquifers. **Plate 1** and **Plate 2** show the regional geology and hydrogeology and the locations of the cross-sections. **Figure 3-1** describes the hydrogeologic units displayed in the cross-sections. Geologic cross-sections sections A-A' through K-K are **Figure 3-2, Figure 3-3**, and **Figure 3-4**, and are referred to throughout this section.

The modeled area is in the Basin and Range physiographic province, which is characterized by the most severe extension (pulling apart) of continental crust in the World (Rowley and Dixon, 2000, in press). Ground-water flow in the study area may be controlled in part by faults of two major Tertiary extensional episodes. They are equally important in terms of magnitude of structural deformation, but the younger episode is more important in terms of producing structures that may facilitate ground-water flow. The older of these episodes, the middle Cenozoic pre-basin-range episode, has formed many of the faults in the study area. However, these faults may be less conducive to ground-water flow because they are older and thus their accompanying fractures tend to have rehealed, since stress was transtensional rather than pure extensional. The faults that led to the older fracturing generally strike (that is, are oriented) northeast and northwest. Offset along these faults is known as oblique slip, that is, it combines normal-slip and strike-slip movement. The age of this episode is from about 25 to 14 million years, in the Miocene. Fault deformation was accompanied by volcanism that formed most of the tuffaceous volcanic rocks in the area, including their two eruptive centers. The faults in the Caliente area are the best examples of this fault type because this area, within the Caliente caldera complex, has been less affected by the younger of the two episodes of deformation.

The younger of the two episodes of deformation is the late Cenozoic basin-range episode. This episode blocked out the present topography into north-striking ranges and intervening basins. These basins and ranges were created by north-striking normal faults, which formed when the crust was pulled apart (extended) in an east-west direction. In parts of the study area, however, range front faults trend northeast, as along the northwestern side of the Meadow Valley Mountains and southern Delamar Range. The fault along the northwestern side of the southern Delamar Mountains continues southwest of the study area as the Pahranagat shear zone, which was mapped by Ekren and others (1977). The Pahranagat shear zone is a left-lateral strike-slip transfer fault zone, which connects at both ends with northeast-striking normal faults. These northeast-striking faults, then, "transfer" the strain of east-west pulling apart along a different

HYDROGEOLOGIC UNITS DISPLAYED IN CROSS-SECTIONS

Unit	Description
Qs / QTs / Ts	QTs -- Quaternary and Tertiary sediments. Composite unit in the ground-water model locally divided on cross-sections into Qs and Ts. The Qs unit is chiefly unconsolidated alluvium and colluvium of Quaternary age deposited in basins. Thickness ranges from 0 to 2,500 feet. Unit is highly permeable. The Ts unit is chiefly the Muddy Creek Formation that is predominately siltstones, sandstone, and conglomerates. The Muddy Creek Formation is of Tertiary age and variable in thickness (up to 3,000 feet). Unit is very permeable where sandy and coarse grained, poorly permeable where clays are present. In the southern part of the flow system, unit includes Lovell Wash-Bitter Ridge basin rocks, Thumb Formation, and rocks of the Rainbow Gardens.
Tv	Tv --Tertiary volcanic rocks. Includes non to densely welded ash-flow tuffs, rhyolites, basalt flows, volcanic breccias, andesites, quartz latites, and tuffaceous sediments. Volcanic rocks are much thicker in the northern part of area but present to the south near the southern border of flow system. Volcanic rocks are Tertiary in age and range in thickness from 0 to greater than 10,000 feet. Unit is moderately permeable, especially where fractured.
Ti	Ti -- Tertiary intrusive volcanic and granitic rocks. Primarily associated with the Caliente Caldera complex, Kane Spring Caldera, and the Cleopatra/Black Mountain intrusive as ring fractures, stocks, dikes, and resurgent domes. Unit has very poor permeablilty.
KPs	KPs -- Cretaceous through Permian clastic (siliciclastic) rocks. Permian and Mesozoic rocks of the Colorado Plateau. Includes unnamed Permian red beds possibly equivalent to the Supai Formation. Also includes: Kaibab and Toroweap Formations (cherty limestones with abundant gypsum, sandstone, and shale, these two formations are lithologically similar but separated by an unconformity), (Kayenta Formation (silty shale and sandstone), Moenave Formation (sandstone, conglomerate, and mudstone), Chinle Formation (mudstone, shale, and conglomerate), and Moenkopi Formation (mudstone, sandstone, siltstone) with several members that are chiefly siltstones, shales, silty limestones, dolomites, sandstones, and conglomerates. Unit is thin to the north (less than 1,000 feet) to over 10,000 feet in the south central part of the area. Overall the unit has low permeability, however where limestones predominate, the unit is moderately permeable.
POc	POc -- Permian through Ordovician carbonate rocks. Upper Paleozoic carbonate section (a.k.a. "upper carbonate aquifer"). Includes the Bird Spring Formation (limestone and minor dolomites), Monte Cristo Group that includes Yellowpine Limestone, Bullion Dolomite, Ancor Limestone, and the Dawn Limestone (limestone, minor dolomite, interbedded cherts in lower part of section), Guilmette Formation with upper and lower members of predominately limestones and dolomites, Simonson Dolomite and Laketown Dolomite of Silurian age, through the Ely Springs Dolomite to the Eureka Quartzite. With the exception of shales in the Mississippian and the Eureka Quartizite, the unit is very permeable. Accumulative thickness of approximately 15,000 feet.
Cc	Cc -- Cambrian carbonate rocks. Lower Paleozoic carbonate section (a.k.a. "lower carbonate aquifer"). Composed of all carbonate rocks below Eureka Quartzite and therefore includes units that are, in part, lower Ordovician, and upper pre-Cambrian. Includes Antelope Valley Limestone, Goodwin Limestone, and the carbonate part of the Nopah Formation. Unit is approximately 3,500 feet thick and generally very permeable and was therefore combined with overlying unit (POc) in the associated ground-water model of this study.
CpCs	CpCs -- Cambrian and pre-Cambrian siliciclastic rocks. Lower clastic aquitard. Includes Cambrian Prospect Mountain Quartzite, Zabriskie Quartzite and Wood Canyon Formation which is composed of shales, quartzites, quartzose sandstones, and metasedimentary rocks. Unit is greater than 3,500 feet thick of poorly permeable to impermeable rock.
pCm	pCm -- pre-Cambrian igneous and metamorphic rocks. Gniess, schists, quartzites, granites, and metasedimentary rocks. Unit forms the core of Mormon Mountains, Virgin Mountains, and Gold Butte. Unit is very impermeable. Combined with the overlying unit (CpCs) and represented as a "no-flow" boundary at the base of the associated ground-water model in this study.

Figure 3-1. Hydrogeologic unit descriptions.

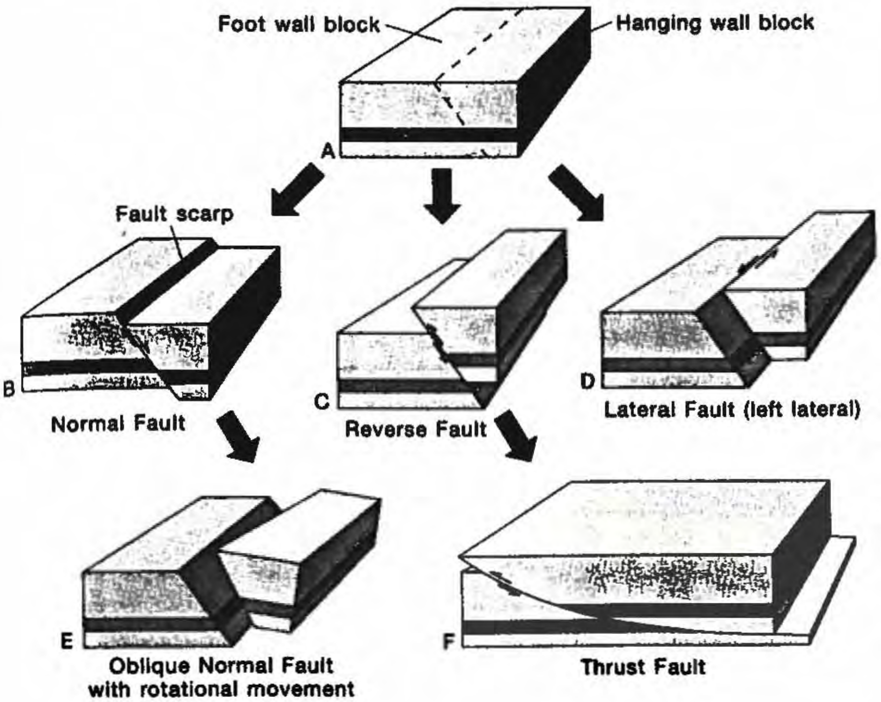

FIGURE 5–18 Types of faults. (A) The unfaulted block with the position of the potential fault shown by dashed line. In nature, movements along faults may vary in direction, as shown in (E). A thrust fault (F) is a type of reverse fault that is inclined at a low angle from the horizontal.

FIGURE 5–19 Air photo mosaic in which the trace of the right-lateral strike-slip San Andreas fault is clearly visible. Notice the offset streams (arrows). San Luis Obispo County, California. *(Courtesy of U.S. Geological Survey.)*

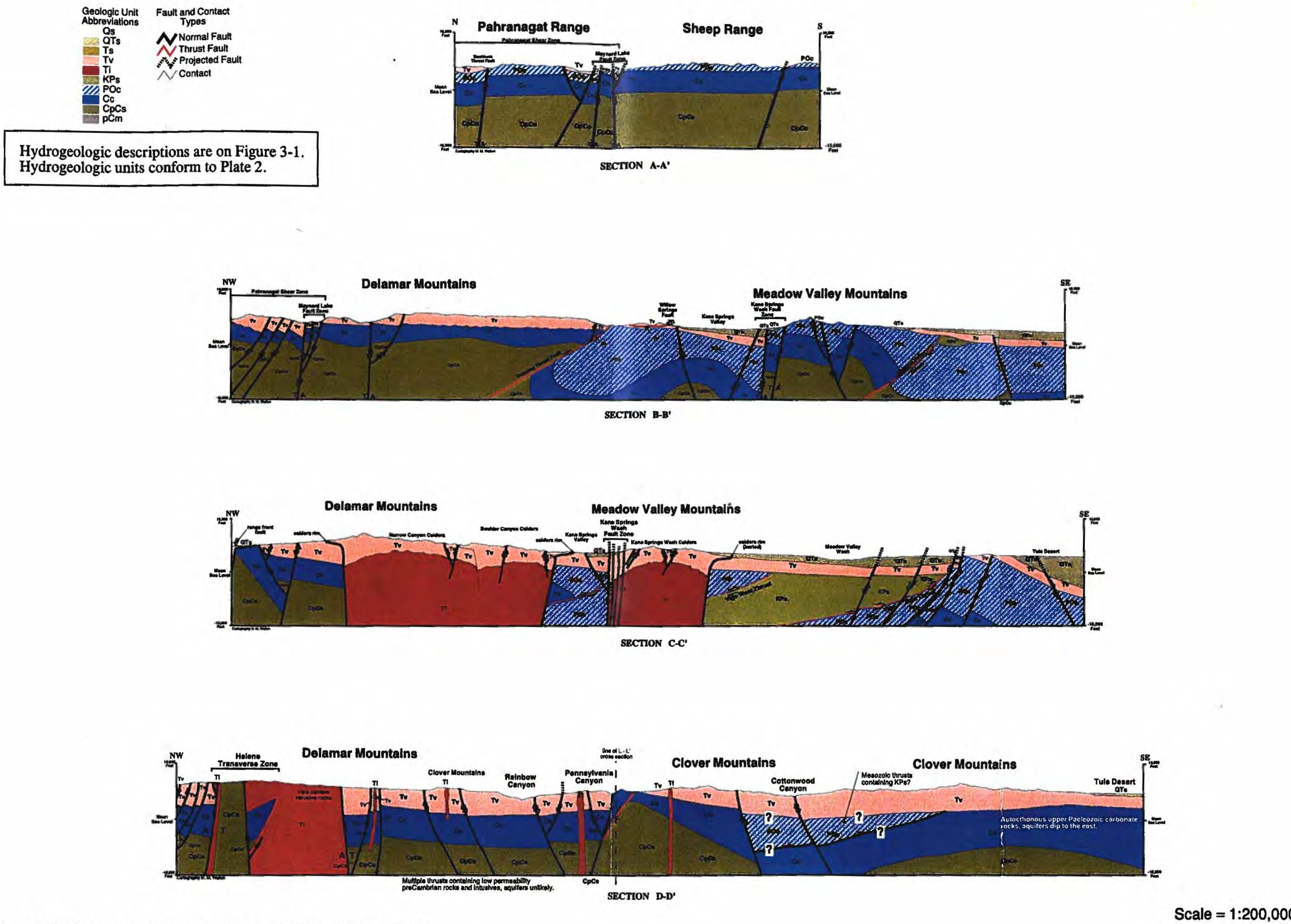

Figure 3-2. Hydrogeologic cross sections A-A', B-B', C-C', and D-D'.

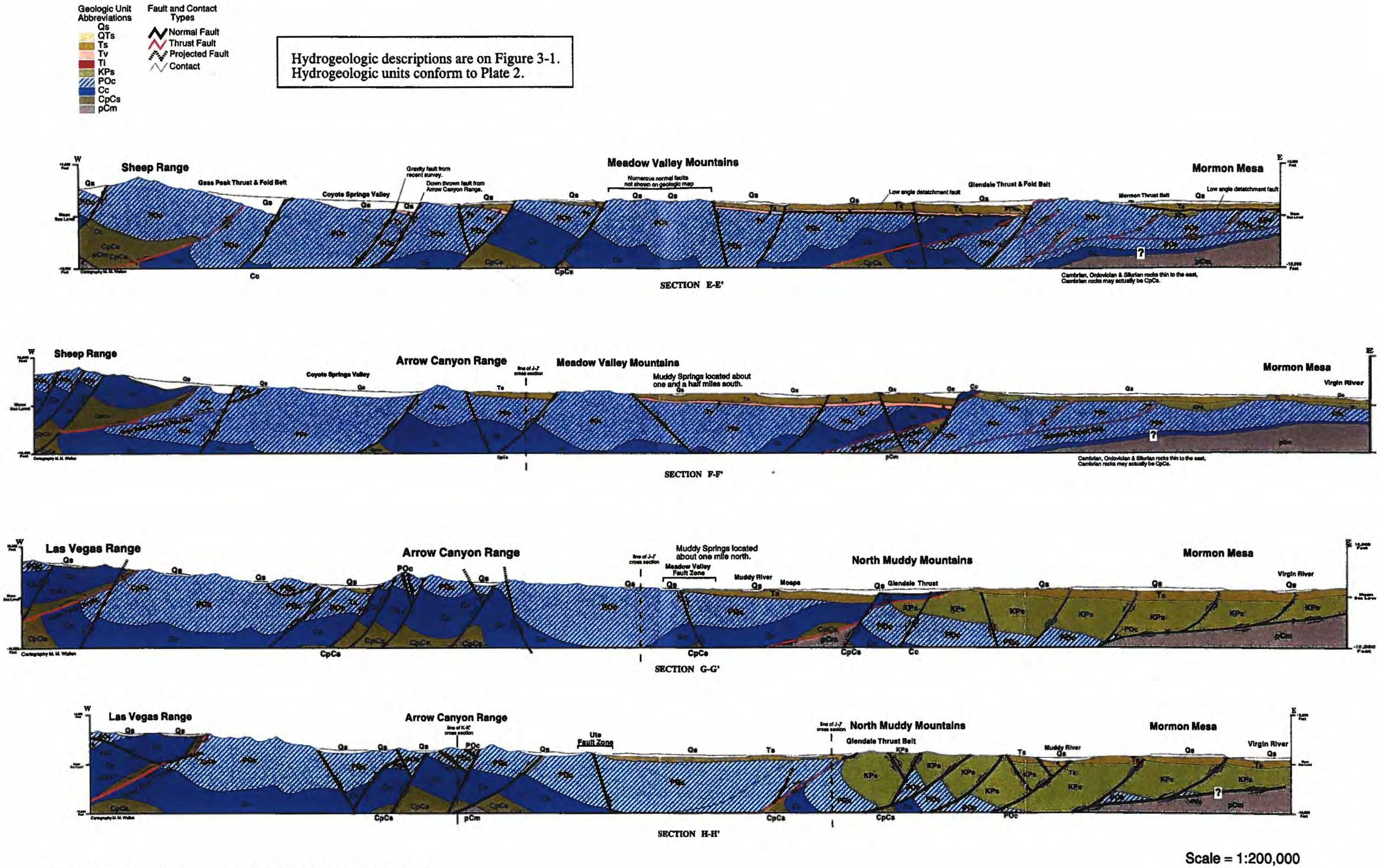

Figure 3-3. Hydrogeologic cross sections E-E', F-F', G-G' and H-H'.

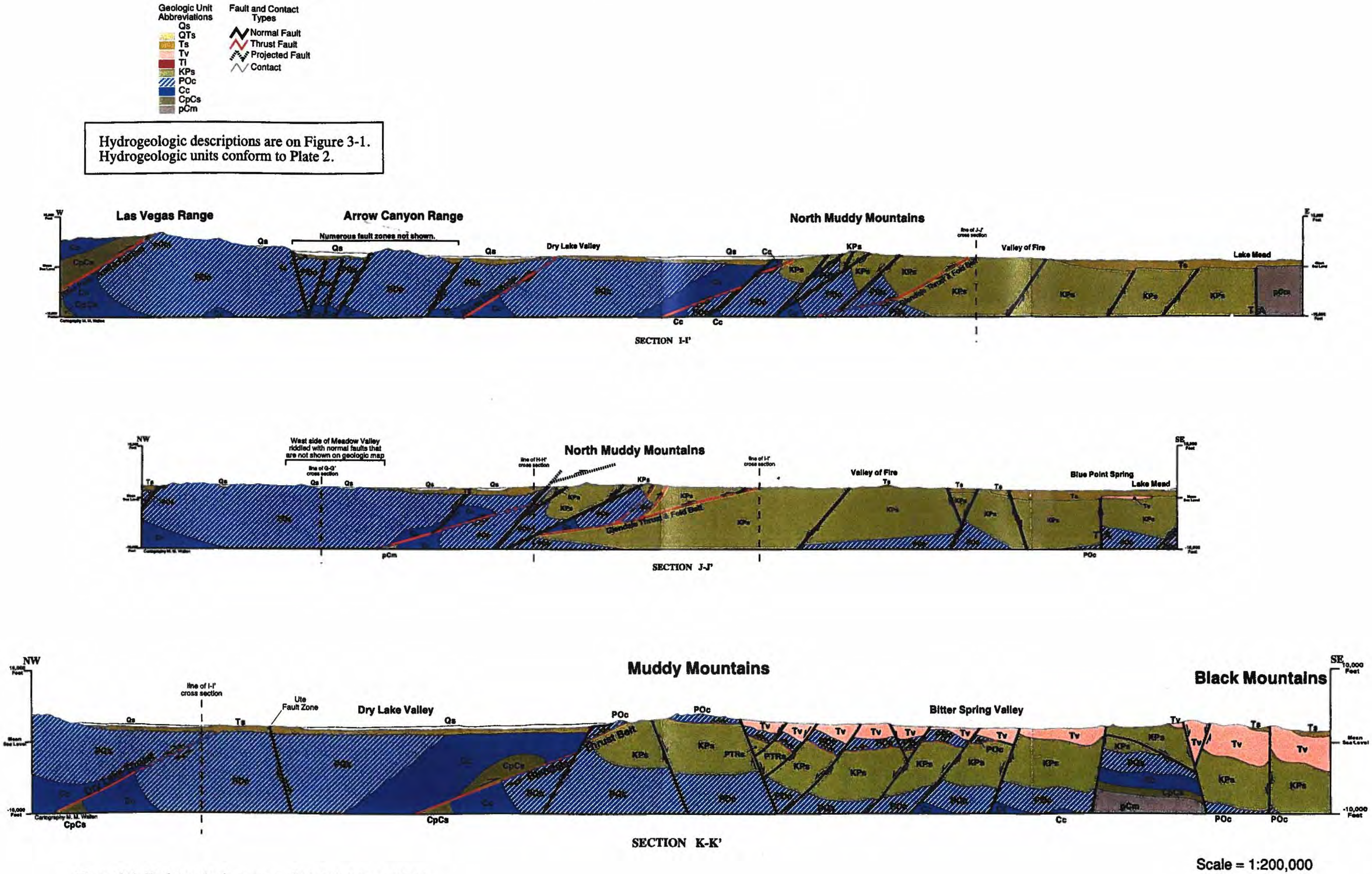

Figure 3-4. Hydrogeologic cross sections I-I', J-J, and K-K'.

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(northeast) fracture. More than likely, this younger northeast-striking fracture followed older northeast-striking oblique faults of the middle Cenozoic episode. The normal and left-lateral faults of the basin-range episode in most places obscure the faults and fractures of the middle Cenozoic episode. The basin-range episode formed some time after about 12 million years ago and continues today, as evidenced by young north-striking faults that cut Quaternary basin-fill sediments in many parts of the study area. In places, basin-range faults were synchronous with sparse rhyolite tuffs and basalt lava flows in the study area. Because these basin-range faults, and the parallel fractures (joints) formed by them, are recent, they can remain open as conduits for ground water.

One other structural type, which is synchronous with the faulting and volcanism of both the middle and late Cenozoic episodes, consists of zones of major east-striking faults, fractures, dikes, folds, and eruptive centers known as transverse zones. Two of these zones cut through north of the model area and probably impact ground-water flow to unknown extent. These are the Timpahute and the Helene transverse zones, which respectively bound the northern side and southern side of the Caliente caldera complex (Ekren and others, 1976, 1977; Rowley, 1998; Rowley and others, 1998). In other words, the Timpahute zone passes through the north of Caliente, whereas the Helene passes through the ghost mining towns of Delamar and Helene.

3.2 STRUCTURAL SETTING

3.2.1 Western Clover Mountains and Northern Delamar Range

Rainbow Canyon separates the western Clover Mountains on the east from the western Delamar Range on the west (geologic cross section B-B', C-C', and D-D').

The southern Panaca basin, and Caliente area have been geologically mapped, first at 1:250,000 scale (Ekren and others, 1977) and later at 1:24,000 scale (Rowley and Shroba, 1991; Rowley and others, 1992, 1994). Between Panaca Basin and the area of the railroad siding of Boyd, in central Rainbow Canyon, Meadow Valley Wash cuts through the Caliente caldera complex, one of the largest caldera complexes in the conterminous U.S. The caldera extends about 50 miles east-west and about 21 miles north-south and it underlies an area from Delamar Valley on the west, through the highest parts of the northern Delamar Range (7800 ft) and Clover Mountains (7500 ft), to the western Bull Valley Mountains of Utah on the east. The age of the Caldera Complex ranges from at least 23 to 13 million years (Nealey and others, 1995; Rowley and others, 1995; Unruh and others, 1995; Snee and Rowley, 2000; Rowley and others, in press). It consists of intracaldera rhyolite ash-flow tuff and local rhyolite volcanic domes that are several kilometers thick. The northern and southern sides of this east-elongated caldera complex are controlled by east-striking transverse zones: the Timpahute on the north and the Helene on the south (Ekren and others, 1976, 1977; Rowley and others, 1995, in press; Scott and others, 1996).

The faults bounding and within the Panaca basin are abundant and consist entirely of basin-range normal faults that strike northerly (Rowley and Shroba, 1991; Rowley and others, 1994). Many of these faults appear to pass across the east-striking faults of the Timpahute transverse zone. Within the caldera complex, northwest-striking oblique-slip faults of the middle Cenozoic tectonic episode are abundant and long (Ekren and others, 1977; Rowley and Shroba, 1991; Rowley and others, 1992, 1994; P.D. Rowley, unpub. mapping, 1995). Younger less common, north-striking basin-range faults, also continue southward. Although the Helene transverse zone may form a local barrier to southward flow of ground water through the caldera complex, the abundant north- to northwest-striking faults cutting through this transverse zone probably act as conduits for ground-water flow through the barrier.

South of the caldera complex and the stratovolcanoes and intrusions that mark the southern side of the complex (Helene transverse zone), the volcanic rocks consist of much thinner outflow ash-flow tuffs and intermediate-composition lava flows. These volcanic rocks unconformably overlie apparently east-dipping, thick Proterozoic to lower Cambrian quartzite (Sterling Quartzite, Wood Canyon Formation, Zabriskie Quartzite) and thick lower Cambrian carbonates (Highland Peak Formation). Although heavily faulted and fractured, the quartzite is likely an aquitard, whereas the Paleozoic carbonate rocks are aquifers. Here, at the latitude of the southern part of Rainbow Canyon (the southern end is just south of Elgin), the older northwest-striking oblique slip faults and presumably younger (basin-range) north-striking faults continue to dominate the structural pattern (Ekren and others, 1977). The same pattern is seen east of Rainbow Canyon, in the Clover Mountains, including the small Pennsylvania gold district. And at Delamar, a major gold mining district, controlled by east-striking faults, dikes, and eruptive centers of the Helene transverse zone, northwest-striking oblique-slip faults and north-striking normal faults likewise are common (Rowley, unpub. mapping, 1995). But increasingly, farther southward, north-northwest-striking faults pass into north-striking faults; strike-slip movement decreases southward and normal faults become dominant. This is especially apparent along the western margin of the Delamar Range, which trends northward and is formed by the Delamar Valley basin-range fault zone (Scott and others, 1995a) that uplifts the range with respect to Delamar Valley at and north of the latitude of Elgin. The Delamar Valley fault zone has significant Quaternary normal displacement on it.

3.2.2 Southern Delamar Range

South of the latitude of Elgin, the southern Delamar Range trends northeast and is cut by many north- and northeast-striking faults (geologic cross section C-C'). The western range front fault, however, trends northeast and is defined by one strand (Maynard Lake fault zone) of the northeast-striking Pahranagat shear zone (Ekren and others, 1977). To the northeast, this strand passes into the north-striking Delamar Valley fault zone. Elsewhere, all southwest and northeast ends of strands of the shear zone pass into major north-striking normal faults of the basin-range episode (Ekren and others, 1977; Scott and others, 1990a, b, 1993, 1995a; Swadley and Scott, 1990). The shear zone thus is a transfer fault zone that formed, like the basin-range faults, in an environment of east-west extension and transferred displacement to the northeast (Ekren and others, 1976, 1977; Scott and others, 1995a, 1996; Rowley, 1998).

Farther to the south in the Delamar Range, the 17-12-Ma Kane Springs Wash caldera complex (geologic cross section C-C') (Harding and others, 1995; Scott and others, 1995a, b, 1996) underlies an area about 18 miles by 15 miles in the southern Delamar Range, and extending eastward into part of the Meadow Valley Mountains. As with the Caliente caldera complex, intracaldera tuffs of at least several kilometers thickness were deposited in the calderas, and intracaldera intrusions have been emplaced into these tuffs, although they are exposed only locally. The caldera complex is likely a barrier to southward flow of ground water in the Delamar Range, but in Kane Springs Valley it is cut and offset left-laterally about 3 miles by the north-northeast-striking oblique-slip (left lateral and down-to-the-west normal) Kane Springs Valley fault zone. This major fault zone underlies the north-northeast-trending Kane Springs Valley and uplifts the Meadow Valley Mountains on the east with respect to the Valley. The Kane Springs Wash caldera complex and adjacent parts of the southern Delamar Range have been mapped in detail by Scott and others (1990a, b, c, 1991, 1993), Swadley and Scott (1990), and Swadley and others (1994). South of the caldera complex, north-striking faults characterize the southern end of the Delamar Range and probably provide ground-water pathways from southern Delamar Valley into Kane Springs Valley. this isn't shown on figure 0-1

3.2.3 Kane Springs Valley and Meadow Valley Mountains

The northern Meadow Valley Mountains are separated from the southern Clover Mountains by a deep canyon cut by Meadow Valley Wash (geologic cross section C-C'). From there, the mostly low altitude Meadow Valley Mountains extend southwest to just past the Lincoln County line into Clark County. The northern part of the range consists, except for the faulted eastern lobe of the Kane Springs Wash caldera complex (Harding and others, 1995), of mostly outflow ash-flow tuffs that are as much as 2 km thick (Pampeyan, 1993). These volcanic rocks, as well as underlying Tertiary sedimentary rocks less than 300 ft thick, thin southward and pinches out north of the southern end of the range. Pre-Cenozoic sedimentary rocks, which unconformably underlie the Cenozoic rocks, are exposed in the central to southern part of the range (Pampeyan, 1993; Page and Pampeyan, 1996). Pampeyan (1993) showed these pre-Cenozoic rocks occupying several north-striking, east-verging Sevier thrust sheets. In one of these thrust sheets, exposed in the central part of the range, the youngest of the pre-Cenozoic rocks are the Triassic Moenkopi and Chinle Formations. These formations include a thick, Lower Permian redbed sequence and, where not removed by Triassic erosion, thin eroded parts of the Lower Permian Kaibab Limestone and Toroweap Formation. These fine-grained clastic rocks are about one mile thick and likely represent an aquitard. In the other thrust sheets, the rocks are about 2 miles thick ad dominated by carbonates of Ordovician to late Permian age. They are underlain by Cambrian rocks that are exposed to a thickness of about a half mile thick and also are dominated by carbonates. Both of these carbonate packages are important aquifers in Nevada and are, in turn, underlain by the thick Cambrian to Proterozoic quartzite (aquitard) section.

Northeast-trending Kane Springs Valley bounds the Meadow Valley Mountains on the west. The basin-fill sediments in the valley consist mostly of Quaternary deposits that overlie deposits at least as old as latest Miocene or early Pliocene (Scott and others, 1991; Pampeyan, 1993; Swadley and others, 1994). The Meadow Valley Mountains were uplifted relative to Kane Springs Valley by the major oblique Kane Springs Valley fault zone (Scott and others, 1991, 1995a; Pampeyan, 1993; Swadley and others, 1994). Despite its oblique motion, most if not all of the motion along the fault zone is considered part of the basin-range extensional episode. Some of that offset is Quaternary, and recent mapping by G.L. Dixon (unpublished) indicates that, like the major oblique-slip Pahranagat shear zone, at least the southern end of the Kane

Spring Valley fault zone passes southward into a north-striking basin-range fault. The western edge of the southern end of the Meadow Valley Mountains, changes trend southward from northeast to north, and the basin-range fault that causes this north-trending range front continues due south to define the western edge of the Arrow Canyon Range as well (Page and Pampeyan, 1996). The northeastern end of the Kane Springs Valley fault zone, which passes northeastward across Meadow Valley Wash into the southern Clover Mountains, is less apparent from the topography and has not yet been mapped completely. But mapping by Scott and Rowley (unpub. mapping, 1995) suggests that it also changes strike direction, from northeast to north and northwest. Thus the Kane Springs Valley fault zone is another transfer fault, like the Pahranagat shear zone.

Because the structure of the generally narrow Meadow Valley Mountains is dominated by the Kane Springs Valley fault zone, faults in the range likewise strike northeast (Scott and others, 1991, 1995a; Pampeyan, 1993; Swadley and others, 1994). Farther south, as the range widens and, at its southern end where it bends south, most faults strike north and normal slips dominate (Pampeyan, 1993; Page and Pampeyan, 1996). Large fractures filled with veins of coarsely crystalline calcite represent orifices of ancient spring discharge are well exposed in the Wildcat Wash area of the southern Meadow Valley Mountains, north of Nevada Highway 168 (Page and Pampeyan, 1996).

3.2.4 Lower Meadow Valley Wash

The basin referred to as the Glendale basin by Schmidt (1994), that is occupied by lower Meadow Valley Wash, is broad and contains a thick sequence of basin-fill clastic sediments (geologic cross sections E-E' and F-F'). A small part of the basin has been geologically mapped in reconnaissance or detail. The youngest part of the basin-fill sequence is made up of unconsolidated Quaternary sediments. These are underlain by clastic sedimentary deposits that Pampeyan (1993) lumped together as the Pliocene (?) and Miocene Muddy Creek Formation. The northern most area where detailed investigation of the basin – fill sediments has been undertaken in the Farrier quadrangle (Schmidt, 1994), along the Lincoln-Clark County line. The oldest deposits of the basin-fill sequence here belong to the Horse Spring Formation, correlated with deposits of the same name studied in the Lake Mead area (Bohannon, 1984). In the Farrier area, it consists largely of conglomerate considered by Schmidt (1994) to range from 20 to 12 Ma and to represent syn-extensional deposition during opening and deepening of the basin during the basin-range episode. The Horse Spring is overlain by the Muddy Creek Formation, considered by Schmidt to range from 12 to 5 Ma. in age Schmidt (1994) proposed that the Muddy Creek here represents deposition of finer grained clastic and lacustrine sediments that largely postdate the main extensional development of the basin. In the Riverside area (lower Virgin Basin), about 12 miles to the east and outside the study area, Williams and others (1997) mapped the Muddy Creek likewise as Miocene, however, continuing eastward to the Mesquite area, it is coarsely clastic (well exposed along U.S. Highway I-15) and thus clearly is not post-extensional. Some of the faults mapped in basin-fill deposits in the Farrier quadrangle strike north-northeast and north-northwest; these cut deposits as old as the Horse Spring, suggesting that they represent deformation of the pre-basin-range tectonic episode. More abundant basin-range faults that strike north cut deposits as young as Quaternary. Schmidt (1994) concluded that the Muddy

Creek Formation is the youngest unit representing closed-basin deposition and that, at least in the Glendale basin (Lower Meadow Valley Wash), integration began at about the end of the Miocene or beginning of the Pliocene. Pliocene sediments that Schmidt mapped are primarily alternating cut and fill stream sediments that contain abundant carbonate spring deposits, evidence of a wetter climate in the Pliocene.

In the Moapa and Glendale area to the south, at the southern end of the basin (geologic cross section E-E'), the stratigraphy of the basin-fill deposits is generally the same as that in the Farrier quadrangle, although an underlying limestone member of the Horse Spring Formation is also exposed (Schmidt and others, 1996). North-striking basin-range faults, some associated with Pliocene carbonate spring deposits, are abundant throughout the area.

3.2.5 Western Mormon Mountains

The Mormon Mountains are a high (about 7500 feet altitude) domal mountain range whose crest is on the eastern side of the Glendale basin and the study area (geologic cross section F-F'). To the north of the Mormon Mountains, a low, south-pointing prong of the Clover Mountains, and to the south of the Mormon Mountains, another south-trending ridge at the same longitude also mark the eastern edge of the Glendale basin (Lower Meadow Valley Wash) and the eastern edge of the model area. The Mormon Mountains are underlain by about 2,000 m of Cambrian through Pennsylvanian carbonate rocks. Cambrian and younger rocks were thrust eastward over Mississippian and Pennsylvanian rocks in the area of the range during Sevier deformation (Wernicke and others, 1985). The present form of the range has been suggested by Wernicke and others (1985) and Axen and others (1990) to result from a gently west-dipping Tertiary detachment fault that partly followed the Sevier thrusts and passed westward in the subsurface beneath the Meadow Valley Mountains. In places on the western side of the range, the low-angle normal fault rests on Proterozoic crystalline metamorphic and igneous rocks, and elsewhere at shallow depth below the Cambrian rocks, these basement rocks are exposed. During and after the suggested detachment, the deroofed footwall block to the east apparently arched upward, as a core complex, to form the present dome shape of the Mormon Mountains (Axen and others, 1990). Flat-lying Muddy Creek Formation in the Glendale basin unconformably overlies the low-angle normal fault.

Anderson and Barnhard (1993a, b) and Anderson and Bohannon (1993) criticized the detachment model for the Mormon Mountains and adjacent areas. They concluded that extension in the area was accompanied by major vertical structural uplift of the Mormon Mountains and adjacent ranges that produced structural thinning (attenuation) of the rocks on the crest of the uplifts. As mapped by Wernicke and others (1985), most normal faults at the surface in the Mormon Mountains are low angle but, based on tilts of strata in the hanging walls of these faults, Anderson and Barnhard (1993a, b) interpreted that the faults become steeper with depth, as in basement-cored uplifts in Wyoming and other parts of the Rocky Mountains. Such an interpretation seems more reasonable. But, regardless of the geologic model for the evolution of the Mormon Mountains, the Proterozoic basement rocks beneath the Mormon Mountains form an aquitard that blocks ground-water flow through the range. We interpret this large regional domal uplift not only to impede ground-water flow through the range, but also acts as a barrier to ground-water moving from the Tule Desert into the lower Meadow Valley Wash. Glancy and Van Denburgh (1969) indicated Tule Desert is part of the Lower Virgin River Valley, as did subsequent investigators (Brothers et al. (1992); and Dixon and Katzer (in review, 2001)).

Wernicke and others (1985) noted that, in the Mormon Mountains area, "No evidence was found for a younger episode of widely spaced high-angle normal faults ("Basin and Range" faulting)." Yet the youthful age of the Mormon Mountains suggests to us that this is an example of the basin-range episode of faulting, which here was expressed as low-angle normal faults at the surface, rather than as high-angle normal faults. The south-trending ridge of the Clover Mountains just north of the Mormon Mountains is underlain by east-dipping Tertiary volcanic rocks (Ekren and others, 1977) bounded by a high-angle basin-range fault on its western side. Similarly, the south-trending ridge south of the Mormon Mountains is bounded by a high-angle basin-range fault along its western side. This latter fault, in fact, abruptly changes its northern strike at the northern end of the ridge, just south of the Mormon Mountains, and strikes east-northeast, where its motion is oblique left lateral (G.L. Dixon, unpub. data, 2000). Then, east of the study area, the fault abruptly turns northward and bounds the western side (Carp road fault and Sam's camp fault of Axen and others, 1990) of the East Mormon Mountains, a low north-trending range east of the Mormon Mountains that was mapped by Axen and others (1990), Anderson and Barnhard (1993a, b), and Anderson and Bohannon (1993). This left-lateral part of the fault, like the Pahranagat shear zone and the Kane Springs Valley fault zone, represents another example of a transfer fault that passes into north-striking normal faults at both of its ends (G.L. Dixon, unpub. mapping, 2000).

3.2.6 Sheep Range, Las Vegas Range, and Elbow Range

The Sheep Range is an abrupt (almost 10,000 ft high in the wider southern part of the range; 7500 ft high in the narrow northern part), north-trending range that bounds the southwestern side of the study area. Its rocks are mainly Cambrian through Devonian carbonate sedimentary rocks that dip generally eastward (Guth, 1980) (geologic cross sections G-G', H-H', and I-I'). The main basin-range fault that creates the range is on its western side, but the eastern side also is uplifted along a north-striking normal fault; thus the range is a large horst block. Within the range, minor north-striking faults dominate, but some cross-faults that strike east to east-northeast also have been mapped. The northern end of the main Sheep Range is terminated against the southern strand (Maynard Lake fault zone) of the east-northeast-striking left-lateral oblique-slip Pahranagat shear zone (Jayko, 1990) (geologic cross section A-A'). We interpret that the western part of this strand of the shear zone joins the main normal fault and defines the western side of the main Sheep Range. Under this interpretation, the Maynard Lake zone is a transfer fault that transfers east-west pulling apart into left lateral shear. In other words, where faults strike north, all east-west extension is taken up by normal movement down the dip of the fault plane; where faults strike northeast, east-west pulling apart is taken up partly by left slip and partly by normal slip, in other words oblique movement.

A small north-trending range, whose northern end also terminates against the Maynard Lake fault zone, lies just to the east of the northern end of the main Sheep Range. This lessor range is also called the Sheep Range, but it forms a separate basin-range tilt block that consists largely of east-dipping volcanic rocks (Jayko, 1990). These rocks rest unconformably on Pennsylvanian and Permian carbonate rocks making up what Jayko (1990) calls the Coyote Spring syncline. Numerous north-striking normal faults that uplifted this tilt block occur on its western side. Minor north-striking faults occur within the smaller range. All these faults, which terminate against the Maynard Lake fault zone, are interpreted to pass into the Maynard Lake transfer zone and likewise transfer the slip northward from normal slip to oblique slip. In addition to these north-striking normal faults, Jayko (1990) projects the buried north-striking trace of the Gass Peak thrust fault (Sevier age) beneath the normal faults. The valley between the northern end of the main Sheep Range and the tilt block to the east is the northern part of Coyote Spring Valley.

East of the eastern tilt block of the northern Sheep Range is a valley occupied by U.S. Highway 93 and by Pahranagat Wash, which drains southward from Maynard Lake (dry) and other parts of Pahranagat Valley into northern Coyote Spring Valley. Basalt lava flows that issued from vents along the Maynard Lake fault zone are exposed along and beneath the wash as it drains southward. This valley, referred to as Evergreen Flat, continues southward and joins Coyote Spring Valley about 4 miles to the south. This gap is the boundary between the bedrock ridges of the northeastern Sheep Range to the west and the southwestern Delamar Range to the east. On the eastern side of Evergreen Flat, however, a north-striking basin-range fault zone several miles east of the gap uplifts the southwestern end of the Delamar Range. Here, Cambrian through Devonian carbonates overlain by volcanic rocks are uplifted and tilted to the east.

The western side of the model area is the crest of the Sheep Range and at the southern end of the Sheep Range, the boundary runs eastward along a series of hills making up the broad southeastern part of the range. From there the boundary swings south, then east across the southern Las Vegas Range, a low north-trending basin-range east of the southern Sheep Range. The boundary of the model area continues east to just south of Apex in Garnet Valley. The Las Vegas Range northwest of Apex is defined by the Gass Peak thrust, which transports rocks as old as the Cambrian Wood Canyon Formation over Mississippian, Pennsylvanian, and Permian carbonates of the thick Bird Spring Formation (Maldonado and Schmidt, 1991) (geologic cross section F-F'). Most of the Las Vegas Range is made up of folded Bird Spring limestones and minor dolomites, with the Gass Peak thrust striking north along its western side and continuing beneath Quaternary deposits east of the main part of the Sheep Range (Maldonado and Schmidt, 1991; Page, 1998). The small Elbow Range, which bounds the Las Vegas Range on the northeast, is made up of thrusted and folded Bird Spring Formation (Page and Pampeyan, 1996). The folds and faults in the range strike north and may provide conduits for ground-water flow.

3.2.7 Coyote Spring Valley and the Arrow Canyon Range

The Arrow Canyon Range is a sharp, narrow north-trending basin range consisting of a syncline of Cambrian to Mississippian carbonates. It is uplifted along its western side by normal faults of the Arrow Canyon Range fault zone (Page and Pampeyan, 1996; Schmidt and Dixon, 1995; Page, 1998) (geologic cross section I-I'). The trace of the north-striking Dry Lake thrust, which carries Cambrian rocks over Silurian through Permian carbonates, is exposed and projected north just east of the Range (Schmidt and Dixon, 1995). East of the Dry Lake thrust, the Silurian through Permian rocks form a series of low unnamed, north-trending hills. These hills are controlled by north-striking normal faults, along some of which are Pleistocene carbonate spring-mound deposits that indicate that the faults formerly carried significant ground water (Schmidt and Dixon, 1995).

3.2.8 Northern Muddy Mountains, and Muddy Mountains, and Dry Lake Range

The southern end of the study area is defined by north-striking ridges of the North Muddy Mountains and, to the south, the northern and northwestern parts of the larger Muddy Mountains (Bohannon, 1983) (geologic cross sections H-H', I-I, and K-K'). The North Muddy Mountains separate the Glendale basin on the west from the Mesquite basin to the east. The Muddy Mountains occupy the northern side of Lake Mead. The southernmost part of the study area extends southwest to include the small Dry Lake Range east of Apex. This range is made up mostly of Bird Spring carbonates. A bedrock gap at Apex connects the Dry Lake Range with the southern Arrow Canyon Range/Las Vegas Range. This gap most probably was a pathway for Tertiary and Quaternary basin-fill sediments entering the Las Vegas Valley, just southwest of the study area. The gap also is along the trace of the Dry Lake Thrust (Page and Dixon, 1996) Basin-fill sediments to the northeast along the I-15 corridor (Glendale basin) thus are not connected with those in the Las Vegas Valley and, from limited mapping in the area, are not correlated with those in the Las Vegas Valley. In the Muddy Mountains and in the North Muddy Mountains, faults strike north-northeast (Bohannon, 1983), and the gap between the two ranges, now occupied by Tertiary and Quaternary basin-fill sediments, likely also is underlain by fractures of the same strike. The northern Muddy Mountains and North Muddy Mountains contain significant Jurassic sedimentary rocks (Bohannon, 1983), some of which (Aztec Formation) make up a prominent aquifer in southwestern Utah (where it is called the Navajo Sandstone), but here the sandstone has very low permeabilities and forms an aquitard, as do other Jurassic rocks in the area. The northwestern side of the North Muddy Mountains contains carbonates. Nonetheless, the Mesozoic sediments create a barrier to most southward flow that might pass through them into Lake Mead. An additional ground-water flow barrier is provided by east-striking faults of the northern Muddy Mountains, notably the northeast–verging Glendale thrust (Bohannon, 1983). Bohannon interpreted this structure as the northern continuation of the Keystone Thrust system which has been displaced approximately 40 miles right laterally by the Las Vegas Shear Zone. As with the Keystone/Glendale Thrust system, the Dry Lake Thrust (thrust fault system just west of the Keystone/Glendale thrust) has been displaced 40 miles by the same shear zone and its southern equivalent is the Deer Creek Thrust in the Spring Mountains.

The southeastern part of the study area, where the Muddy and Virgin Rivers enter the Overton Arm of Lake Mead, is probably an area of ground-water discharge. Basin-fill sediments, dominated at the surface by resistant Quaternary calcretes also underlie Mormon Mesa and its northward extension. This prominent calcrete is underlain by Pliocene to upper Miocene basin-fill deposits that underlie the southwestern end of the Mesquite basin The Black Mountains and Gold Butte areas form the eastern margin of the study area in a series of complex Proterozoic metamorphic rocks which extends from the southwestern Virgin Mountains south to the southern edge of Lake Mead. Numerous fault zones have been mapped in this area including faults that are discharge points of Rogers and Blue Point springs in the Lake Mead National Recreation

Area. These faults most likely are related to a series of faults that strike to the northeast, have oblique dip-slip motion, and are part of the Lake Mead Fault Zone (Anderson and Barnhard, 1993a).

4 GROUND-WATER FLOW SYSTEM

The ground-water flow system for the Colorado River basins **(Figure 1-1)** in the study area covers an extensive area of about 12,084 mi^2 and is roughly a north-south zone marked by major mountain blocks. From north to south the western boundary is: Maverick Springs Range, the White Pine Range, the Grant and Quinn Canyon Ranges, the Pahranagat Range, and the Sheep Range. The eastern boundary is the mountain blocks of: Butte Mountains, Egan Range, Wilson Creek Range, Clover Mountains, and the Mormon Mountains. This is a very large part of the carbonate rock province of eastern Nevada described by numerous investigators, most recently Dettinger et al. (1995), Prudic et al. (1995), Thomas et al. (1996), and Plume (1996). The hydrologic properties have a great deal of similarity throughout this area, however, the hydrologic connectivity is not known exactly. It is for certain though that ground-water flow begins at the higher altitudes in the northern edge of the province and moves to the south gaining in flow volume as recharge from the various mountain blocks enters the ground-water system in the carbonate rocks. Undoubtedly the carbonates discharge some water to the overlying alluvial aquifer systems.

Part of the ground water in the White River Flow System discharges into the Muddy River ground- and surface-water system (Muddy Springs) with the remainder discharging through the carbonate rocks underlying Hidden and Garnet Valleys, and California Wash. A minor amount of this flow in California Wash probably flows to the Black Mountain Area discharging at Roger and Blue Point Springs. The remainder of the ground-water flow discharges into the Muddy River system and from great depth in the carbonate rocks discharges either into the Virgin and Colorado Rivers or further to the south at undefined locations.

The Meadow Valley Flow System, both surface- and ground-water, is also tributary to the Muddy River and Lower Moapa Valley and like the White River system discharges from great depth through the carbonate rocks underlying Lake Mead and the Colorado River.

The individual valleys in the two flow systems are generally connected by surface drainage, such as White River and Meadow Valley Wash, and in some valleys, ground-water flow in the alluvial aquifer systems such as between Dry Lake and Delamar Valley and between several of the Valleys in the Meadow Valley Flow System. However, it is at varying depths in the underlying carbonate rocks that there is a complete hydrologic connection. It is also this part of the flow system that is the most difficult to define. There are water-level maps such as by Rush (1974) and Harrill and Prudic (1998), Thomas et. al. (1986), based on sparse data, that show the general direction of ground-water flow in the carbonate rocks, but the data points are generally in the valley lowlands and virtually nothing is known about the mountain blocks. There may be ground-water mounding in some blocks that act as barriers or partial barriers to flow from one block to another. There are also differences in permeability between the various carbonate rocks that create preferred directions of flow. High permeable zones within the carbonate rocks are probably caused by mineral dissolution in the rock and fractures caused by faults. Volcanic rocks are less permeable than carbonate rocks, but where fractured are able to readily transmit ground water. There are low-permeability rocks within the study area that act as a barrier to ground-water flow such as clastic sedimentary rocks and crystalline basement and granitic rocks.

4.1 GROUND-WATER SOURCE

All ground water, regardless of where it is starts out as surface water, is from precipitation in the form of rain and snow on the mountain blocks, which are the main recharge areas. Water that has evaporated from principally the Pacific Ocean moves inland as atmospheric water, condenses and falls as rain and snow upon the mountain blocks. Undoubtedly summer storms provide significant amounts of moisture, but it is winter storms that are the most important for water resources because the effect of summer storms at higher altitudes is minimal. Storm tracts are eastward and northeastward from the South Pacific Ocean and the Gulf of California, and in the more northern basins the tracks are more to the southeast from the northern Pacific Ocean.

Once water falls on the ground some of it evaporates immediately and returns to the atmosphere (sublimation takes its toll from snow packs), some of it runs off into stream channels where it may infiltrate to the water table as the streams transect alluvial fans. Most of the water infiltrates the shallow soil mantle overlying the bedrock and is used by the plant life and returns to the atmosphere by way of transpiration. That amount of water that is excess to the plant's needs and exceeds the moisture holding content of the soil infiltrates through the soil mantle into the underlying bedrock. Ultimately the water reaches the water table and becomes part of the ground-water system. Over large parts of many of the mountain blocks the soil cover is thin to non-existent and the water infiltrates directly into the bedrock. Ground-water recharge is generally greater and mountain front runoff is less in carbonate rocks compared to volcanic rocks.

4.2 PRECIPITATION

Precipitation in Nevada is strongly controlled by orographic effect because there is a definite increase of precipitation with altitude. Most researchers also assume the natural recharge efficiency (the percent of precipitation that becomes ground water recharge) increases with altitude and this increase is proportional to the precipitation. This results in an interpretation that the surrounding mountain ranges of any valley are the most important areas for analyzing climate and natural recharge.

The orographic effect in eastern Nevada although distinct is relatively minor compared to the Sierra Nevada or other major ranges of the Pacific Coast. Those ranges are transverse to the paths of storms and large rain shadows are located downwind of the ranges. West central Nevada is in the rain shadow of the central Sierra Nevada. Eastern Nevada commonly receives precipitation from Pacific Winter storms moving around the south end of the Sierra then north northeastward across eastern Nevada. The larger ranges in eastern Nevada are usually northeasterly (Grant, Quinn Canyon, Clover) subparallel with storm tracks and the windward (wetter) may be on the eastern rather than western side of these ranges.

Microclimates or local altitude-precipitation relationships are probably quite common but the details of most of them are unknown because of the low density of precipitation gages. The low density of gages in Nevada is partially related to the low density of population and the gages that exist with records of sufficient length are concentrated near population centers, in the valley lowlands. Like most natural systems, precipitation, is time dependent in addition to being a spatial phenomenon, and a distinction is usually made between weather (daily to yearly variations) and climate (10's to 1000's of years). Climate is of primary interest to ground-water hydrology, but both weather and climate are of interest to surface-water hydrologists. Long-term precipitation records become climatic data once sufficient data is collected to minimize the effects of yearly variations. Climatologists usually assume thirty years of record is required to minimize the yearly variation, however, some data is always better than none.

4.2.1 Existing Precipitation Estimates and Maps in the Study Area

Bixby and Hardman (1928, p. 8-9) documented the first estimate of orographic effects (local altitude-precipitation relationships) in Clark County. In the same report, they mentioned, but did not formally reference, two previous reports where the precipitation increase with altitude was estimated. L. H. Taylor in the Truckee River Basin, estimated an increase of 12.8 inches per 1,000 feet of altitude rise in the Sierra Nevada. The other report by W. O. Clark and C. W. Riddell estimated an increase of 4.5 inches per 1,000 feet of altitude rise in Steptoe Valley. Bixby and Hardman (1928) assumed this altitude precipitation relationship applied over most of central and eastern Nevada including Clark County and most of the orographic effect occurs between 6,000 and 9,000 feet of altitude. They also assumed that 8 inches of precipitation occurs approximately at 6,000 feet of altitude and there is minimal orographic effect below 6,000 feet and above 9,000 feet of altitude.

These same estimates and assumptions are well embedded in the literature. Hardman's first state-wide precipitation map was created in 1936 (Hardman, 1936) this map was published in 1949 (Hardman and Mason, 1949, p. 10), and was revised in, July 1965 (Hardman, 1965). The 1965 map was used to create the Nevada Division of Water Resources precipitation map (NDWR, 1971) published in the State Water Plan of 1972 (Bruce Scott, formerly with NDWR, personal communication, 2000). Both of the Hardman (1936, 1965) maps were not widely disseminated and are very difficult to obtain. Notes on both the 1965 map and in Hardman and Mason indicate this map, (Hardman and Mason, 1949, p. 10), is an exact reproduction of the 1936 Hardman map.

Hardman 1936 1949 1965 SWP 1972

Both versions of Hardman's map have contour intervals of 5, 8, 12, 15, and 20. The 8-inch contour is usually close to 6,000 feet in eastern Nevada, at higher altitude in west-central Nevada, probably due the Sierra rainshadow effect, and at lower altitude in eastern and southern Clark County due to monsoonal storms. The NDWR 1971 precipitation map has slightly different intervals (uniform 4-inch intervals between 4 and 20).

Basin reports published by NDWR and USGS used the Hardman (1936, 1965) precipitation maps because no other source was available. Earlier reports reference either the 1936 map or Hardman and Mason, and later reports reference the 1965 map. The similarity between the Hardman maps (1936, 1965) and the Maxey-Eakin (Maxey and Eakin, 1949, p. 40) methodology extends to the choice of contour intervals (8, 12, 15, and 20) but as summarized by Eakin in 1966 (p. 260 - 262), and in several other reports, precipitation was generally estimated from altitude intervals of the 1:250,000 scale maps rather than directly from the Hardman maps. Avon and Durbin (1992, p.12) reported that USGS investigators deviated from the "standard" Maxey-Eakin technique about 37 percent of the time, for various reasons.

37% deviation from Maxey-Eakin

Precipitation maps, for Nevada and the rest of the United States, have been created since the early 1990s using a climatic model called the Parameter-elevation Regressions on Independent Slopes Model (PRISM) by Daly and others (1994) of the Oregon Climatic Service. As the name implies PRISM is a model or process and the maps of precipitation and other climatic variables are revised fairly often. These maps have been widely distributed through the Internet since the late 1990s. Their widespread use is related, in part, to availability, cost (free), and the format of the maps. The maps can be downloaded and directly imported into the "ARC" geographic information system (GIS) software of Environmental Systems Research Institute (ESRI), the most commonly used GIS software.

PRISM is specifically designed for use in mountainous terrain but uses the thirty year 1961-1990 climatic mean data. This means the data set in Nevada at high altitude was quite limited, because the USGS high altitude bulk precipitation gages were not installed until the mid 1980's. Long-term precipitation records in Nevada are generally uncommon and it appears never have been collected in some valleys. The May, 1997 version of the PRISM precipitation map was used in conjunction with an evapotranspiration and basin budget study by Nichols (2000, a, b, c) in east-central Nevada.

4.2.2 Differences between This and Other Estimates of Precipitation

Precipitation in this study was estimated using a modified Maxey-Eakin technique pioneered by Donovan and Katzer (2000) in Las Vegas Valley. The total estimate of precipitation for the study area (~ 6,636,000 acre-feet per year) by the modified Maxey-Eakin technique pioneered by Donovan and Katzer (2000) in Las Vegas Valley is significantly larger than the NDWR 1971 map (~ 5,516,000 acre-feet per year) but smaller than the May 1997 version of PRISM (~ 6,985,000 acre-feet per year). The maps vary in detail but the primary difference in interpretation between the older and more recent precipitation distributions is the amount of precipitation between 4,000 and 7,000 feet. This altitude interval contains 67 percent (2/3) of the total area and is composed of 12 percent between 4,000 and 5,000 feet, 30 percent between 5,000 and 6,000 feet and 25 percent between 6,000 and 7,000 feet.

On the NDWR 1971 and the Hardman (1936, 1965) precipitation maps significant parts of Long and Jakes Valleys, above 6,000 feet, are characterized as receiving less than 8 inches of precipitation but in general the 8-inch precipitation contour occurs close to 6,000 feet of altitude. Alternatively, on the PRISM precipitation map all of the study area above 4,000 feet is interpreted as receiving greater than 8 inches of precipitation.

Also large blocks (millions of acres) were assumed to have similar altitude-precipitation relationships. In the USGS and NDWR basin reports 19 out of the 27 valleys studied for this report were assumed to have the same ("standard" Maxey-Eakin) altitude-precipitation relationship summarized in Eakin (1966, p 260-262). Of the other eight, five have another relationship that is significantly "wetter" although the increase with altitude was the same, one is similar to the "standard" although slightly "dryer" and two are unreported.

4.2.3 Available Precipitation Data

The precipitation data used for this study are color coded by agency on **Figure 4-1**. The precipitation data for this analysis were selected for both quality of record and spatial distribution. The precipitation data in this analysis came from three sources, Desert Research Institute's Western Regional Climate Center (WRCC), Nevada Department of Conservation and Natural Resources, Division of Water Resources (NDWR), and the U.S. Geological Survey's (USGS) High Altitude Precipitation Network. The precipitation data used for this study are listed in **Table 4-1**.

The WRCC data were accessed through their website (http://www.wrcc.dri.edu) and includes historical (climatological) data for the National Oceanic and Atmospheric Admisistration's National Weather Service precipitation sites. These are daily low altitude gages with generally long periods of record. One issue associated with these sites are missed daily readings. These missed readings have a very high probability of occurring on days when precipitation actually occurred as the record commonly indicates either the station keeper could not access the gage (due to bad weather) or a mechanical failure became apparent to the station keeper because the gage did not record known precipitation. Because these missed readings have a high probability of occurring on a days when precipitation actually occurred, and precipitation is a rare event, this can be very serious problem in short duration records and may significantly underestimate the station's "average precipitation". Therefore only station with low percentages (< 7 %) of "missed" days were used for this analysis.

The NDWR data are from bulk precipitation gages measured annually and were installed in the mid 1950s and mid 1960s. At these gages, vandalism is the usual reason for "missing data". Because vandalism is a random event, not related to weather, these years of missing data may or may not bias the gage averages. The primary reason for under reporting of precipitation at these sites, if it occurs, would be related to insufficient gage size to contain very large snowfalls. This type of error would be difficult to detect or demonstrate.

The USGS High Altitude Precipitation Gage Network was established in the mid 1980's in support of the Carbonate Rock Study. The gages are measured semi-annually and are 12 feet in height, 1 foot in diameter and are designed to the Department of Agriculture, National Resources Conservation Service's (NRCS), Snowpack Telemetry (SnoTel) specifications. These gages are bulk precipitation gages, however, and not telemetered. Both the height of the gage and the periodicity of measurement are designed to minimize under reportage of precipitation. Vandalism and even forest fires have destroyed some of these gages and affected the records.

Over estimation of precipitation from gage data can also quite commonly occur, either because the data were collected in unrepresentative years or because of poor gage placement. The under estimates are "compensated" by the over estimates, however both can be serious problems and can significantly affect the representativeness of any particular gage record. The period of record

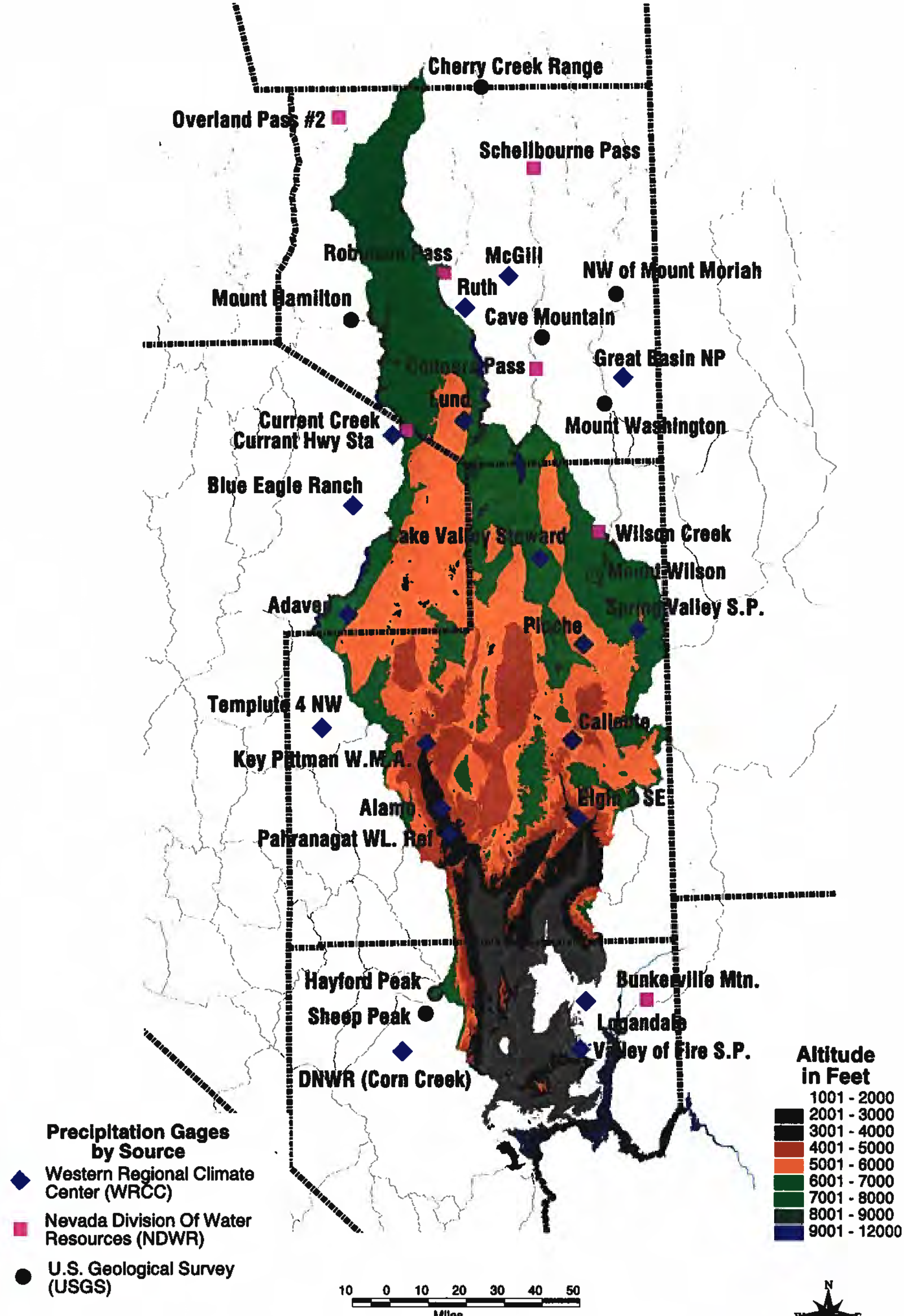

Figure 4-1. Altitude distribution in study area with precipitation gages.

Table 4-1. Precipitation data used in this analysis.

Site No.	Site Name	P[1]	Agency[2]	UTM[3]-X	UTM[3]-Y	Altitude	Years of Record		Average Annual Precipitation
				Meters	Meters	feet	start	last	Inches
	Group 1 ("Western" or "Dry")								
1	DNWR (Corn Creek)	D	WRCC	647,271	4,033,702	2,920	1948	1998	4.41
2	Bunkerville Mountain	A	NDWR	751,159	4,055,820	3,250	1967	1998	6.18
3	Pahranagat WL. Ref.	D	WRCC	666,997	4,125,914	3,400	1964	2000	6.40
4	Alamo	D	WRCC	663,824	4,136,951	3,600	1948	1962	4.88
5	Key Pittman W.M.A.	D	WRCC	657,394	4,164,575	3,950	1964	1989	7.94
6	Blue Eagle Ranch Hk	D	WRCC	626,385	4,265,782	4,780	1978	2000	9.38
7	Tempiute 4 NW	D	WRCC	613,161	4,171,251	4,890	1972	1985	7.87
8	Lund	D	WRCC	673,561	4,301,824	5,570	1957	2000	10.37
9	Currant Hwy Station	D	WRCC	643,286	4,295,668	6,240	1963	1977	10.59
10	McGill	D	WRCC	692,309	4,363,337	6,300	1914	2000	8.84
11	Great Basin Natl. Pk.	D	WRCC	741,040	4,320,255	6,830	1948	2000	13.11
12	Ruth	D	WRCC	673,940	4,349,949	6,840	1958	2000	12.17
13	Schellbourne Pass	A	NDWR	702,954	44089648	7,100	1954	1998	13.28
14	Conners Pass	A	NDWR	703,749	4,323,830	7,732	1954	1998	13.98
15	Robinson Pass	A	NDWR	665,000	4,364,560	7,800	1954	1998	12.70
16	Sheep Peak	S	USGS	656,987	4,049,883	9,600	1985	1999	16.95
17	Cherry Creek Range	S	USGS	680,671	4,443,452	9,700	1985	1999	14.74
18	Hayford Peak	S	USGS	660,932	4,058,248	9,840	1985	1999	16.52
	Group 2 ("Eastern or "Wet")								
19	Logandale	D	WRCC	725,069	4,055,097	1,410	1968	1992	5.14
20	Valley of Fire St. Pk.	D	WRCC	722,612	4,034,678	2,000	1972	2000	6.70
21	Elgin 3 SE	D	WRCC	721,539	4,132,729	3,300	1965	1985	14.07
22	Caliente	D	WRCC	719,183	4,165,980	4,440	1928	2000	9.06
23	Spring Valley St. Pk.	D	WRCC	747,214	4,213,053	5,950	1974	2000	12.31
24	Pioche	D	WRCC	723,958	4,206,828	6,180	1948	2000	13.38
25	Adaven	D	WRCC	624,188	4,219,501	6,250	1928	1982	12.73
26	Lake Valley Steward	D	WRCC	705,452	4,243,357	6,350	1971	1998	15.69
27	Overland Pass #2	A	NDWR	620,902	4,430,358	6,790	1966	1998	14.10
28	Wilson Creek	A	NDWR	730,287	4,254,672	7,200	1954	1998	16.45
29	Current Creek	A	NDWR	649,041	4,297,624	5,999	1954	1998	13.17
30	Mount Wilson	S	USGS	728,196	4,235,885	9,200	1985	1999	22.49
31	NW of Mount Moriah	S	USGS	737,769	4,355,738	9,300	1985	1999	18.28
32	Mount Washington	S	USGS	732,842	4,309,177	10,440	1985	1999	25.80
33	Mount Hamilton	S	USGS	625,636	4,344,581	10,600	1985	1999	21.81
34	Cave Mountain	S	USGS	706,185	4,337,345	10,650	1985	1999	21.40

[1] P = Periodicity of measurement, D (Daily), A (Annual), S (Semi-Annual)

[2] Proper names of agencies, Western Regional Climate Center (WRCC), Nevada, Division of Water Resources (NDWR), U.S Geological Survey (USGS)

[3] UTM = Universal Transverse Mercator, North American Datum 1927 (NAD27)

annual averages reported in **Table 4-1** of the precipitation gages are assumed to be representative of the precipitation at the site of the gage and over a relatively large area (millions of acres). This assumption, however, may introduce errors into this or any other precipitation analysis.

A significant issue in this analysis was the low density of precipitation data. Precipitation data are available from existing or recently existing sites in 11 of the 27 valleys in the study area. No records were found for gages in the other valleys. Because of the low density, precipitation data from adjacent valleys were used to augment the data set. This low density of data also effects any precipitation analysis.

4.2.4 Development of Altitude-Precipitation Relationships

The precipitation-altitude relationships used in this study were estimated slightly differently than was done in Las Vegas Valley (Donovan and Katzer, 2000). Las Vegas Valley is a much smaller area, has a higher density of data, and much more apparent variability. The historic precedents all assumed the altitude-precipitation relationships were different in the two major mountain ranges (Spring Mountains and Sheep / Las Vegas Ranges). Donovan and Katzer (2000) simply used the gage data to better define the differences between the two mountain ranges. The plot of the data (Donovan and Katzer, 2000; Figures 1 and 2) displays some very obvious geographic groupings consistent with historical analysis. In Las Vegas Valley the data were simply separated into four groups and regressed.

The historical precedents for this current study all assumed the altitude-precipitation relationship was similar throughout the entire area. The one general distinction was a difference between northern basins (dryer) and southern basins (wetter). This difference was presumably related to the influence of summer monsoonal precipitation. Therefore it was originally thought that one uniform altitude-precipitation relationship could serve to characterize the area.

The first step in developing an altitude-precipitation relationship is plotting the station period of record averages **(Figure 4-1** and **Figure 4-2)** to determine if a geographic relationships exist. The precipitation gages on **Figure 4-2** are shape-varied by the source of the data.

This general regression appears to generally explain the altitude-precipitation relationship but the coefficient of determination is not very high (Adjusted $r^2 = 0.78$) indicating 22 percent of the variation is not explained by the regression.

Rather than northern-southern, a general eastern-western relationship was observed. That is; stations on the eastern side, of the study area, tended to plot above the regression line ("wetter" than predicted) and stations on the western side tend to plot below the regression line ("dryer" than predicted). Therefore it was hypothesized that the western part of the study area (White River Flow System) is "dryer" than the eastern (Meadow Valley Flow System) part and use of a "general" altitude-precipitation relationship would tend to over estimate precipitation in the White River Flow System and under estimate precipitation in the Meadow Valley Flow System.

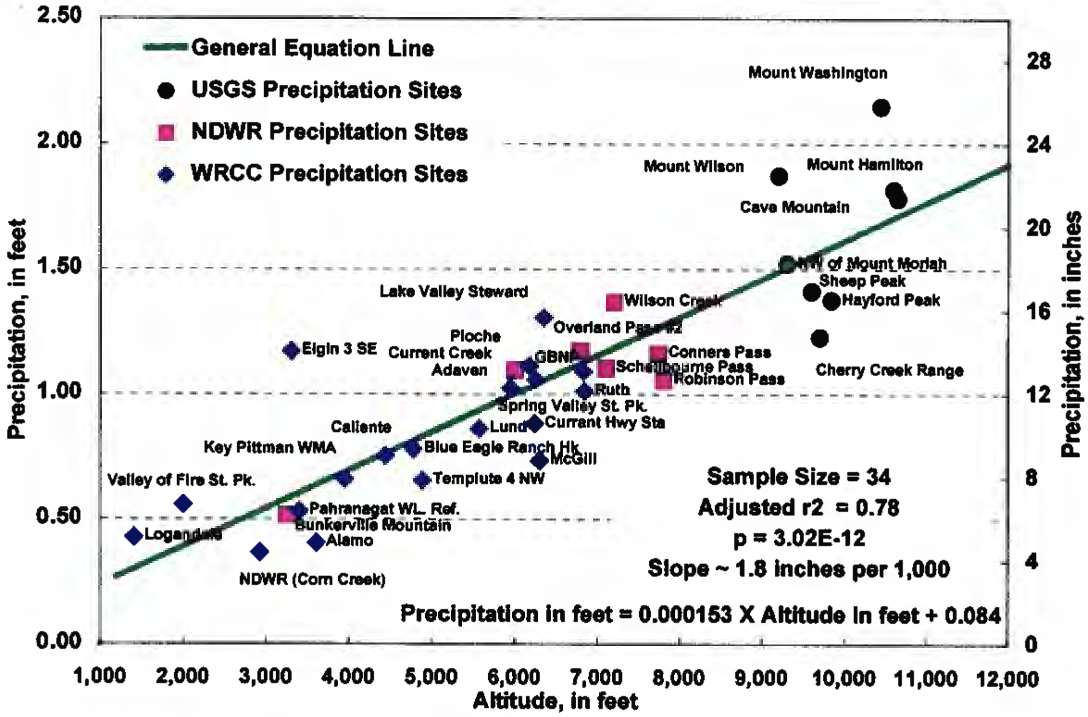

Figure 4-2. General regression of precipitation gage data in this study.

"Dryer" implies that a location at a specific altitude in one area receives less precipitation than in other areas at the same altitude. This "dryness" is also most obvious on the valley floors where most humans interact with the environment. Use of "dryer" and "wetter" is unsatisfying because these terms do not differentiate between reduction in the slope of the local altitude-precipitation relationship and "regional dryness" associated with large and perhaps overlapping rainshadows.

The period of record averages were separated into two groups simply based on whether the point plotted below (**Table 4-1**, Group 1) or above (**Table 4-1**, Group 2) the general regression line, with one exception. Caliente was included in the "wet" group (Group 2) to balance the influence of the Elgin precipitation station. These observed groupings were thought to be a combination of; overlapping rainshadows, general geometry of the valleys, including the height of the ranges above the valley floors, and orientation of the ranges with respect to storm tracks. The data and regressions are portrayed on **Figure 4-3** (Group 1) and **Figure 4-4** (Group 2).

The "dry" regression includes some of the same data used to create the "Sheep Range" altitude-precipitation relationship in Las Vegas Valley (Donovan and Katzer, 2000) which is "dryer" (both slightly shallower slope and smaller intercept). This appeared reasonable because the physical meaning of this regression suggests the valleys included within this particular analysis are relatively "dry" but not as "dry" as the nearby region within Las Vegas Valley.

These basically fell below the line with a total of 34 Fig 4.2

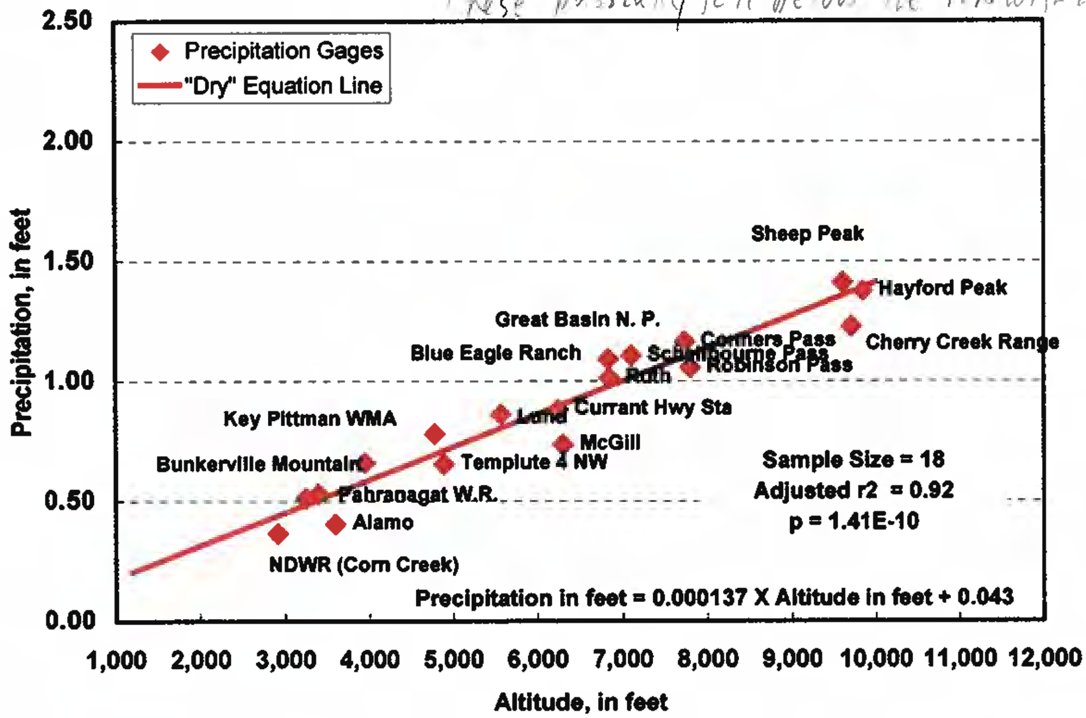

Figure 4-3. Data and regression of the "dry" group (Group 1).

above line Fig 4.2

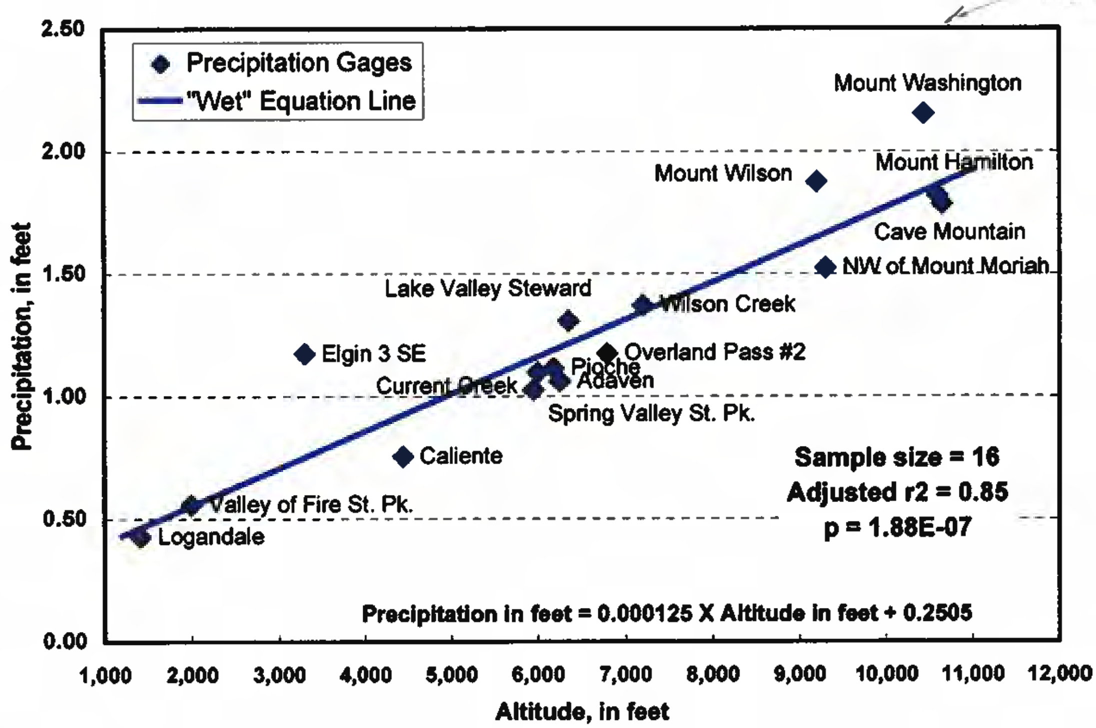

Figure 4-4. Data and regression of the "wet" group (Group2).

These regression analyses resulted in two roughly parallel equations with slopes that are slightly shallower (less steep) than the general altitude-precipitation relationship. The regression coefficient are somewhat improved (adjusted $r^2 = 0.92$ and 0.85) but generally not as good as observed in Las Vegas Valley (Donovan and Katzer, 2000).

It was also observed from plotting the data on **Figure 4-1** and **Figure 4-2** that stations in the northern White River Flow System were generally "dry" on the valley floors and "wet" in the mountain ranges. This implies the altitude-precipitation relationship is relatively steep in this area. It was also recognized that the highest ranges (from valley floor) in the study area are generally along the western margin of the study area and that the Quinn Canyon, Grant, and White Pine Ranges form a long continuous range.

The precipitation stations in and near the northern White River Flow System were then separated and regressed as a separate group. This part of the White River Flow System is dominated by White River Valley proper and therefore was called the "White River Valley" regression. This resulted in the fourth (altitude-precipitation) regression of this study, shown in **Figure 4-5**. Unlike the other regressions the intercept is negative. This was thought to be unimportant because the physical meaning of the intercept is the value of precipitation at 0 feet of altitude. No part of this study area is less than 1,200 feet of altitude and no part of the northern White River Flow System where this estimate was used is less than 5,000 feet of altitude.

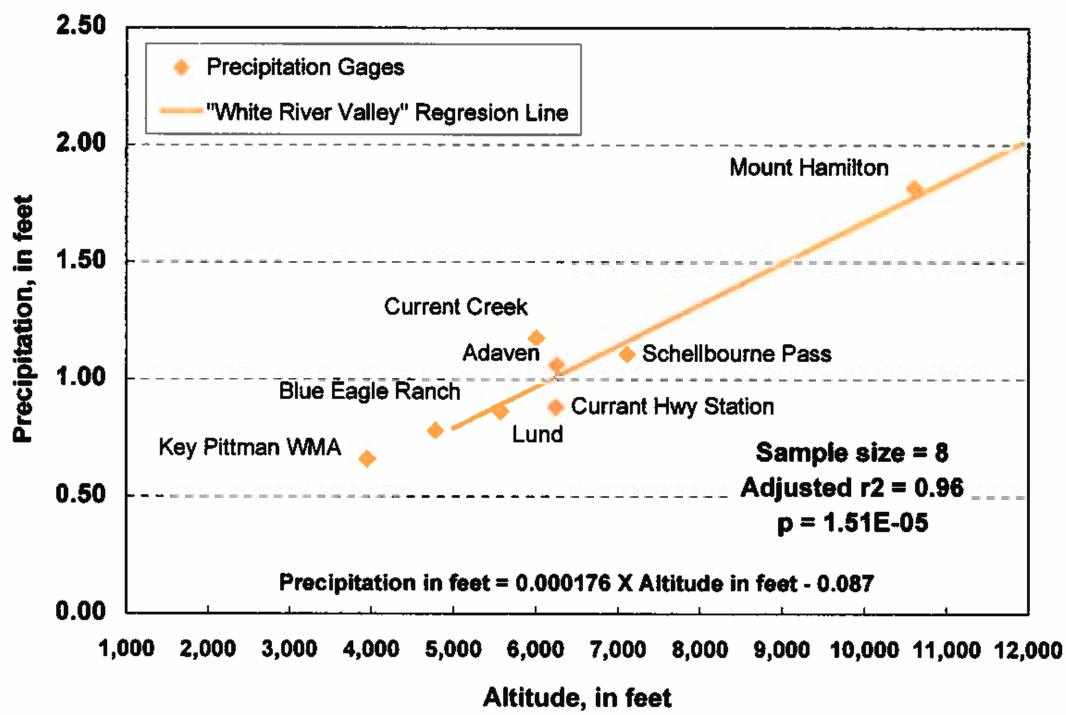

Figure 4-5. "White River Valley" precipitation data and regression.

Once the altitude-precipitation relationships were developed they were applied to various valleys within the study area. This was done to reduce the precipitation estimate of the entire study area and provide an appropriate altitude-precipitation relationship. The choice was determined by the locations of the various precipitation gages and physiography of the various valleys. This reduces the total estimate of precipitation in the study area by about 3 percent from 6,827,000 afy (general relationship, **Figure 4-2**.) to 6,636,000 afy, the sum of the precipitation based on all relationships.

The regression line as portrayed on **Figure 4-2** through **Figure 4-5** intentionally does not cover the entire altitude interval of the study area. The regression line portrays only the altitude intervals where the regression equation was applied. **Table 4-2** summarizes which of the various precipitation gages averages were used to create the various regression equations and then how the regression equations were applied. The predicted precipitation column is denoted to indicate which altitude-precipitation relationship was considered appropriate for the various sites ("general", "dry", "wet", "WRV"). **Figure 4-6** displays the spatial distribution of where the equations were applied. The hydrographic basin number (Valley Number) included in **Table 4-2** to minimize confusion caused by using valley names. There is precipitation data from two "Spring Valleys" in the precipitation analysis. One is the large valley (184) between the Schell Creek and Snake Ranges, the other (201) is located near Ursine.

Once the altitude-precipitation relationships were created through the four regressions, precipitation was estimated by multiplying the area of the 1,000-foot altitude intervals (in acres) in each valley by the predicted precipitation (in feet per year). This results in a estimated amount of precipitation in afy. The totals of the 1,000 foot altitude intervals are summed for in each valley and then for the total area. For any one 1,000-foot altitude interval, the rate of precipitation was calculated from one of the altitude-precipitation relationships. Only one altitude-precipitation relationship was used in each of the 27 valleys. **Table 4-3** summarizes the precipitation analysis for each valley. The full analysis is included in Appendix A

Although this precipitation analysis is characterized as a "modified Maxey-Eakin" the precipitation estimates cannot be directly compared to the precipitation estimates in the various basin reports. Commonly, precipitation was not estimated for areas that receive less than eight inches of precipitation and therefore the reported value reported may or may not be an estimate of the "total" precipitation in any one valley. Both total precipitation and the precipitation for the area that receives greater than eight inches of precipitation are listed in **Table 4-3**. All of the values reported in **Table 4-3** are rounded to the nearest 1,000 unless the estimated value is less than 1000.

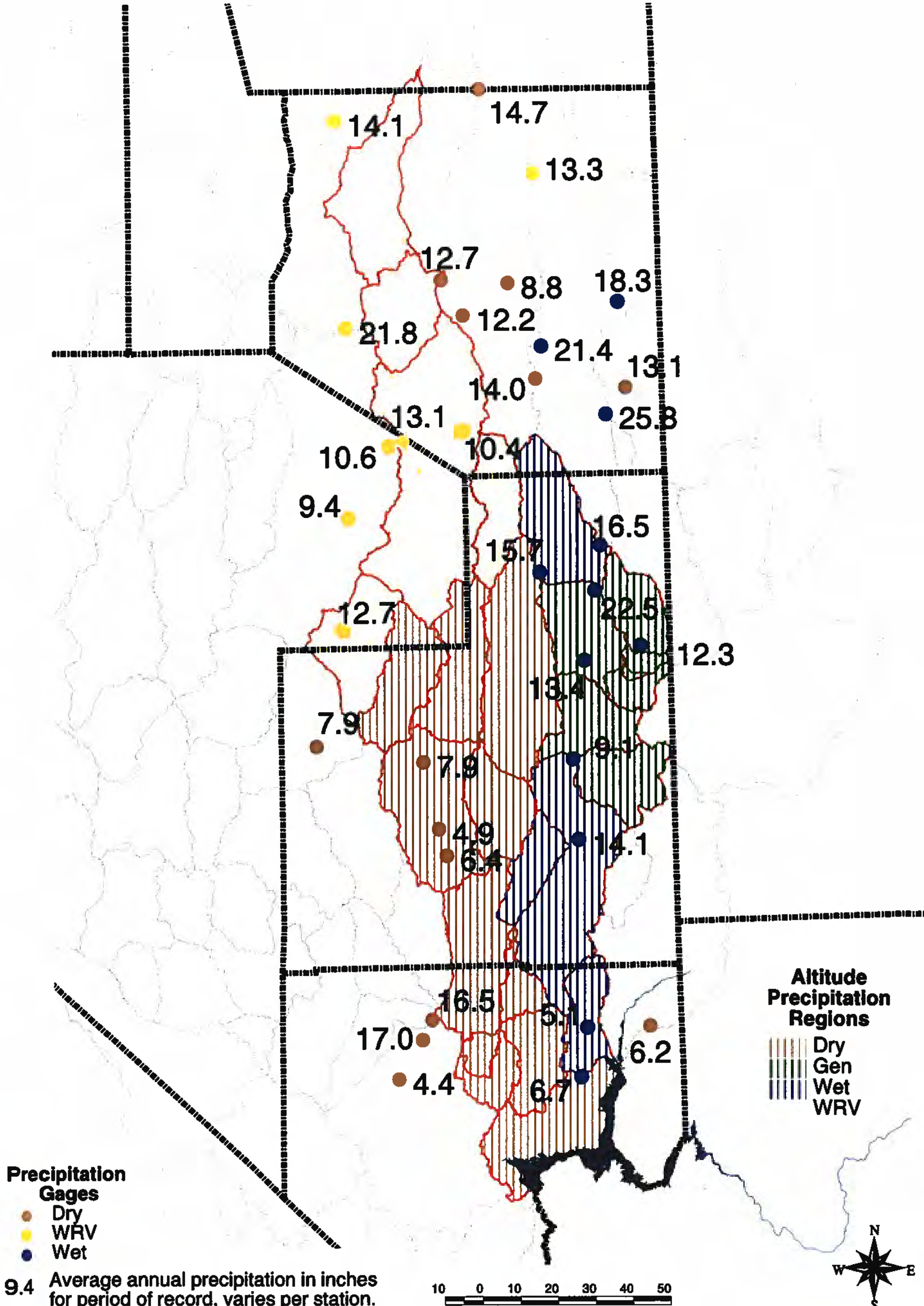

Figure 4-6. Distribution of local altitude - precipitation relationships and precipitation gage locations.

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Table 4-2. Use of data and application of regression equations at precipitation gage sites.

Site No.	Valley No.	Valley Name	Grp.[1]	Use of data for regression	Application of regression	Site contained within study area	Actual Average Precip. (ft)	Predicted Precip. (ft)
1	212	Las Vegas	1	Dry	N/A	OUT	**0.43**	0.44[b]
2	223	Gold Butte	1	Dry	N/A	OUT	**0.56**	0.49[b]
3	209	Pahranagat	1	Dry	Dry	IN	**0.37**	0.51[b]
4	209	Pahranagat	1	Dry	Dry	IN	**0.52**	0.54[b]
5	209	Pahranagat	1	WRV	Dry	IN	**1.17**	0.58[b]
6	173B	Railroad	1	WRV	N/A	OUT	**0.41**	0.75[d]
7	170	Penoyer	1	Dry	N/A	OUT	**0.66**	0.71[b]
8	207	White R. V.	1	WRV	WRV	IN	**0.76**	0.89[d]
9	173B	Railroad	1	WRV	N/A	OUT	**0.78**	1.01[d]
10	179	Steptoe	1	Dry	N/A	OUT	**0.66**	0.91[b]
11	195	Snake	1	Dry	N/A	OUT	**0.86**	0.98[b]
12	179	Steptoe	1	Dry	N/A	OUT	**1.03**	0.98[b]
13	179	Steptoe	1	WRV	N/A	OUT	**1.12**	1.16[d]
14	179	Steptoe	1	Dry	N/A	OUT	**0.88**	1.10[b]
15	179	Steptoe	1	Dry	N/A	OUT	**1.06**	1.11[b]
16	212	Las Vegas	1	Dry	N/A	OUT	**0.74**	1.36[b]
17	178B	S. Butte V.	1	Dry	N/A	OUT	**1.31**	1.37[b]
18	210	Coyote	1	Dry	Dry	IN	**1.18**	1.39[b]
19	220	L. Moapa	2	Wet	Wet	IN	**1.09**	0.46[c]
20	215	Black Mtns.	2	Wet	Dry	IN	**1.01**	0.55[c]
21	205	L. MVW	2	Wet	Wet	IN	**1.11**	0.75[c]
22	203	Panaca	2	Wet	Gen	IN	**0.53**	0.76[a]
23	201	Spring V. (L)	2	Wet	Gen	IN	**1.37**	0.99[a]
24	202	Patterson	2	Wet	Gen	IN	**1.30**	1.03[a]
25	172	Garden	2	WRV	WRV	IN	**1.17**	1.01[d]
26	183	Lake	2	Wet	Wet	IN	**1.06**	1.22[c]
27	176	Ruby V..	2	WRV	WRV	OUT	**1.87**	1.11[d]
28	183	Lake.	2	Wet	Wet	IN	**1.52**	1.34[c]
29	207	White R. V.	2	WRV	WRV	IN	**1.10**	1.00[c]
30	183	Lake	2	Wet	Wet	IN	**1.23**	1.65[c]
31	184	Spring V.	2	Wet	N/A	OUT	**1.38**	1.66[c]
32	184	Spring V.	2	Wet	N/A	OUT	**2.15**	1.84[c]
33	154	Newark	2	WRV	N/A	OUT	**1.82**	1.78[d]
34	184	Spring V.	2	Wet	N/A	OUT	**1.78**	1.87[c]

[1] *Grp. = Indicates in which group (1 or 2, "dry" or "wet") the site was initially included. All stations were used in the "general" regression.*

[a] *Indicates precipitation was estimated using the "general" altitude-precipitation relationship.*

[b] *Indicates precipitation was estimated using the "dry" altitude-precipitation relationship.*

[c] *Indicates precipitation was estimated using the "wet" altitude-precipitation relationship.*

[d] *Indicates precipitation was estimated using the "WRV" altitude-precipitation relationship.*

Table 4-3. Summary table of precipitation analysis.

Hydrographic No.	Valley Name	Area (ac.)	Total Precipitation (af.)	Precipitation greater than 8 inches (af.)
175	Long Valley	417,000	460,000 [d]	460,000 [d]
174	Jakes Valley	271,000	312,000 [d]	312,000 [d]
207	White River Valley	1,017,000	1,032,000 [d]	1,032,000 [d]
172	Garden Valley	318,000	320,000 [d]	320,000
171	Coal Valley	290,000	234,000 [b]	201,000 [b]
180	Cave Valley	230,000	258,000 [d]	258,000 [d]
208	Pahroc Valley	325,000	260,000 [b]	219,000 [b]
181	Dry Lake Valley	574,000	455,000 [b]	343,000 [b]
182	Delamar Valley	232,000	176,000 [b]	108,000 [b]
209	Pahranagat Valley	497,000	344,000 [b]	139,000 [b]
206	Kane Springs Valley	150,000	140,000 [c]	139,000 [c]
210	Coyote Springs Valley	392,000	224,000 [b]	72,000 [b]
219	Muddy River Springs Area	93,000	38,000 [b]	200 [b]
220	Lower Moapa Valley	176,000	101,000 [c]	12,000 [c]
217	Hidden Valley	52,000	28,000 [b]	5,000 [b]
216	Garnet Valley	102,000	45,000 [b]	5,000 [b]
218	California Wash	206,000	76,000 [b]	15 [b]
183	Lake Valley	354,000	437,000 [c]	437,000 [c]
202	Patterson Valley	267,000	275,000 [a]	275,000 [a]
201	Spring Valley	185,000	212,000 [a]	212,000 [a]
200	Eagle Valley	34,000	37,000 [a]	37,000 [a]
199	Rose Valley	8,000	7,000 [a]	7,000 [a]
198	Dry Valley	76,000	77,000 [a]	77,000 [a]
204	Panaca Valley	232,000	224,000 [a]	224,000 [a]
203	Clover Valley	220,000	205,000 [a]	205,000 [a]
205	Lower Meadow Valley Wash	606,000	523,000 [c]	437,000 [c]
215	Black Mountains Area	409,000	132,000 [b]	200 [b]
Total		**7,734,000**	**6,636,000**	**5,540,000**

[a] Indicates precipitation was estimated using the "general" altitude-precipitation relationship.
[b] Indicates precipitation was estimated using the "dry" altitude-precipitation relationship.
[c] Indicates precipitation was estimated using the "wet" altitude-precipitation relationship.
[d] Indicates precipitation was estimated using the "WRV" altitude-precipitation relationship.

4.2.5 Discussion of Precipitation Analysis Related to Previous Studies

The strong conservativeness of the earlier precipitation estimates can be demonstrated by plotting the gage averages **(Figure 4-7)** on the NDWR 1971 precipitation map. The precipitation gage data from Caliente (9.1 inches, altitude 4,400 feet) in Panaca Valley, Key Pittman Wildlife Refuge (7.9 inches, altitude 3950 feet) in Pahranagat Valley and Elgin (14.1 inches, altitude 3,300 feet) in Lower Meadow Valley Wash all suggest the altitude of eight inches of precipitation is about 4,000 rather than 6,000 feet of altitude and is probably lower in Lower Meadow Valley Wash. In addition, the altitude-precipitation relationship is not as steep as

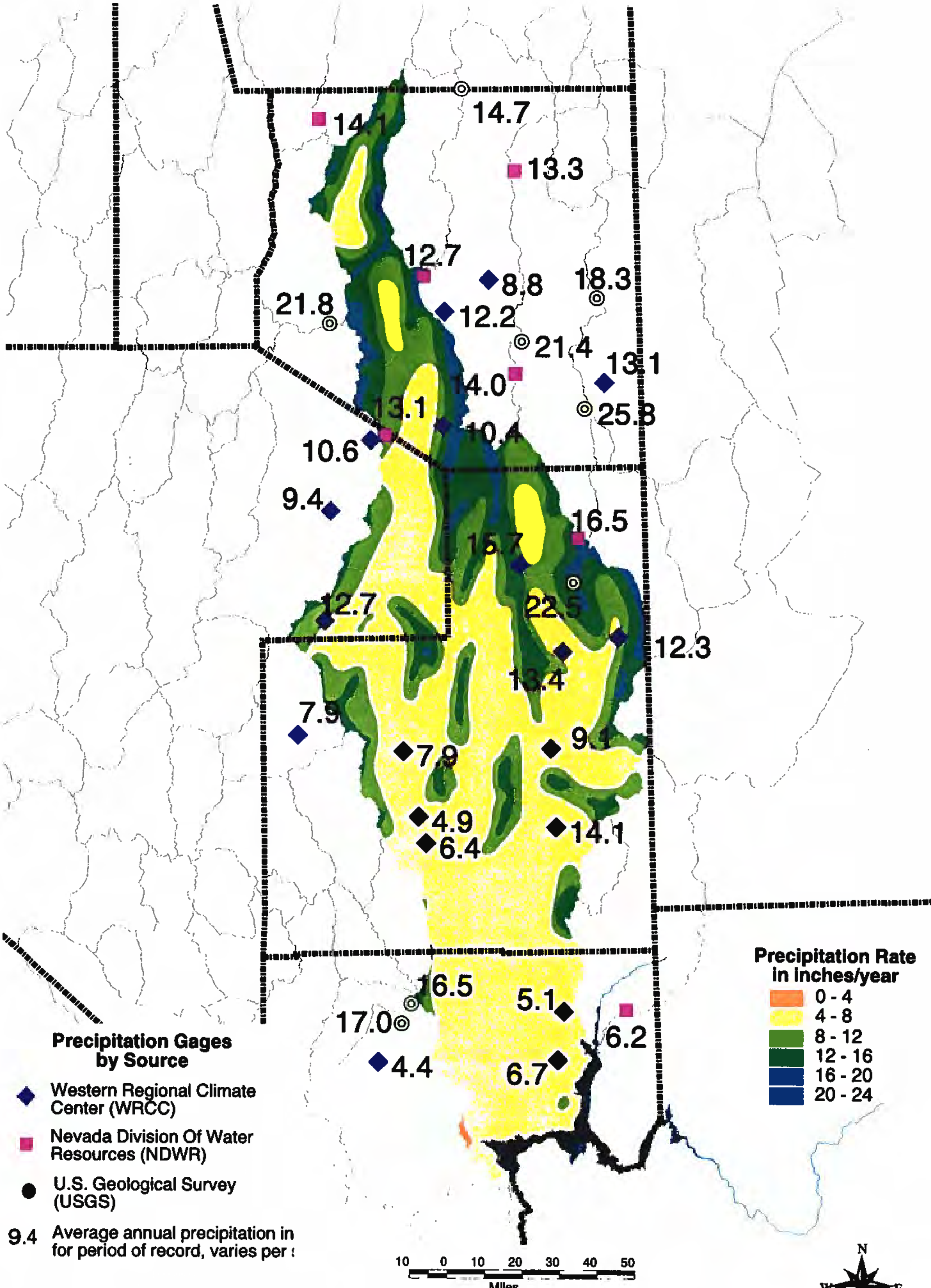

Figure 4-7 Digitized version of Nevada Division of Water Resources (NDWR) 1971 precipitation map with precipitation gages.

reported by Bixby and Hardman (1928) (4.5 inches per 1,000 feet of altitude rise) but rather approximately 1.8 inches per 1,000 feet **(Figure 4-2)** of altitude rise. This altitude-precipitation relationship also appears to apply over the entire range of altitude.

This is a very different conclusion than would be expected from the Hardman (1936, 1965) or NDWR (1971) precipitation maps. This implies all of the acreage above 6,000 feet of altitude (36 percent) and 5,000 feet (66 percent) and potentially all of the acreage above 4,000 feet (78 percent) may receive "effective" precipitation that at least partially becomes natural recharge.

This can also be demonstrated by comparing the composite altitude-precipitation relationships in the various precipitation maps with the actual precipitation data **(Figure 4-8)**. This is fairly simple when comparing the precipitation data with a Maxey-Eakin analysis (including the modified form used here), because the altitude-precipitation relationship used in a particular valley or region is clearly stated. When using a precipitation map this relationship can only be determined either by visual inspection (visually comparing the altitude intervals and precipitation intervals) or GIS analysis (combining two digital geographic data sets, then determining the numerical relationship between them, typically by weighted averages). The curves determined by GIS analysis of the two precipitation maps (NDWR 1971) and PRISM are presented on **Figure 4-8** for comparative purposes and were created using standard GIS processing techniques. The GIS technique was preferred over visual inspection because it is reproducible.

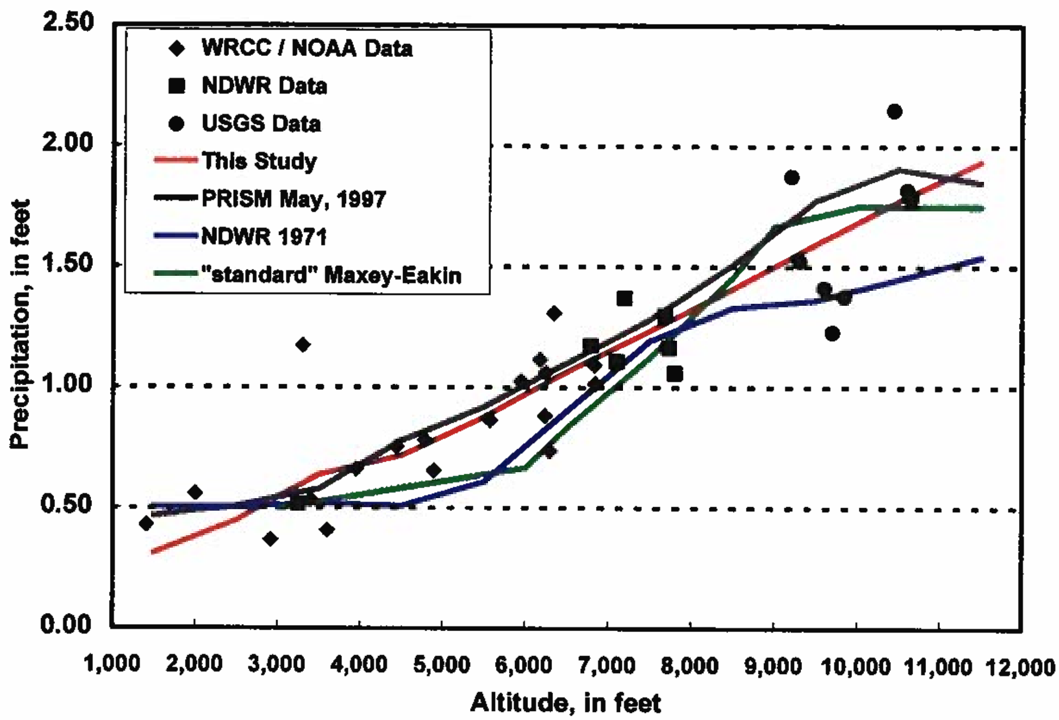

Figure 4-8. Composite altitude-precipitation relationships compared to gage data.

The line presented as "This study" is a weighted average line influenced by the relative size and altitude of the regions where the four altitude-precipitation relationships were used and was presented on this graphic for comparison with the other precipitation maps. This is a relatively straight line because the four altitude-precipitation relationships are similar. Four very different altitude-precipitation relationships would combine to create a very curved line. The four altitude-precipitation relationships were created simply to better characterize individual valleys within the study area; the four are local altitude-precipitation relationships that apply to specific valleys within the entire study area.

The distribution of precipitation presented in this study, although at variance with USGS and NDWR basin reports, is similar to the PRISM map. The PRISM precipitation distribution map, downloaded May 1997, has a similar but more generous distribution of precipitation. For the three precipitation maps, the total estimate of precipitation (~ 6,636,000 afy) in this study is significantly larger than the NDWR 1971 map (~ 5,516,000 afy) but smaller than the May 1997 version of PRISM (~ 6,985,000 afy).

Figure 4-9 is included for comparison with **Figure 4-7**. Precipitation was estimated by the modified Maxey-Eakin technique pioneered by Donovan and Katzer (2000) in Las Vegas Valley. In this technique, precipitation was estimated using 1,000-foot altitude interval tables and therefore a precipitation map was not required. The map is included here only for comparative purposes.

In Donovan and Katzer's (2000) precipitation estimation technique the altitude-precipitation relationship is determined by regression of the available precipitation data. This altitude-precipitation relationship is then applied to summary tables of 1,000-foot altitude intervals. Both the use of 1,000 foot intervals and the fact that the amount of precipitation is estimated from altitude intervals are features of the Maxey-Eakin technique as summarized by Eakin (1966, p. 260-262). Because of the similarities in the manner in which precipitation and natural recharge is estimated, Donovan and Katzer's (2000) method is characterized as a "modified Maxey-Eakin" rather than a new technique.

4.3 GROUND-WATER MOVEMENT

Ground-water in the study area flows from areas of high head in the upper altitudes of the basins to areas of lower head (lower altitude) in response to gravity. There is a change in altitude from the northern edge of the study area in Long Valley (Valley floor ~ 6,100 feet altitude) to the Colorado River (downstream from Hoover Dam ~ 600 feet altitude) of about 5,500 feet. Several of the mountain blocks have peaks that add an additional 4000-5,000 feet to this head change.

Ground water movement from areas of higher head, such as recharge areas, is toward the carbonate aquifer systems that underlie the entire Colorado River Basin Province of Nevada. Most of the valley fill aquifer systems are directly on top of the carbonate aquifer system and the movement of ground water is upwards from the carbonate aquifer to the alluvial aquifers. There are numerous valleys where these two aquifer systems are separated by a sequence of volcanic rocks, such as is in Dry Lake, Delamar, and Pahranagat Valleys. There is undoubtedly ground-water movement upward from the carbonate rocks through the overlying volcanic rocks to the

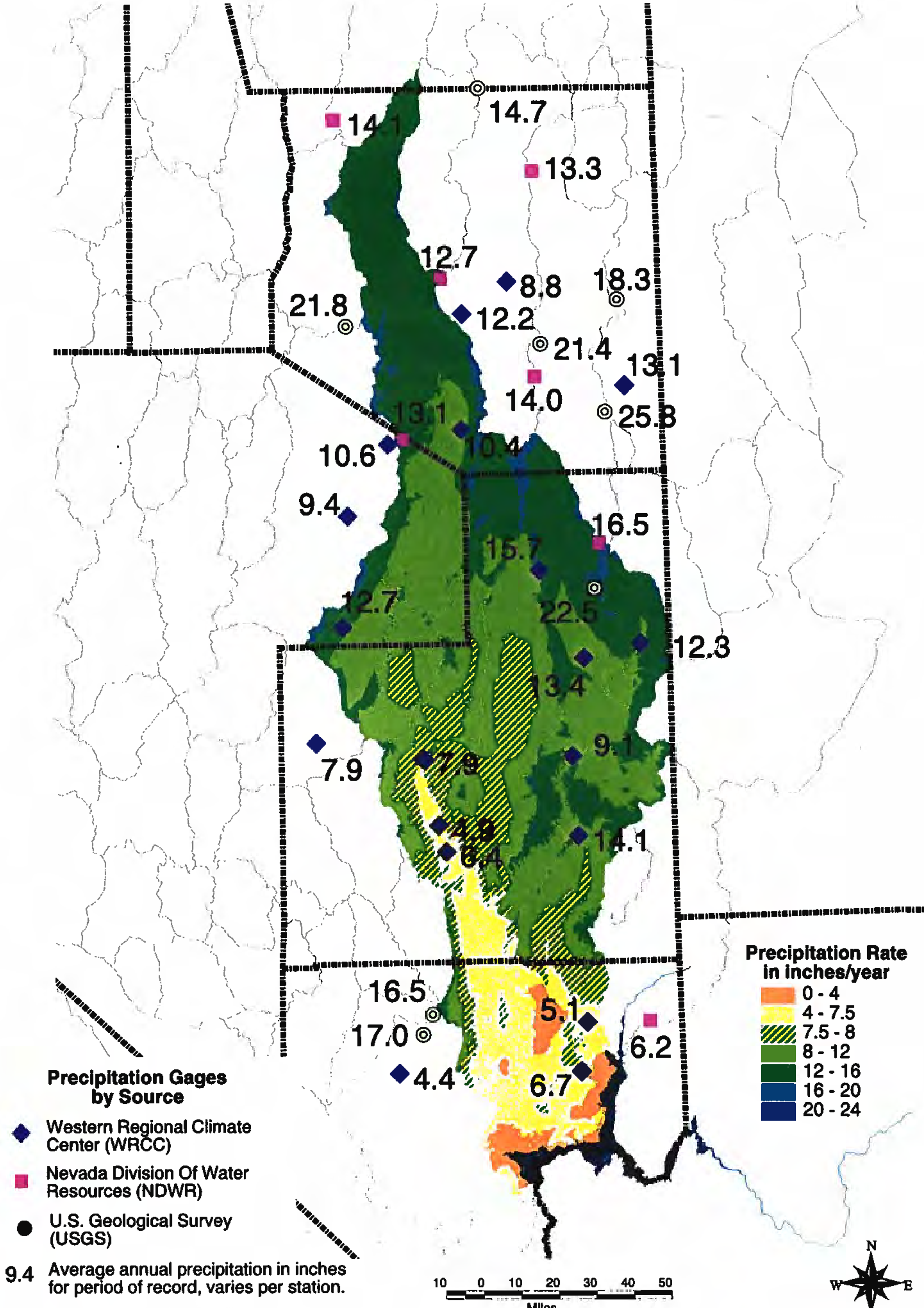

Figure 4-9. Distribution map of precipitation used in this study with precipitation gages.

alluvial aquifer systems. Ground water also moves down through the volcanic rocks, in the recharge areas to the alluvial aquifer with lateral downgradient flow. There is ground-water movement from recharge areas at low altitude, such as in alluvial fans, directly down to the alluvial aquifer system and perhaps in some cases there may be flow from the alluvial aquifer through the volcanic rocks to the carbonate aquifer. There also may be flow from one basin to another through the connecting alluvial aquifer system such as in Dry Lake and Delamar Valleys. There is ground-water flow in the carbonate aquifer from the northern end of the system to the southern end, specifically from the carbonates underlying Long Valley to the carbonate rocks underlying Lake Mead and the Colorado River. The same holds true for the carbonates underlying Lake Valley at the north end of the Meadow Valley Flow System, for these carbonate rocks are also connected to the same carbonates underlying Lake Mead and the Colorado River. Even though this ground water system is extremely complex with ground-water mounding, degrees of permeability, varying lithologies, and structural complexities, there is most probably some degree of hydraulic connectivity throughout the study area.

4.3.1 White River Ground-Water Flow System

Ground water begins its circuitous path in the mountains and alluvial slopes of Long Valley exiting the valley in the underlying carbonate rocks to Jakes Valley. Local recharge in Jakes Valley from the Eagan and White Pine Ranges joins the outflow from Long Valley and moves south into White River Valley. Large springs in White River Valley discharge a significant amount of water from the underlying carbonate rocks. Recharge to the basin's alluvial ground-water system is from spring discharge from local recharge and from the underlying carbonate aquifer. There is also a component of local recharge in some of the springs, but most of the local recharge from the surrounding mountain blocks becomes part of the regional flow in the underlying carbonate aquifer.

Cave Valley, immediately east of White River Valley, contributes ground water to either the south end of White River Valley in the vicinity of the Shingle Pass fault zone or to the north end of Pahroc Valley. The width of the flow section in northern Pahroc Valley stretches from the Quinn Canyon Range on the west (including Garden and Coal Valleys) to the Bristol Range on the east (including Cave, Dry Lake, and Delamar Valleys). It is uncertain where the ground-water recharge from Garden and Coal Valleys actually joins the regional carbonate aquifer, but the ground water from both valleys may move east and south along a series of north trending faults until finally moving into the regional carbonate aquifer underlying Pahranagat Valley. East of Pahranagat Valley ground-water recharge from Dry Lake and Delamar Valleys is probably moving mostly to the south with some westerly component. The recharge from these two valleys originates mostly in the carbonates of the Bristol-Highland Range and the volcanic rocks of the Delamar Mountains.

Ground-water flow out of Delamar Mountains into Kane Springs Valley and Coyote Spring Valley must move through the Caliente caldera complex, an assemblage of tuffaceous and basaltic rocks. These rocks have undergone extensive structural deformation that allows ground water to flow through the caldera complex along numerous north trending fault structures. It is these same faults that breach the Pahranagat Valley shear zone, a northeast structure that cuts through the south end of Pahranagat Valley. The ground-water gradient across this shear zone was first defined by Eakin (1966, Figure 5) who attributed the steep gradient (based on sparse data) to a barrier effect caused by structure. We suggest the steep gradient is caused by an increase in permeabilities in the volcanic rock across this fault zone as the flow moves downward and southward into the underlying carbonate rocks in Coyote Spring Valley. Conversely there may not be a gradient and the water is simply perched above the regional carbonate flow system. Winograd and Friedman (1972) thought the barrier described by Eakin (1966) deflected about 6,000 acre-feet/year of regional ground water from the White River Flow System to the west toward the Amargosa Desert (not shown on **Figure 1-1**). According to Jim Thomas (DRI, oral commun.,2001) ground water in the carbonate rocks west of this theoretical barrier does not need the geochemical imprint from the White River Flow System to be explained, because local recharge, for instance from the Spring Mountains, has the same geochemical signature. Thus, the evidence is inconclusive and we have chosen to construct our ground-water model so ground water does not leave the White River ground-water system in this area.

Don't know flow across Pahranagat shear zone

The exact nature of the ground water flowing south in the carbonate rocks in Coyote Spring Valley is unknown, but in the northern part of the valley it probably moves differentially across a broad front. This front extends from the top of a ground-water mound in the Sheep Range bounding the valley on the west, through the Meadow Valley Mountains, to a similar ground-water mound under the Morman Mountains. White River ground water in the northern part of Coyote Spring Valley is moving mostly south and not mixing significantly with Meadow Valley Wash water, but it is connected hydraulically. The range front fault on the east side of the Sheep Range is highly permeable and is a major conduit for the southward moving ground water. Additional preferential flow is thought to occur along the range front fault on the west side of the Meadow Valley Mountains including the course of Pahranagat Wash. Groundwater from the valley moves as fracture flow to the east-southeast along the general course of Pahranagat Wash through Arrow Canyon to discharge at the Muddy Springs. According to Thomas et al. (2001) the temperature of the ground water in MX wells 4 and 5 is nearly the same, (30° and 31° C) and compares favorably with the Muddy Springs water temperature at 32.1°C ; these elevated temperatures indicate vertical flow paths of several thousand feet. The remainder of the ground water exiting Coyote Spring Valley continues to the south and is somewhat split by the Arrow Canyon Range causing some flow into Hidden and Garnet Valleys with the remainder into California Wash. Some ground water in Coyote Spring Valley moves along the range front fault on the east side of the Sheep and Las Vegas Ranges and flows into Hidden Valley and on into Garnet Valley. The southern edge of Garnet Valley is bounded, in part, by a thick section of Muddy Creek Formation sediments that are thought to have low permeabilities. Additionally, the Dry Lake thrust, and further to the northeast the Glendale thrust, appear to act as partial barriers to, not only White River ground-water flow, but also Meadow Valley ground-water flow, because ground-water levels are fairly uniform on the north side of these thrust systems over a large area, about a 15-20 mile radius from the Muddy Springs. Thus the southern end of these two ground-water flow systems merge into one large system with a very flat gradient to the east-southeast. Even though these fault structures act as barriers to ground-water flow, permeabilities across the fault zones are sufficient to allow a flow of about 36,000 afy to leave the area.

A greater part of ground-water flows from Garnet and Coyote Spring Valleys flows to California Wash with a minor amount moving to the south through the Dry Lake thrust to Black Mountain

Basin. According to Thomas et al., (2001) the spring discharge and phreatophyte ET (~ 2,000 acre-feet/year) at Rogers and Blue Point Springs on the eastern edge of Black Mountain Basin is made up of about 1/3 local recharge with the remainder coming from the White River Flow System. It is also possible that the discharge at these springs is from the Meadow Valley Flow System. If there is additional flow from Black Mountain Basin greater than spring flow and ET, it undoubtedly discharges from the carbonate rocks underlying Lake Mead and the Colorado River. The remainder of the ground water in California Wash probably discharges to the Muddy River up gradient from the Glendale thrust complex with some amount moving through the complex to discharge from the carbonate rocks beneath Lake Mead and the Colorado River.

4.3.2 Meadow Valley Ground-Water Flow System

The Meadow Valley Flow System is very similar to the White River Flow System with numerous valleys linked together by the carbonate rock aquifer and a ground-water gradient to the south. This flow system also discharges in part to the Muddy River in Lower Moapa Valley with the remainder of the flow discharging from the lower carbonate aquifer beneath Lake Mead and the Colorado River.

Lake Valley is the most northern valley in this flow system and ground-water recharge from the Fairview, Fortification and the Wilson Creek Ranges provides most of the ground-water outflow from this valley. As this flow moves south to Patterson Valley it increases in volume from recharge in the southern part of the Fairview Range, the Bristol Range and the southwest part of the Wilson Creek Range. This ground-water flow is separated by topographic divides from valleys to the east, (Spring, Eagle, Rose, and Dry), but is undoubtedly connected hydraulically with them. Flow patterns in these eastern valleys are complicated by several thousand feet of volcanic rocks that overlie the carbonate rock aquifer. Nevertheless, some amount of ground-water recharge occurs in the volcanic rocks and ultimately reaches the underlying carbonate rocks. Because volcanic rocks have considerably less permeability than carbonate rocks some of the potential recharge does not reach the deeper ground-water system, but ends up as surface flow in Meadow Valley Wash

Panaca Valley receives a mixture of ground-water flow from up-gradient areas; carbonate water from Lake and Patterson Valleys and water from volcanic rocks in Spring, Rose, Eagle, and Dry Valleys. There is a significant amount of local recharge in Panaca Valley, mostly from the Highland Range (carbonate rock) to the west and the Clover Mountains (volcanic rock) to the east. All of this flow is tributary to Lower Meadow Valley Wash and the ground-water outflow from Clover Valley.

Ground-water flow in Lower Meadow Valley Wash moves to the south and is in hydraulic connection with ground water from the White River Flow System in the volcanic rocks of the Caliente caldera near Kane Springs Valley. Ground-water flow from Lower Meadow Valley Wash ultimately discharges at great depth from the volcanic rocks to the carbonate rocks and near the southern boundary of the valley is constrained by the northeast end of the Glendale thrust. This thrust, as discussed previously, is in part responsible for the pooling effect defined by wells in the carbonate rocks that have nearly the same water-level in a 15-20 mile radius centered on the Muddy Springs. This reduction in permeability at the fault zone is in part caused by the lower permeabilities of the Mesozoic clastic rocks. However, ground-water flow across and through this thrust does take place along zones of structural weakness and in the fractured carbonate rocks of Paleozoic age and probably to a lessor extent in some of the Mesozoic rocks.

Ground-water outflow from both flow systems is toward the southeast. Some of the outflow surfaces in the Muddy River in Lower Moapa Valley, but most of the flow discharges probably into several fault structures that define the present trace of the Colorado River or to undefined areas to the south.

4.4 GROUND-WATER RECHARGE

Ground-water recharge to the various aquifer systems within the CRBP in the study area starts as precipitation on the recharge areas. Precipitation in the form of snow is probably the most important source of recharge, but winter rain and summer convection storms also add appreciable volumes of water to the general area. Ground-water recharge processes have not been fully defined and there are significant differences in the amount of recharge in the various geologic terrain dependent on rock types and the degree of permeability. Rocks with greater permeability, such as carbonates, have greater amounts of recharge than other types of rocks within the study area. Although we recognize the actual recharge rate is strongly affected by rock type and other factors, the method used to estimate natural recharge in this study, Maxey-Eakin, has been used for over half a century, all over Nevada, in a wide variety of geologic terrains and climatic settings.

4.4.1 Development of Natural Recharge Estimates from Altitude-Precipitation Relationships

Natural recharge for the basins in this study were estimated from precipitation by a technique pioneered in Las Vegas Valley (Donovan and Katzer, 2000). It is conceptually similar to, and borrows heavily from, the Maxey-Eakin technique (Maxey and Eakin, 1949) and is characterized in the report as a "modified Maxey-Eakin". The primary variation between the two techniques is the relationship between altitude and precipitation. Nichols (2000) has also pioneered a new technique for estimating natural recharge but his technique varies significantly from the Maxey-Eakin technique in both the manner in which precipitation and the assumed recharge efficiency (recharge coefficients) are estimated. Nichols' (2000) technique is specifically for use with a modified version of the May 1997 Parameter-elevation Regressions on Independent Slopes Model (PRISM) map by Daly and others (1994) of the Oregon Climatic Service.

The "standard" Maxey-Eakin technique as summarized by Eakin (1966, p. 260-262) has been in use for over a half century and has probably been applied to every valley in Nevada although the estimate may not have been published. When the U.S. Geological Survey (USGS) and the Nevada Division of Water Resources (NDWR) estimated most of the basin budgets, either the standard or variants of the Maxey-Eakin technique were used. Avon and Durbin (1994, p.102) reported investigators deviated from the standard form of the method about 37 percent of the time.

In the "standard" Maxey-Eakin technique the acreage of an individual valley was divided into five altitude intervals listed below in **Table 4-4** (Eakin, 1966, Table 2):

Table 4-4. "Standard" Maxey-Eakin assumptions.

Precipitation Zone (in.)	Altitude Zone (ft.)	Average Annual Precipitation (ft.)	Recharge Efficiency (%)
< 8	< 6,000	Variable	Negligible
8 to 12	6,000 to 7,000	0.83	3
12 to 15	7,000 to 8,000	1.12	7
15 to 20	8,000 to 9,000	1.46	15
> 20	> 9,000	1.75	25

The acreage of the altitude intervals was multiplied by the average precipitation in feet, then multiplied by the recharge efficiency (the percentage of precipitation that becomes natural recharge), then summed to estimate the natural recharge as shown in **Table 4-5**. Typical variation of the technique was modification of the altitude intervals. Implicit in the technique, is that the recharge efficiency is a function of precipitation rather than altitude and at least two precipitation maps Hardman (1936 and 1965) were used in the USGS and NDWR basin reports.

The acreage of the valleys as reported in this study are within 3 percent of the acreage as reported in the various basin reports with exception of Coyote Spring and Muddy Springs Valleys. These small differences are mostly related to round-off, digitizing errors, and map scales. The major increase (~ 25 percent) in Muddy Springs Valley is due to the inclusion of Wildcat Wash which was historically included in Coyote Spring Valley on USGS hydrographic basin maps.

In the modified Maxey-Eakin technique (Donovan and Katzer, 2000), the available precipitation data is selected based on quality (length of record, percentage of record completeness). The data are separated into geographic regions, and processed through regression analysis to determine the local altitude-precipitation relationships. The development of the four local altitude-precipitation relationships, ("general", "dry", "wet", and "WRV") used in this study was described and presented in the Precipitation (4.2) section.

Donovan and Katzer (2000) introduced a slight variation in calculating the Maxey-Eakin natural recharge efficiency coefficients. The coefficients are calculated directly from the precipitation rate using the equation $r_e = 0.05\ (P)^{2.75}$ where r_e is the natural recharge efficiency coefficient and P is equal to precipitation rate in feet per year. The only purpose of this equation was to minimize calculation errors and the time required to calculate the estimate of natural recharge. The assumptions of mathematical approximation used by Donovan and Katzer (2000) were the same as Maxey-Eakin; Precipitation falling on areas that receive less than 8 inches is considered ineffective for producing ground-water recharge, the maximum recharge efficiency (25 percent) occurs at 20 inches and the recharge efficiency of the intervening intervals are the same. Donovan and Katzer (2000, p. 1142) reported that the mathematical approximation of the Maxey-Eakin efficiency coefficients reduced the natural recharge estimate by 3 percent when compared to the traditional methodology.

Table 4-5. Comparison of this study to previous Maxey-Eakin (1949) natural recharge estimates.

Valley	Acres	Volume of Precipitation (afy)		Ground-water Recharge (afy)	
		Maxey-Eakin[1]	This Study	Maxey-Eakin	This Study
Long Valley	416,966	296,940	459,937	10,300	31,112
Jakes Valley	271,493	NR	312,462	13,000	24,194
White River Valley	1,016,871	NR	1,032,143	40,000	62,133
Garden Valley	318,055	137,080	320,039	10,000	19,153
Coal Valley	289,998	62,038	234,361	2,000	7,002
Cave Valley	229,755	206,495	258,445	14,000	19,595
Pahroc Valley	325,289	56,764	260,197	2,200	7,545
Dry Lake Valley	574,417	117,562	454,998	5,000	13,254
Delamar Valley	231,582	33,530	176,189	1,000	4,597
Pahranagat Valley	497,312	42,640	344,195	1,800	7,407
Kane Springs Valley	150,429	48,878	140,218	2,600	6,757
Coyote Spring Valley	391,621		224,278		4,000
Muddy River Springs Area	92,541	NR	38,380	Minor	237
Lower Moapa Valley	175,656	1,160	101,358	50	1,354
Hidden Valley	52,435	11,400	27,512	400	339
Garnet Valley	101,981	10,600	45,268	400	393
California Wash	205,550	2,000	75,608	100	311
Lake Valley	354,246	228,930	437,170	13,000	41,320
Patterson Valley	267,430	136,860	275,015	6,000	15,761
Spring Valley	184,945	176,600	212,364	10,000	16,151
Eagle Valley	34,458	197,810	36,927	8,000	2,349
Rose Valley	7,647		7,349		352
Dry Valley	76,339		77,388		4,237
Panaca Valley	220,435		204,587		9,041
Clover Valley	231,964		223,852		10,557
Lower Meadow Valley Wash	605,723		523,247		22,823
Black Mountains Area	408,919	132,254	132,254	100	438
Total	7,734,059	1,899,541	6,635,742	147,950	332,413

[1] *Only represents precipitation greater than 8 inches.*

In estimating the precipitation for this study, the standard assumption that precipitation less than 8 inches is "ineffective" had no impact on the estimation of natural recharge in valleys where the "general" and "WRV" local altitude-precipitation relationship was used. These are generally high northern valleys with minimal or no acreage below 5,000 feet. All of the local altitude-precipitation relationships predict, and the available gage suggests, that all of the acreage above 5,000 feet of altitude in the study area receive greater than 8 inches of precipitation. This assumption also had no effect on the only northern valley (Lake) where precipitation was estimated using the "wet" local altitude-precipitation relationship.

It was observed, however, (**Figure 4-9**) that, in valleys where the "wet" local altitude-precipitation equation was used to estimate precipitation the interval between 3,000 and 4,000 feet of elevation is about 7.6 inches. It was also noted that, in valleys where the "dry" local altitude-precipitation equation was used to estimate precipitation the interval between 4,000 and 5,000 feet of elevation is about 7.9 inches.

These transitional altitude intervals are a significant amount of acreage in the valleys in the central and southern parts of the study area. If the standard Maxey-Eakin assumptions are used, the precipitation in these intervals could either be considered "ineffective" (none of the precipitation in these areas becomes natural recharge), or partially effective (part of the precipitation could have been included in the recharge estimate). Another possibility exists however.

When Pohlmann and others (1998) analyzed the springs in the Lake Mead area, using stable and radio isotopes they concluded that the recharge sources of one-third of springs are "local" and low altitude. The area described in Pohlmann and others (1998) is the southernmost valley (Black Mountains Area) of this current study area **(Figure 4-1)**. Most of the area is at low altitude (< 3,000 feet) and the highest peak, Muddy Peak, is at an altitude of 5,363 feet. The use of the term "local" introduces the idea that precipitation below 8 inches may be "effective" although the recharge efficiency is very low (less than a percent). Eakin's (1966, p. 260-262) summary of the Maxey-Eakin method characterizes recharge in areas that receive less than 8 inches of precipitation as "negligible" rather than "none".

The Maxey-Eakin technique, as originally developed, is a step function designed for use with paper maps, planimeters, and adding machines. As long as the precipitation is reported by the same irregular intervals (8, 12, 15 and 20 inches of precipitation) of the traditional method no confusion exists as to the appropriate recharge efficiency coefficients. If an alternative precipitation map with either regular intervals (NDWR, 1971), other irregular intervals (some variations of the PRISM map), or in units other than feet and inches (meters, centimeters, millimeters) questions arise about the appropriate recharge efficiency coefficients to use near the break points. Because the Donovan and Katzer's (2000) mathematical approximation of the Maxey-Eakin efficiencies is a continuous function it can easily be used in conjunction with non-traditional precipitation maps and estimates.

Donovan and Katzer (2000) examined the potential use of the equation to estimate the natural recharge efficiency directly from the precipitation estimate of a given altitude interval ($r_e = 0.05 (P)^{2.75}$) for estimating the recharge efficiency coefficients for areas that receive less than 8 inches of precipitation. The increase in the Las Vegas Valley natural recharge estimate would have been about 5 percent.

Because of the large size of the transitional altitude areas in this current study, the same logic was applied. The increase in the natural recharge estimate in the whole area is about 3.5 percent from about 321,000 afy to 332,000 afy. As mentioned previously, modification of the assumption that precipitation of less than 8 inches is "ineffective" has no effect on the recharge estimate of the high altitude northern valleys and a minor increase (5 percent) in the Lower Meadow Valley natural recharge estimate. The largest percentage increases are in the 5 small valleys (including the Black Mountains Area) where recharge is estimated to be less than 500 afy and the one valley

(Lower Moapa) where the recharge is estimated to be about 1,400 afy. In the center of the study area where there are large areas of the transitional altitude zones, the natural recharge estimate for the valleys increased by about 20 percent. The 20 percent increase in the natural recharge estimate was assumed to be similar to the increase that would have occurred if the altitude intervals were adjusted, as was done on many Maxey-Eakin analysis, to include part of the acreage (the part of the area that receives greater than 8 inches) of the transitional altitude intervals.

Table 4-6 summarizes the natural recharge estimates used in this study. The complete analysis is included in Appendix A. Note: The recharge within the modeled area is reported as 37,000 afy because it is rounded off to the nearest 1,000 afy. The actual estimated natural recharge within the modeled area is 36,652 afy, which was rounded to 37,000 afy in the ground water model.

Although this approach is a partial modification of the Maxey-Eakin assumptions, there are several advantages. One advantage is that the distribution of the Maxey-Eakin natural recharge efficiency coefficients for precipitation greater than 8 inches is preserved within Donovan and Katzer (2000) mathematical approximation. The Maxey-Eakin technique and the USGS and NDWR basin reports have well served the citizens of Nevada, for over half a century by consistent use of a simple, easy to understand, natural recharge estimation technique with a reasonable distribution of the relationship between precipitation and natural recharge coefficients. Another advantage of the approach used in this study is consistency, because a uniform methodology is applied to all of the precipitation that is estimated to fall on any valley. Two natural recharge analyses using two radically different precipitation maps can be compared directly on the influence of the precipitation estimate alone rather than on a combination of the precipitation distribution and the technique used to estimate natural recharge. The Hardman precipitation maps (1936, 1965) are no longer the only estimates of precipitation distributions available. Since the early 1990s, PRISM through it's widespread availability on the Internet, support by, and linked to, websites of important sources of climatic information like Desert Research Institute's Western Regional Climate Center (WRCC) (http://www.wrcc.dri.edu/precip.html), and The U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service, SCS) (http://www.ftw.nrcs.usda.gov/prism/prism.htmldistribution), is the most commonly used precipitation distribution map.

There are also disadvantages to the approach used to estimate natural recharge in this study. The approached used is a modified Maxey-Eakin therefore the advantages of the method are the advantages of the Maxey-Eakin (consistency, ease of use) and the disadvantages are the same as those of the Maxey-Eakin. Although the relationship between precipitation and natural recharge is reasonable, it is an assumption (non-unique), since the natural recharge estimate is strongly dependent on the precipitation estimate. The relationship between natural recharge and mountain front runoff is not intuitive. No factor that actually determines what portion of precipitation becomes natural recharge is actually included in the estimation technique. A short list of these factors includes: rock type, vegetation, average temperature, soil type, form (snow or rain) of the precipitation, typical storm size and duration, and the time of year when the precipitation occurs.

Table 4-6. Summary of annual natural recharge estimated for this study.

Valley No.	Valley Name	Area (ac.)	Total Estimated Precipitation (af.)	Natural Recharge Estimate (af)		Within Model Area
				A	B	
175	Long Valley	417,000	460,000[4]	31,000	31,000[a]	Tributary
174	Jakes Valley	271,000	312,000[4]	24,000	24,000	Tributary
207	White River Valley	1,017,000	1,032,000[4]	62,000	62,000	Tributary
172	Garden Valley	318,000	320,000[4]	19,000	19,000	Tributary
171	Coal Valley	290,000	234,000[2]	6,000	7,000	Tributary
180	Cave Valley	230,000	258,000[4]	20,000	20,000	Tributary
208	Pahroc Valley	325,000	260,000[2]	7,000	8,000	Tributary
181	Dry Lake Valley	574,000	455,000[2]	11,000	13,000	Tributary
182	Delamar Valley	232,000	176,000[2]	4,000	5,000	Tributary
209	Pahranagat Valley	497,000	344,000[2]	5,000	7,000	Tributary
206	Kane Springs Valley	150,000	140,000[3]	7,000	7,000	Modeled
210	Coyote Spring Valley	392,000	224,000[2]	3,000	4,000	Modeled
219	Muddy River Springs Area	93,000	38,000[2]	5	200	Modeled
220	Lower Moapa Valley	176,000	101,000[3]	400	1,400	Modeled
217	Hidden Valley	52,000	28,000[2]	150	300	Modeled
216	Garnet Valley	102,000	45,000[2]	150	400	Modeled
218	California Wash	206,000	76,000[2]	0	300	Modeled
183	Lake Valley	354,000	437,000[3]	41,000	41,000	Tributary
202	Patterson Valley	267,000	275,000[1]	16,000	16,000	Tributary
201	Spring Valley	185,000	212,000[1]	16,000	16,000	Tributary
200	Eagle Valley	34,000	37,000[1]	2,000	2,000	Tributary
199	Rose Valley	8,000	7,000[1]	400	400	Tributary
198	Dry Valley	76,000	77,000[1]	4,000	4,000	Tributary
203	Clover Valley	220,000	205,000[1]	11,000	11,000	Tributary
204	Panaca Valley	232,000	224,000[1]	9,000	9,000	Tributary
205	L. Meadow Valley Wash	606,000	523,000[3]	22,000	23,000	Modeled
215	Black Mountains Area	409,000	132,000[2]	5	400	Modeled
	Totals	**7,734,000**	**6,636,000**	**321,000**	**332,000**	**37,000[5]**

Recharge estimate "B" is the estimate used in this study, Estimate "A" is provided only for comparison.
[1] Precipitation was estimated using the "general" local altitude-precipitation relationship (Section 4.2)
[2] Precipitation was estimated using the "dry" local altitude-precipitation relationship (Section 4.2)
[3] Precipitation was estimated using the "wet" local altitude-precipitation relationship (Section 4.2)
[4] Precipitation was estimated using the "WRV" local altitude-precipitation relationship (Section 4.2)
[5] Total natural recharge of modeled area, Actual estimate = 36,652 acre-feet per year, Area = 2,186,000 acres, Total estimated precipitation = 1,307,000 acre-feet per year
[a] Only 23,000 afy is used in total because of ground-water outflow to non-White River Flow System Valleys based on proportionality of outflow defined by Nichols (2000).

Maxey-Eakin is one of numerous natural recharge estimation techniques, although it is the oldest and most commonly used in Nevada. In addition to numerous geochemical techniques, which include: conservative ion (usually Chloride), stable isotopes (Hydrogen and Oxygen), radiogenic isotopes (Chloride, Carbon, Uranium, etc..), tracers (chemical and isotopic) and combinations of the various technique appropriate at the "local" or regional scale. There are other empirical precipitation "budget" types techniques conceptually similar and dissimilar to Maxey-Eakin. There are also manual and computerized (models) techniques related to the Darcy equation. There are other runoff estimation techniques that may or may not include an estimate of the natural recharge. At least one natural recharge technique is strongly tied to soil types. All of these grow out of standard assumptions from Civil Engineering, Chemistry, Hydrology, Climatology and Soil Physics, and Biological Sciences.

An example of an empirical precipitation "budget" type of technique that are dissimilar to the Maxey-Eakin was discussed in Harrill and Prudic (1998, p A25). This technique is defined by the equation: $\log Q_r = -1.74 + 1.10 \log P_{p>8}$. Where Q_r is equal to the total natural recharge estimate in afy and $P_{p>8}$ is equal to the total volume of precipitation, where average annual precipitation is greater than 8 inches. This was developed following the example of Anderson (1985, p. 102-103) for the Southwest Alluvial Basins study area. Anderson's equation for southern Arizona is: $\log Q_r = -1.40 + 0.98 \log P_{p>8}$. Use of these equations implies that the total natural recharge estimate can be estimated directly from the total "effective" precipitation and all of the "effective" precipitation is equally "effective". This is very different conceptually from the Maxey-Eakin because the various recharge efficiency zones are distributed over the range of precipitation. The primary assumption in the Maxey-Eakin method is that higher precipitation rates yield a higher percentage of natural recharge, they further specify that the distribution of the percentages increase in a specific non-liner relationship with respect to increases in precipitation.

4.4.2 Mountain-Front Runoff

Mountain front runoff has its origin in precipitation that falls on mountain blocks. It is one component of precipitation that exits the mountain block in three ways. The other two are ground water recharge and evapotranspiration. Even though these are separate processes they are greatly interrelated. Mountain front runoff is defined as the volume of surface water that crosses the contact between the consolidated rocks of the mountain block and the unconsolidated sediments of the alluvial basin. How does it occur? It is caused when water from melting snow or rain literally runs off of the mountain block. This occurs when the infiltration capacity of the soil and rock and the evapotranspiration rate is exceeded by the volume of available water. Precipitation that infiltrates through the soil mantel and escapes evapotranspiration and moves down-gradient is often intersected by a drainage channel or is brought to the surface by springflow. Also fractures in the mountain block intercept ground water flow and provide a conduit to the surface where the water emerges from spring orifices. Thus ground water, which started as surface water, reappears through specific springflow orifices or as diffuse springflow and is considered once again to be surface water. This surface water is subject to evapotranspiration during its transient time to the valley and also, depending on other hydrogeologic parameters, may reinfiltrate to the ground water system. Springflow that does not reach a channel in sufficient volume to create runoff either evapotranspires or reinfiltrates to the ground water system once more becoming ground water recharge. Depending on the individual drainage, surface water runoff in perennial streams probably always has a component of ground water in it when it reaches the mountain front contact.

There is a significant amount of runoff into many of the valleys from ephemeral drainages, which do not have a ground-water component. The flow in these channels is generally sudden and last for perhaps just a few short days one or more times a year. In an effort to account for some of this runoff that potentially can become ground-water recharge we have extended the recharge efficiencies down to the lowest altitude in those basin that receive precipitation less than 8 inches as defined by the altitude precipitation relationships discussed previously. In an effort to collaborate this low-altitude recharge process we evaluated the ephemeral flow in Kane Springs and Coyote Spring Valleys using a technique described by Hedmen and Osterkamp (1982). This technique is based on certain channel characteristics that are formed by the discharge of water and sediment in a natural channel. The magnitude, duration, and frequency of flows dictate stream channel geometry, with additional control imposed by the distribution and size of sediment on the channel bed and banks. The channel characteristic measured in the ephemeral tributaries was the active channel width and the equations governing its use are found in Hedman and Osterkamp (1982, Table 2, p. 13, equations 12 -15). The standard error for these equations has not been determined, but is believed to be large, perhaps as much as 50 percent. The results of these measurements are listed in **Table 4-7** and the sites are shown on **Figure 4-10**. Measurements could not be made at some sites for a variety of reasons and the notation of ND (not determined) is indicated.

The results of this limited investigation show there may be a minimum of ~3,000 afy of runoff in Kane Springs Valley and nearly the same amount in Coyote Spring Valley that is lost from the respective channels. In reality there is probably much more, but because of tributary inflow and lack of reliable data, sites measurements could not be made. Some amount of this water that saturates the channel beds is lost to the atmosphere through ET and the remainder, probably a large percentage because of the coarse-grained nature of the channel sediments, infiltrates through the channel bed and moves down the soil column to the water table as ground-water recharge.

In this study all of Kane Springs Valley is in the precipitation zone that produces ground-water recharge, yet there is a significant amount of runoff from the mountain block that may be unaccounted for in the Maxey-Eakin method. If this is true then the amount of ground-water recharge estimated for this valley is conservative. Conversely this runoff may simply be rejected recharge from the mountain block because of the low permeabilities of the volcanic rock. In Coyote Spring Valley parts of the basin are below the effective precipitation threshold of 8 inches and by extending the Maxey-Eakin method to include this area results in an additional 1,000 afy (**Table 4-6**) of ground-water recharge. This value is within the estimated ground-water recharge that takes place as a result of mountain front runoff. This process of ground-water recharge from ephemeral channels has been discussed by other investigators such as Glancy and Van Denburgh (1969), Osterkamp et al (1994), Berger (2000a and b), and Savard (1998).

4.5 GROUND-WATER DISCHARGE

Discharge from the basins in pre-development times was by spring flow, evapotranspiration, and ground- and surface-water outflow. In some of the basins there has been no significant development and hydrologic conditions remain unchanged. In other basins there has been a high degree of water-resource development and pumpage for agriculture has replaced or is additive to spring flow use by phreatophytes. In some basins evapotranspiration increases yearly as

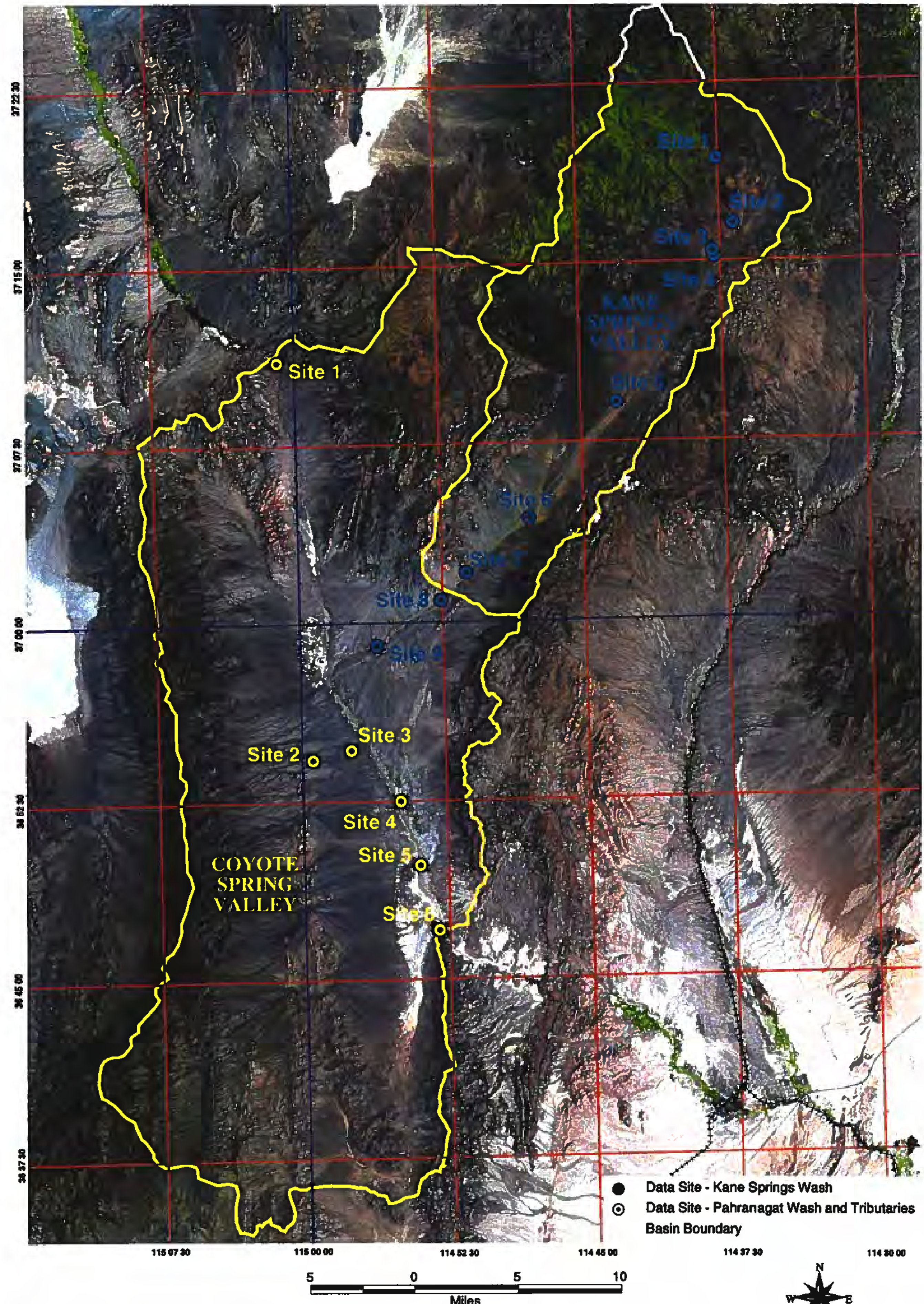

Figure 4-10. Mountain runoff sites in Coyote Spring and Kane Springs Valleys.

urbanization continues. Regardless of the amount of ground-water pumpage, ground-water outflow remains about the same in many of the basins simply because of the vast amount of ground water in storage in the various aquifer systems.

Discharge from the Colorado River Basins is by ground-water outflow and ET. Many of the basins have significant discharge by both processes, but it is the discharge through the ET that dominants the hydrologic system. Little of this discharge can be actually measured and inter-basin flow can only be inferred with large potential errors. The value that represents this flow is usually the difference between the estimated recharge and the estimated ET. There are several large springs that discharge from carbonate rocks and are assumed to represent part of the inter-basin flow. The most critical of these springs with regard to the purpose of this study are the Muddy River Springs. The measured discharge from these springs represents a significant amount of ground-water flow from the White River flow system. A lessor amount of flow has also been gaged from Rogers and Blue Point Springs. These are the only points in the lower part of the flow systems where actual measurements with time have been made.

Ground-water outflow from the model area occurs over a broad front as described in the Ground-Water Movement and Model Section. The fate of this outflow is unknown, but believed to be the fault structure that contains the lower Virgin/Muddy River or even the Colorado River. How is it possible that 36,000 afy could be tributary to a river system yet unknown by geologists mapping the Colorado River prior to the construction of Hoover Dam? The only model we have to answer such a question is the Littlefield Springs in the Lower Virgin River in Arizona. These springs have been described by Glancy and Van Denburgh (1969), Trudeau (1979), and Cole and Katzer (2000). The average discharge of these springs is about 50 - 60 cfs, not dissimilar to the outflow from the study area, and provides the base flow of the Lower Virgin River. Well over a hundred spring orifices and seeps discharge directly to the river from the channel bed and banks over about eight miles, which equals an acreation rate of about 7 cfs per linear mile of channel. Most of these orifices are within the low-water channel and can not be seen unless the river is at very low flow and there is virtually no sediment being transported. This is a condition never seen in the Colorado River, which by contrast is wide, deep and carries a large sediment load that would preclude the observation of springs emanating from its bed and lower banks. This is one explanation of several for ground-water outflow from the White River and Meadow Valley Flow Systems.

Table 4-7. Mountain Front Runoff at Selected Sites in Coyote Spring and Kane Springs Valley.

Site No. on Figure	Active Channel Width (ft.)	Annual Runoff (af.)	Estimated Channel Loss (afy)	Channel Sediment Characteristics
COYOTE SPRING VALLEY				
1	7	200		Some cobbles, gravel and sand
2	18	880	700	Cobbles, gravel and sand
3	7	200		Gravel
4	26	1,600		Course sand
5	43	3,400	2200	Minor gravel, coarse sand
6	22	1,200		Gravel, coarse sand, some silt
KANE SPRINGS VALLEY				
1	25	1,460	700	Boulders ~ 4 ft., cobbles, gravel
2	17	800	}200	Boulders, cobbles, gravel, coarse sand
3	14	600		Boulder, cobbles, gravel
4	29	1,840		Gravel, sand; cobbles/boulders
5	30	1,940	700	Gravel and coarse sand
6	22	1,200		Gravel and coarse sand, some cobbles, and silt
7	36	2,600	}400	Gravel and coarse sand
8	33	2,250	}400	Gravel and coarse sand
9	29	1,850		Gravel and coarse sand
Total			5,300	

4.5.1 Evapotranspiration

Evapotranspiration (ET) is the process whereby water is returned to the atmosphere through evaporation from soil, wet plant surfaces, open water bodies and transpiration from plants. The type of plants we are most concerned with are termed phreatophytes as first defined by Meinzer (1927) as "plants that habitually grow where they can send their roots down to the water table or the capillary fringe immediately overlying the water table and are then able to obtain a perennial and secure supply of water". The plant assemblage of interest is composed primarily of greasewood (*Sarcobatus vermiculatus*), saltgrass (*Distichlis spicata*), rabbitbrush (*Chrysothamnus nauseosus*), saltbush (*Atriplex canescens*), spiny hopsage (*Grayia spinosa*), shadscale (*Atriplex confertifolia*), and big sagebrush (Artemisia tridentata). There is also a riparian plant assemblage that is of interest and this includes cottonwood (*Populus fremontii*), willow (*Chilopsis linearis*), saltcedar (*Tamarix ramosissima*), mesquite (*Prosopis glandulosa*), and tules (*Typha sp.*).

Water-use rates for phreatophytes in the study area were first estimated starting nearly a half century ago. More recently, in the last ten years, research has shown that the early estimates of water use were low. This recent research in Nevada was conducted mainly by the University of Nevada, Department of Biological Sciences, and the USGS. Of particular importance is the work of Devitt et al., (1998) who conducted a three year study of ET from a stand of salt cedar on the floodplain of the lower Virgin River about 3 miles upstream from Lake Mead. The ET rate varied from a low of 2.8 af to a high of 4.8 af and these values may not represent the actual minimum and maximum caused by climatic differences. This particular ET rate is controlled by the availability of relatively shallow ground water provided by recharge from stream flow, canopy development, atmospheric demand, and the degree of advection (Devitt et al., 1998). Smith et al. (1998) have indicated that the leaf-level transpiration rates along the Virgin River are similar to native species, but in general have a higher transpiration rate than do other native plants. These interpretations probably apply in general to ET throughout the study area and in particular to Lower Meadow Valley Wash and the Muddy River area. In Las Vegas Valley Devitt et al. (in review, 2000) reevaluated ET first estimated by Malmberg (1965) for pre-development conditions in 1905. This reevaluation shows an increase in ET over the original USGS estimate by about 60 percent.

USGS research conducted by Nichols (2000) in 16 valleys in central and eastern Nevada also dramatically increases the ET compared to the original estimates made by earlier USGS investigators. Nichols (2000) increased the ET by an average factor of about 2.7. To match this discharge requires an increase in ground-water recharge of about 2.8 times the original estimates. Nichols (2000) showed that ET rates vary widely, and are similar to the variability defined by Devitt et al. (1998) along the Virgin River. This variability of ET with time and changing climatic conditions casts some uncertainty into ground-water budgets that rely on annual averages.

The two valleys that are common to this study and the study by Nichols (2000) are Long and Jakes Valleys. The ground-water recharge and discharge for these two valleys used in this study are based entirely on the techniques and data described in this study. We did use Nichols' (2000) estimate of ET for both valleys and his distribution of outflow by percent from Long Valley. In other valleys of this study (White River, Garden, Cave, Pahranagat, Lake, Patterson, Spring, Eagle, Rose, Panaca, and Clover) the ET rate for phreatophytes was estimated based on plant density, usually estimated between 10 and 20 percent and an average leaf area index of 2. These factors were substituted into Nichols equation No. 3 (2000, Chapter A, p. A6) to estimate the annual ET rate based on plant cover. The ET rate is very sensitive to densities under 35 percent and, for instance, a 5 percent increase from 15 to 20 percent nearly doubles the rate.

compare Nichols technique

ET rates for Valleys in the model area are based on the work of Devitt et al. (1998, and in review 2001). The same ET rate of 5 af/acre/year is used throughout this area for agriculture and phreatophytes. This rate was used by the USGS and is in the range reported by the HRCS.

The land use and acreage were determined from LANDSAT scenes (July 1998) and virtually all areas were field checked. In the southern end of the flow systems aerial photographs for 1953 and 2000 were used in addition to LANDSAT scenes. Water-use rates used in this study are listed in **Table 4-8** and are compared to rates used by previous USGS investigators for phreatophytes and the Natural Resource Conservation Service (NRCS, formally the Soil Conservation Service) for agriculture. Additionally, and not referenced in **Table 4-8**, are the evaporation rates from open water; these values were taken from Shevenell (1996). The specifics of the valleys in the study area are discussed as follows:

Table 4-8. Water-use rates for valleys with significant ground-water discharge.

Valley	Land use[1] and area (ac.)	Water-Use Rates				
		Acre-feet/acre/year[2]			Volume (afy)	Total Volume (afy/valley)
		This study	USGS[3]	NRCS[4]	This study	This study
Long[5]	P/21,882	--	Variable	--	--	11,000
Jakes[5]	P/416	--	Variable	--	--	600
White River[6]	P/147,211	0.3	6/	--	44,736	
	A/14,736	2.0	--	2 - 4.5	29,472	
	W/1,975	3.0	--	--	5,925	79,560
Garden[7]	P/6,144	0.75	--	--	4,608	4,608
Cave[8]	P/9,272	0.3	--	--	2,781	
	A/1,021	2.0	--	2 – 4.5	2,042	4,823
Pahranagat[6]	P/1,431	0.45	6/	--	644	
	A/6,256	5.0	--	3.5 - 6	31,280	
	W/1,289	5.0	--	--	6,445	38,369
Upper Muddy	P/1,016	5.0	5.0	--	5,080	5,080
California Wash	P/1152	5.0		--	5,760	5,760
Lake	P/6,654	0.45	0.1 – 1.5	--	2,994	
	A/6,883	3.0	--	2.5 -5	20,649	23,643
Patterson	A/1,607	3.0	--	2.5 - 5	4,821	4,821
Spring	P/1,548	0.45	0.1 – 1.5	--	697	
	W/45	3.0	--	--	135	832
Eagle	A/549	2.0	3.0	2.5 - 5	1,098	1,098
Rose	A/350	2.0	3.0	2.5 - 5	700	700
Dry	P/153	0.45	0.1-0.2	--	69	
	A/2,039	2.0	3.0	2.5 - 5	4,078	
	W/58	4.0	--	--	232	4,379
Panaca	P/145	0.45	0.1-0.2	--	65	
	A/8,649	3.0	3.0	2.5 - 5	25,947	26,012
Clover	P/101	0.45	0.2-0.5	--	45	
	A/1,066	2.0	3.0	2 - 4	2,132	2,177
L. Meadow Valley Wash	P/3,854	5.0	0.1-3	--	19,270	
	A/1,576	5.0	5.0	3 - 7	7,880	27,294
Lower Moapa	P/5,301	5.0	--	5 - 7	26,505	26,505

[1] *Abbreviations: P, Phreatophytes; A, Agriculture; and W, open water.*
[2] *If no value is listed then no estimate was made or the estimate was not available.*
[3] *Values referenced are from appropriate USGS Reconnaissance and Bulletin Series.*
[4] *Consumptive use values according to the Natural Resource Conservation Service (NRCS, formally the Soil Conservation Service, 1981), taken from sites closest to indicated valley (rounded to nearest half foot) and represent the range for alfalfa and pasture.*
[5] *Nichols (2000, p. C42-43).*
[6] *Eakin (1966, Table 1) indicates that evapotranspiration is equal to regional spring discharge.*
[7] *Land use acreage includes several hundred acres of undifferentiated agriculture*

4.5.1.1 White River Valley

There are three types of ET that represent current conditions; ET from phreatophytes, agriculture, and open water. Clearly this was not the case in predevelopment times, because there was no agriculture. However, phreatophytes and open water under natural conditions most likely covered the land that is currently being irrigated. There are some irrigated lands on higher parts of the alluvial fans that undoubtedly did not support phreatophytes, but it was beyond the scope of this project to make this determination. Eakin (1966) did not map the phreatophytes, but simply indicated that ET probably took up the spring discharge of 37,000 acre-feet/year. We believe the valley, under natural conditions, had a very high water table near land surface over large areas with extensive marsh land and that the ET rate was much greater than estimated by Eakin. Ground-water levels remain high today along the central axis of the valley, in spite of the numerous wells used for irrigation. Thus ground-water discharge and associated land areas under natural conditions are replaced by pumping for agriculture. We assume the higher rate of ET for agriculture verses the ET rate for phreatophytes is justified to represent natural conditions. The total ET for this valley is estimated at 80,000 acre-feet/year and it falls within the range and magnitude for other large valleys where ET was estimated by Nichols (2000), such as Railroad Valley to the west and Steptoe and Spring Valleys to the east.

4.5.1.2 Garden Valley

There are agriculture lands that are adjacent to perennial drainages such as Cherry and Pine Creeks. These are prime areas for phreatophytes and we believe under natural conditions the lower reaches of these drainages and their relatively small flood plains were covered with phreatophytic vegetation. Many of the canyons draining the east slope of the Quinn Canyon Range and the southern end of the Grant Range have numerous springs of varying discharge. Most of this water is captured by local ET, but some undoubtedly infiltrates to the valley ground-water system. Eakin (1966, Table 1) estimated 2,000 acre-feet/year for ET and we have increased this estimate to 5,000 acre-feet/year.

4.5.1.3 Cave Valley

The single estimate of ET is reported by Eakin (1966, Table 1) to be a few hundred acre-feet/year, however there is a large playa with a healthy stand of greasewood in the south end of the valley. A monitoring well constructed on the southwest side of the playa within the greasewood assemblage showed the water table to be about 30 feet below land surface. The water is obviously perched because most of the other wells (Brothers et al., 1993, Table 1, p. 6) have reported depths over 100 feet to water. Even though part of the ground-water system is perched it is still part of the total water resource for the valley. If the water were not perched it would have infiltrated to the main valley aquifer. The playa altitude is about 6,000 feet, nearly 1,000 feet lower than the north end of the valley so ground water could have reached the playa from the north. However, because the valley floor is well within altitudes commonly accepted as recharge areas we believe there is a component of ground-water recharge that takes place directly from the valley floor and is the principal source of the perched water table. There are other numerous springs in the mountain blocks and there is some agriculture of mostly meadow grass. We estimate the ET for this valley at 5,000 acre-feet/year.

4.5.1.4 Pahranagat Valley

This long and narrow valley floor has been converted from phreatophytes to agriculture. Under natural conditions the floor was probably covered by a dense growth of phreatophytes that, according to Eakin (1966, Table 1) consumed only the estimated regional spring discharge of 25,000 acre-feet/year. Our rationale for increasing this amount to 38,000 acre-feet/year is the same as discussed previously for White River Valley. Water levels were probably shallow and resulted in large marshy areas in the southern and northern parts of the valley. The now breached and dry Maynard Lake at the extreme south end of the valley probably indicates the abundance of water during natural conditions and a redistribution of ET under current conditions.

4.5.1.5 Upper Muddy Springs

The hydrographic area for the Muddy Springs has about 5,000 afy of natural ET. The distribution of ET upstream and downstream of the USGS gage (Muddy River near Moapa) is about 3,000 and 2,000 acre-feet/year respectively. The estimated ET (this study) upstream from the river gage agrees closely with Eakin's (1966, Table 1) original estimate of 2,300 acre-feet/year. Unlike ET estimates in other valleys current conditions for ET were not estimated. The reason for this is natural ET conditions were needed to determine if there were any impacts to total spring discharge. Within error of all hydrologic measurements by many investigators, the volume of spring discharge today appears to be equal to predevelopment conditions.

4.5.1.6 California Wash

Phreatophytic vegetation along the Muddy River corridor during predevelopment conditions was probably dominated by Mesquite and salt grass. The relatively flat flood plain where these phreatophytes grew has been converted to agriculture. We estimate the predevelopment ET was about 6,000 afy.

4.5.1.7 Lake Valley

Spring discharge along the west side of the valley undoubtedly accounted for much of the predevelopment ET. The larger springs are in the northwest part of the valley and under natural conditions there would have been an even larger marshy area than there is today. There is a large amount of agriculture land currently under production that is irrigated by ground-water pumpage and water levels are within a few 10s of feet of land surface throughout much of the valley. We believe that most, if not all, of this land was type converted from natural areas of phreatophytes, mostly the greasewood assemblage, to agriculture. ET for this valley is estimated at 24, 000 afy and is assumed to represent predevelopment conditions.

4.5.1.8 Patterson Valley

There are no remnants of natural ET left in this valley. The estimated ET today of about 5,000 afy is based on agriculture usage. Under natural conditions there was probably a much higher water table than currently exists and Patterson Wash would have had a significant amount of phreatophytes, mostly greasewood, particularly along its lower reach.

4.5.1.9 Panaca Valley

The predevelopment water table in this valley was undoubtedly very near land surface, and despite large scale agricultural development, large areas of standing water are common. Meadow Valley Wash is perennial today and even though there are significant still flows several thousand afy. So under natural conditions the flow was probably much larger. Additionally permeable carbonate rocks are at land surface and are in contact with less permeable volcanic rocks which tends to bring water closer to land surface. Phreatophytes and marsh land probably occupied much of the lands now under agriculture, and the predevelopment ET is estimated to be about 26,000 afy.

4.5.1.10 Remaining Valleys in the White River Flow System

Coal, Pahroc, Dry Lake, Delamar, Kane Springs, Coyote Spring, Hidden, and Garnet Valleys have only small amount of ET. The ET from Hidden and Garnet Valleys is virtually zero. The ET was estimated at a token 1,000 acre-feet/year for each of the other valleys to account for local spring discharge that is consumed including evaporation from bare soil. Most of the springs in these valleys are in the mountain blocks, some have been developed for stock watering. The hydrology of Black Mountain is dominated by surface flow in Las Vegas Wash and also the ET along the wash. These components are not part of this study

Estimates of ET and ground-water outflow are listed in **Table 4-9** and are compared to previous USGS estimates. In general the ET has been increased significantly in this study compared to previous estimates, although only minimally in some valleys. Ground-water outflow is also increased because the ground-water recharge is much higher than previously estimated.

4.5.2 Spring Flow in Model Area

Surface-water discharge in the model area occurs in Kane Springs Wash, Coyote Spring Valley, Lower Meadow Valley, California Wash, the Muddy Springs Area, and Black Mountains Area. The major springs in the model area are shown in **Figure 4-11**.

Several small springs discharge in Kane Springs Wash, Coyote Spring Valley, and California Wash at rates generally less than a few hundred acre-feet per year. The discharge from these springs is consumed locally through ET. In Kane Springs Valley the numerous small "local" springs are not part of the large regional carbonate aquifer system. These local springs are generally in volcanic rock and reflect local recharge and discharge. A single discharge point at the location of Kane Springs was used in the ground-water model to represent the diffuse local

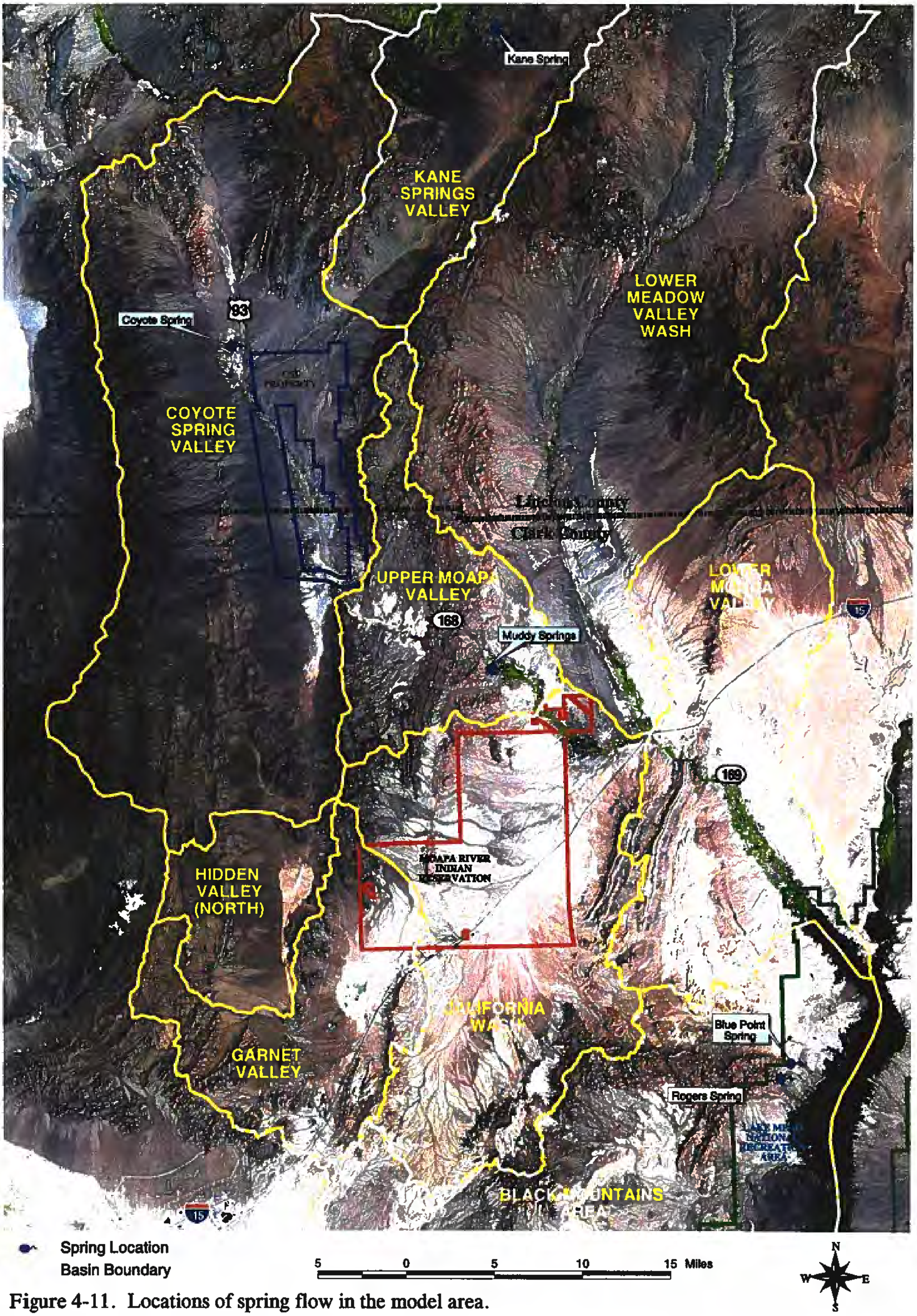

Figure 4-11. Locations of spring flow in the model area.

springs and associated ET in Kane Springs Valley. In Coyote Spring Valley several small springs exist in the mountain block, but a single discharge point at Coyote Spring, located on the valley floor in the northern end of the valley was utilized as the location of ET for the water budget and ground-water model in this study. California Wash has a couple of small local seeps south of the Muddy River that discharge very small volumes of water. These seeps were not considered significant in the overall water budget.

Table 4-9. Comparison of discharge estimated by previous USGS investigators and this study, in acre-feet/year. Numbers in *italics* are this study.

<table>
<tr><th rowspan="2">Valley</th><th colspan="3">Discharge</th><th colspan="2" rowspan="2">Total Discharge</th></tr>
<tr><th>ET</th><th colspan="2">Ground-water Outflow</th></tr>
<tr><td colspan="6">WHITE RIVER FLOW SYSTEM</td></tr>
<tr><td>Long</td><td>2,200[a]/*11,000*</td><td colspan="2">8,000[a]/*12,000*</td><td colspan="2">10,200/*23,000*</td></tr>
<tr><td>Jakes</td><td>Minor/*600*</td><td colspan="2">17,000/*35,000*</td><td colspan="2">17,000/*36,000*</td></tr>
<tr><td>Cave</td><td><1,000/*5,000*</td><td colspan="2">14,000/*15,000*</td><td colspan="2">14,000/*20,000*</td></tr>
<tr><td>White River</td><td>37,000/*80,000*</td><td colspan="2">40,000/*32,000*</td><td colspan="2">77,000/*112,000*</td></tr>
<tr><td>Garden</td><td>2,000/*5,000*</td><td colspan="2">8,000/*14,000*</td><td colspan="2">10,000/*19,000*</td></tr>
<tr><td>Coal</td><td>Minor/*1,000*</td><td colspan="2">10,000/*20,000*</td><td colspan="2">10,000/*21,000*</td></tr>
<tr><td>Pahroc</td><td>Minor/*1,000*</td><td colspan="2">42,000/*59,000*</td><td colspan="2">42,000/*60,000*</td></tr>
<tr><td>Pahranagat</td><td>25,000/*38,000*</td><td colspan="2">35,000/*28,000*</td><td colspan="2">60,000/*66,000*</td></tr>
<tr><td>Dry Lake</td><td>Minor/*1,000*</td><td colspan="2">5,000/*12,000*</td><td colspan="2">5,000/*13,000*</td></tr>
<tr><td>Delamar</td><td>Minor/*1,000*</td><td colspan="2">6,000/*16,000*</td><td colspan="2">6,000/*17,000*</td></tr>
<tr><td>Kane Spring</td><td>Minor/*1,000*</td><td colspan="2">NR/*6,000*</td><td colspan="2">NR/*7,000*</td></tr>
<tr><td>Coyote Spring</td><td><1,000/*1,000*</td><td colspan="2">36,000/*53,000*</td><td colspan="2">36,000/*54,000*</td></tr>
<tr><td>Hidden</td><td>0/*0*</td><td>300/</td><td rowspan="2">*17,000*</td><td colspan="2" rowspan="2">600/*17,000*</td></tr>
<tr><td>Garnet</td><td>0/*0*</td><td>600/</td></tr>
<tr><td>California Wash</td><td>/*6,000*</td><td colspan="2">1/*41,000*</td><td colspan="2">/*47,000*</td></tr>
<tr><td>Black Mountains</td><td>1,200/*2,000*</td><td colspan="2">400/*0.3*</td><td colspan="2">1,600/*2,000*</td></tr>
<tr><td>Upper Moapa</td><td>2,300/*5,000*</td><td colspan="2">36,000/*32,000*[b]</td><td colspan="2">38,000/*37,000*</td></tr>
<tr><td colspan="6">MEADOW VALLEY FLOW SYSTEM</td></tr>
<tr><td>Lake</td><td>8,500/*24,000*</td><td colspan="2">3,000/*17,000*</td><td colspan="2">11,500/*41,000*</td></tr>
<tr><td>Patterson</td><td>80/*5,000*</td><td rowspan="8">*7,000*[c]</td><td>*28,000*</td><td rowspan="8">27,000[c]</td><td>*33,000*</td></tr>
<tr><td>Spring</td><td>1030/*1,000*</td><td>*15,000*</td><td>*16,000*</td></tr>
<tr><td>Eagle</td><td>290/*1,000*</td><td>*16,000*</td><td>*17,000*</td></tr>
<tr><td>Rose</td><td>10/*700*</td><td>*16,000*</td><td>*17,000*</td></tr>
<tr><td>Dry</td><td>10/*4,000*</td><td>*16,000*</td><td>*20,000*</td></tr>
<tr><td>Panaca</td><td>530/*26,000*</td><td>*27,000*</td><td>*53,000*</td></tr>
<tr><td>Clover</td><td>210/*2,000*</td><td>*9,000*</td><td>*11,000*</td></tr>
<tr><td>Meadow Valley Wash</td><td>20,000/*27,000*</td><td>*32,000*</td><td>*59,000*</td></tr>
<tr><td>Lower Moapa</td><td>25,000/*26,000*</td><td colspan="2">11,000[b]/*48,000*[b]</td><td colspan="2">36,000/*74,000*</td></tr>
</table>

a. Eakin (1961), Not Nichlos (2000).
b. Combination of ground and surface water.
c. Rush (1964) lumped all ET, added ET to estimated outflow and subtracted from ground-water recharg.e

The major spring flow in the model area occurs in the Muddy Springs Area, Lower Meadow Valley Wash, and the Black Mountains Area. The Muddy Springs Area has several discrete springs orifices (possibly 30) with varying discharge as described by Eakin (1964). Numerous channels funneling the spring discharge into the Muddy River. These springs are the major surface-water outflow for the White River Flow System. The Muddy Springs are characterized in this study using 3 large springs and the discharge is calibrated to the measured flow as described in Section 5 and Section 8.

Lower Meadow Valley Wash has two carbonate springs at Rox and Ferrier. These springs were not explicitly defined in the model but were treated as part of the ET discharge within the valley.

In the Black Mountains Area along the shore of Overton Arm of Lake Mead, there are several springs referred to as the North Shore Complex (Pohlmann et al., 1998). These springs are located along a series of faults that are part of the Lake Mead Fault Zone (Anderson and Barnhard, 1993a). These springs are idealized as two springs, Rogers and Blue Point Springs and the discharge was calibrated to the measured flow as described in Section 5.0 Surface Water in Model Area.

5 SURFACE WATER IN MODEL AREA

Surface-water flow in the model area occurs in the Muddy Springs area of Upper Moapa Valley, the Black Mountains Area, and Lower Meadow Valley Wash. The dominate surface-water flow is at the Muddy Springs area which flows as the Muddy River through Upper Moapa Valley, California Wash, and Lower Moapa Valley terminating in Lake Mead. The USGS has maintained gaging stations at various locations in some of the Valleys in the modeled area since 1913 **(Figure 5-1)**. The long-term records from these gages are used in the water budget calculations in conjunction with the development and calibration of the ground-water flow model in this study.

5.1 MEASURED FLOWS

5.1.1 Moapa Gage

The largest volume of water discharged in the model area is to the Muddy Springs and is the principal source of ground-water discharge in the White River Regional Flow System (Eakin, 1964). USGS gaging station *09416000 Muddy River near Moapa, NV* (Moapa gage) is located downstream of the springs and measures the baseflow of the springs (i.e. the Muddy River) less surface-water diversions and ET between the gage and the springs (**Figure 5-2**). Records of flow were collected intermittently from 1913 to the present (U.S. Geological Survey Water-Data Reports, Water Years 1913 through 1999).

Runoff from local precipitation events contributes additional stream flow measured at the Moapa gage, which is referred to as flood flows in this study. These flood flows need to be removed from the daily mean flows to determine the actual baseflow at the gage. To remove the flood flows from the daily mean flows, all days with flood flows were identified and the median monthly flow used in its place. This method is described in Johnson (1999, Appendix 2.1 to the *Las Vegas Wash Comprehensive Adaptive Management Plan*).

The annual average flow at the Moapa gage from 1913 to 1947, based on available data without flood flows, is approximately 33,900 afy (47 cfs) **(Figure 5-3)**. This period, for the purposes of this study, represents pre-development conditions, because the first well in Upper Moapa Valley was drilled in 1947 according to the NDWR Well Log Database. Eakin (1964) calculated the average flow of the Muddy Springs to be 46.5 cfs (33,700 afy) based on 25 water years from 1914 to 1962. Eakin further estimated that approximately 2,000 to 3,000 afy of spring flow was being consumed by phreatophytes between the springs and the Moapa gage, which means the spring discharge must be approximately 36,000 to 37,000 afy (50 to 51 cfs).

Figure 5-1. Locations of USGS streamflow gaging stations in the model area.

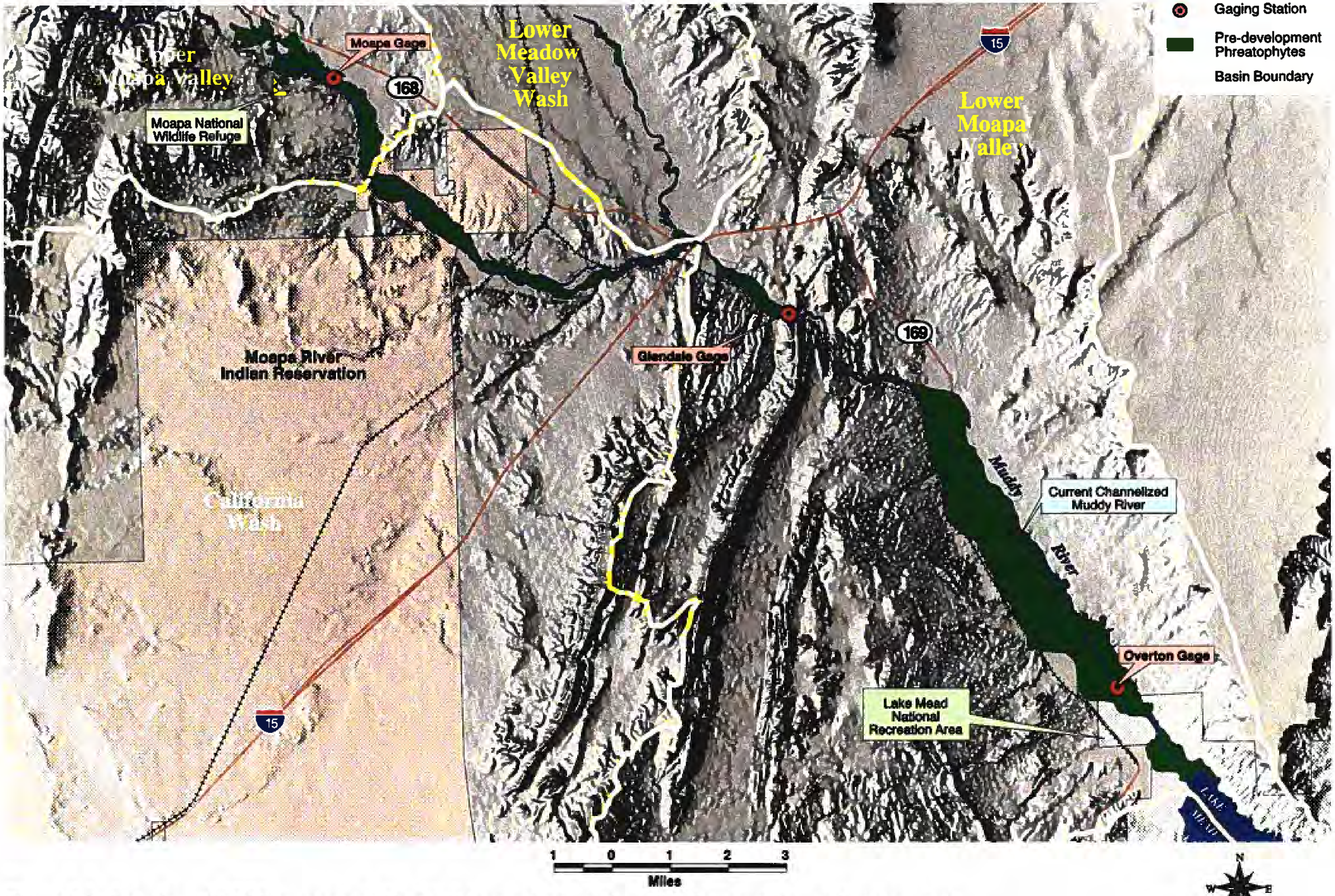

Figure 5-2. Location of USGS gages on the Muddy River and extent of pre-development phreatophyte coverage.

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Figure 5-3. Annual flow with and without flood flows at USGS gaging station *09416000 Muddy River near Moapa, NV*

Analysis of October 1953 aerial photography of the Muddy Springs area, which shows phreatophytes and established agriculture, and September 2000 aerial photography, which shows limited active farming, demonstrated that approximately 600 acres of native phreatophytes existed prior to ground-water development **(Figure 5-4)**. Applying a consumptive use factor of 5 ft per acre per year (Eakin, 1964) results in 3,000 afy of ET above the Moapa gage, which places the annual average spring discharge at 37,000 afy. This flow record is used to develop the water budget and for the calibration of the ground-water flow model.

The annual flow at the Moapa gage was approximately 25,000 af for water year 2000. This reduction in flow is due to nearby ground-water production and surface-water diversions above the gage and is discussed in detail in Section 5.2.

5.1.2 Glendale Gage

USGS gaging station *09419000 Muddy River near Glendale, NV* (Glendale gage) is located in Lower Moapa Valley and measures a depeleted baseflow of the Muddy River along with periodic flood flows from the Muddy River, California Wash, and Lower Meadow Valley Wash. This is discussed in greater detail in Section 5.2. **Figure 5-5** depicts the annual flows at the Glendale gage with and without flood flows (U.S. Geological Survey Water-Data Reports, Water Years

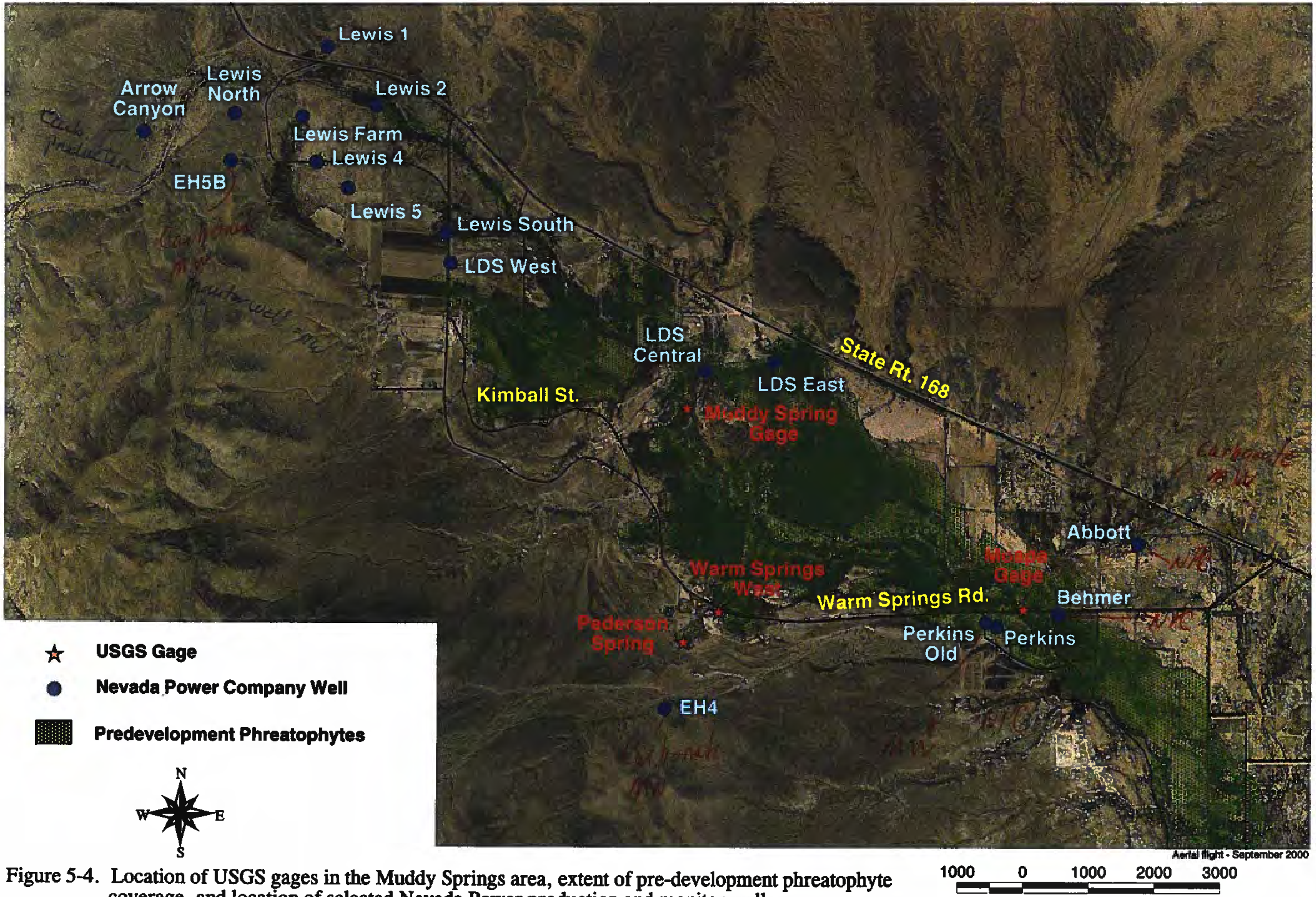

Figure 5-4. Location of USGS gages in the Muddy Springs area, extent of pre-development phreatophyte coverage, and location of selected Nevada Power production and monitor wells.

1951 through 1999). The annual average flow at the Glendale gage from 1951 to 1960 after removing flood flows is 33,600 afy. This gaged flow record is used to develop the water budget and for the calibration of the ground-water flow model.

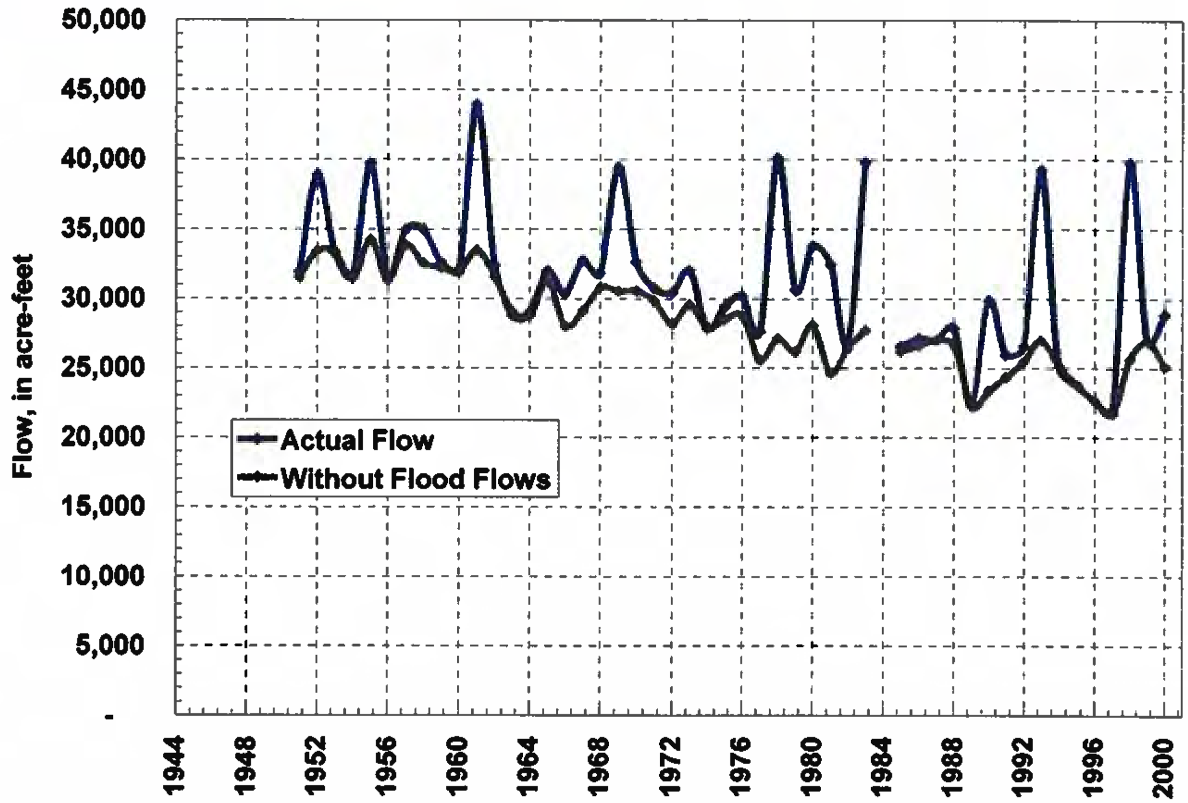

Figure 5-5. Annual flow with and without flood flows at USGS gaging station *09419000 Muddy River near Glendale, NV*

5.1.3 Overton Gage

USGS gaging station *09419507 Muddy River at Lewis Avenue at Overton, NV* (Overton gage) is located in Lower Moapa Valley approximately 1.5 miles above Lake Mead. Flows at the gage are predominantly irrigation returns, because the entire flow of the Muddy River is diverted for agricultural use by the Muddy Valley Irrigation Company at Wells Siting approximately 7 miles upstream; although, there may be ground-water inflows reflected in the flow record of the gage. This gage was installed in August 1997, and the annual flows for water years 1998 and 1999 are 12,960 af and 10,430 af respectively including flood flows. The flow record of the gage is used in the development of the water budget and during the calibration of the ground-water flow model to approximate the magnitude of surface-water flows into Lake Mead. Obtaining the current measured flows at the Overton gage was not an objective of the modeling effort, because the majority of flow is irrigation returns and a detailed analysis of the current acreage of agricultural in Lower Moapa Valley was not conducted in this study.

5.1.4 Lower Meadow Valley Wash

The USGS gaging station *09418500 Lower Meadow Valley Wash near Caliente, NV* (Caliente gage) has been operational since water year 1951. The annual average flow during water years 1951-1999 is 8,160 afy (U.S. Geological Survey Water-Data Reports, Water Year 1999) (**Figure 5-6**). Flow at the gage is influenced by snow melt, which causes the seasonal variability in the flow at the gage. Surface-water flow from the upper portion of Lower Meadow Valley Wash generally does not extend into Clark County except during flood flows. An annual average surface-water inflow of 10,000 afy from Panaca Valley is utilized in the water budget of this study, which accounts for streamflow losses due to ET above the Caliente gage within Lower Meadow Valley Wash.

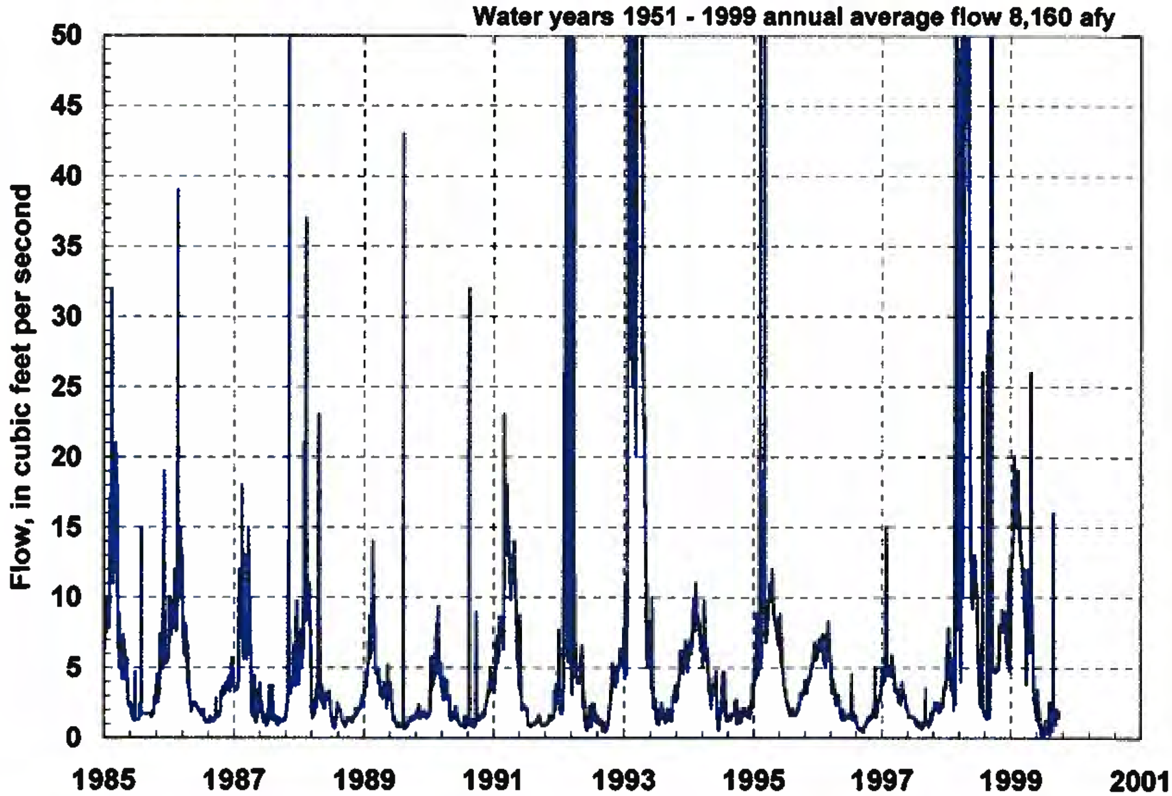

Figure 5-6. Daily mean flow at USGS gaging station *09418500 Lower Meadow Valley Wash near Caliente, NV.*

Spring flow in Lower Meadow Valley Wash also exists near Rox and Ferrier based on field investigations and historic USGS gaging stations *09418700 Meadow Valley Wash near Rox, NV* (**Figure 5-7**) and station *09418750 Meadow Valley Wash below Ferrier near Rox, NV.* Relatively small volumes of water are discharged at these sources and the water is entirely consumed through ET. These locations are utilized as ET areas in the ground-water flow model.

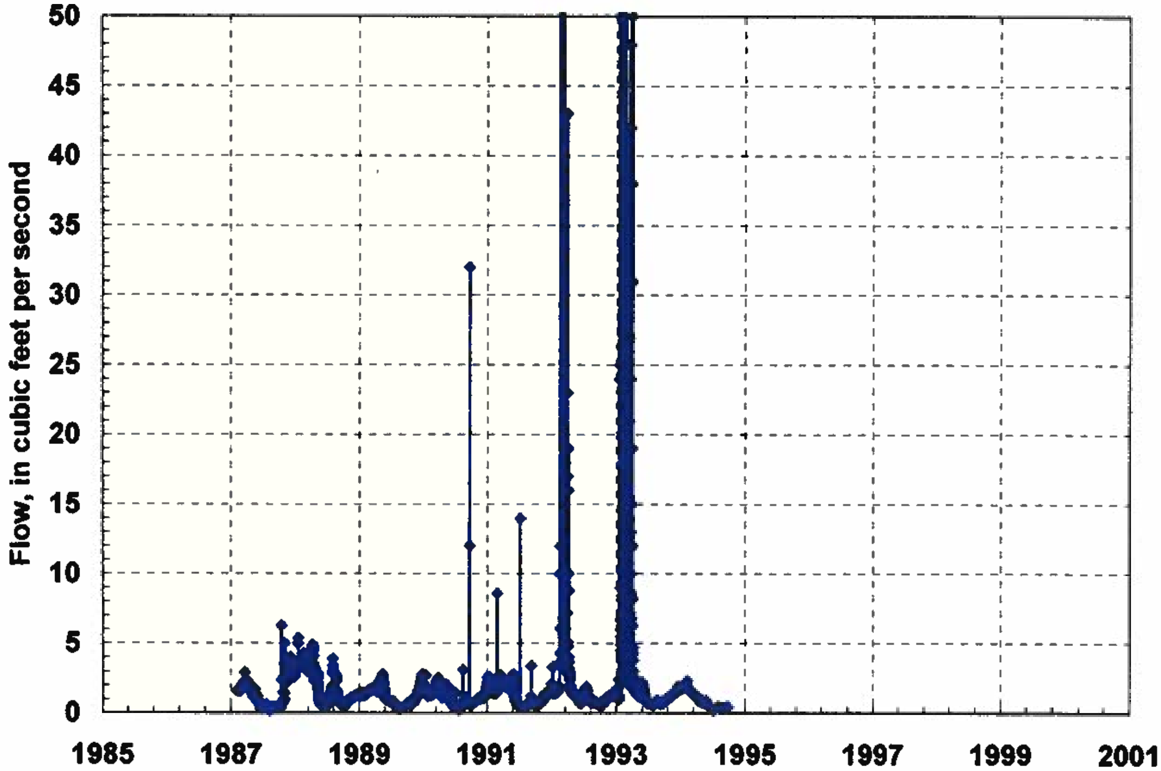

Figure 5-7. Daily mean flow at USGS gaging station *09418700 Lower Meadow Valley Wash near Rox, NV*

5.1.5 Blue Point and Roger Springs (North Shore Complex)

Springs located on the west side of the Overton Arm of Lake Mead, as a group, have been termed the North Shore Complex (Pohlmann et al., 1998). Two of the most notable springs in this complex are Rogers and Blue Point Springs. The USGS has measured Rogers Spring since October 1985, and the average flow has been relatively constant at 1.6 cfs **(Figure 5-8)** (USGS Water-Data Reports, Water Years 1984 through 1999). The average flow of Blue Point spring is 0.6 cfs. Combining these measured flows with additional flow from smaller springs in the complex, an annual average discharge of approximately 2,000 afy is utilized in the water budget and during calibration of the ground-water flow model.

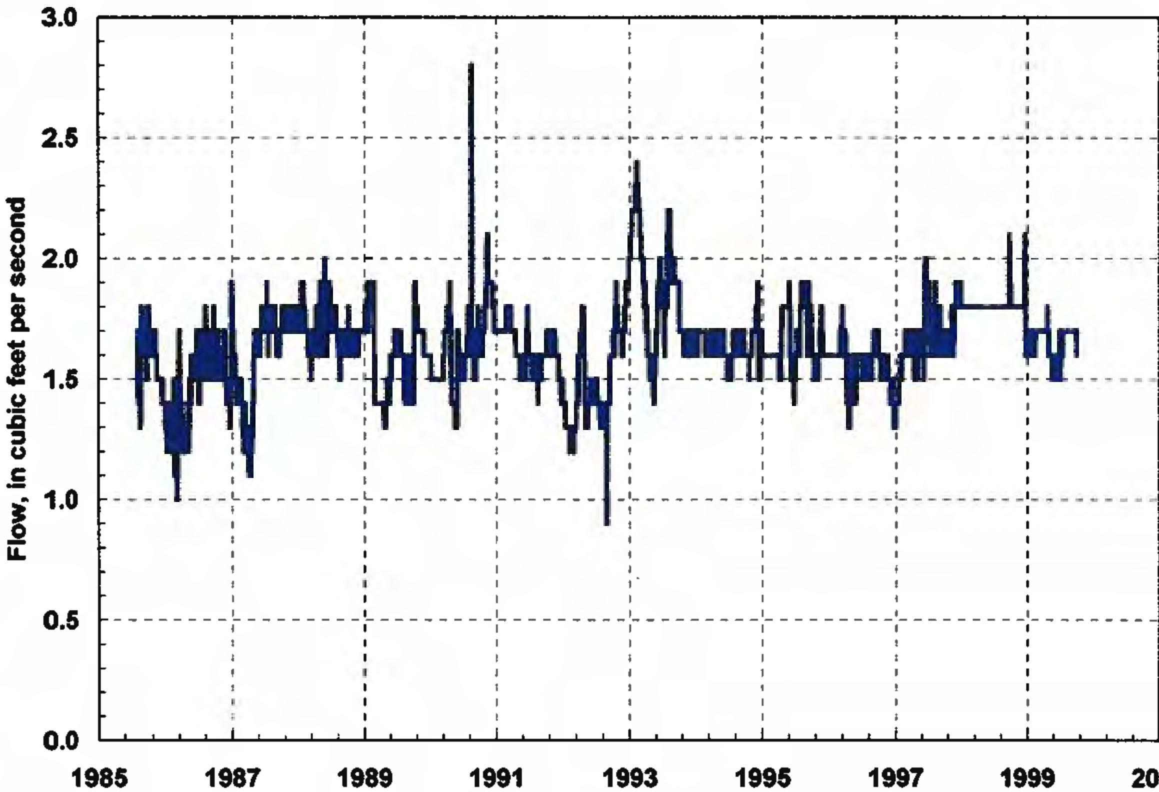

Figure 5-8. Daily mean flow at USGS gaging station *09419550 Rogers Spring near Overton Beach, NV.*

5.2 GROUND WATER AND SURFACE WATER INTERACTION

5.2.1 Muddy Springs Area

Development of water resources in the Muddy Springs area began around 1947 when the first well was drilled as described in Section 8 and Appendix B. Diversions of surface water upstream of the Moapa gage began in 1968 when the Nevada Power Company leased 1920 decreed Muddy River water rights from the Muddy Valley Irrigation Company.

A correlation exists between the ground-water pumpage in the Muddy Springs area of Upper Moapa Valley and the decline in stream flow at the Moapa gage. The measured flow at the Moapa gage without flood flows and the corresponding volume of ground-water pumpage and surface-water diversion, which are described in Section 8 and Appendix B, are shown on **Figure 5-9**. Subtracting ground-water pumpage and surface-water diversions from the pre-development stream flow of water year 1946 for each water year from 1947 to 2000 equals a theoretical flow that closely approximates the actual measured flow **(Figure 5-10)**. This suggests the decline in gage flow at the Moapa gage is directly related to ground-water pumpage and surface-water diversions. The exception to this is water years 1998 to 2000. To correct for this, only the took out carbonate pumping

valley-fill ground-water pumpage and surface-water diversions are subtracted from the pre-development stream flow of water year 1946 (carbonate ground-water pumpage is excluded), and a better comparison is achieved for water years 1998 to 2000 **(Figure 5-11)**. Inclusion of the carbonate pumpage yields a difference from the gage flow, while the exclusion of the carbonate pumpage yields a closer comparison to the gage record. This suggests that ground-water pumpage from the carbonate aquifer may not be having an effect on the flows at the Moapa gage. Future observations of stream flow and ground-water pumpage will need to be collected to further corroborate this hypothesis. The comparison of gage flow and pumpage/surface-water diversion records does not directly answer the question if spring flow is decreasing. Therefore the gage records at spring orifices were also examined.

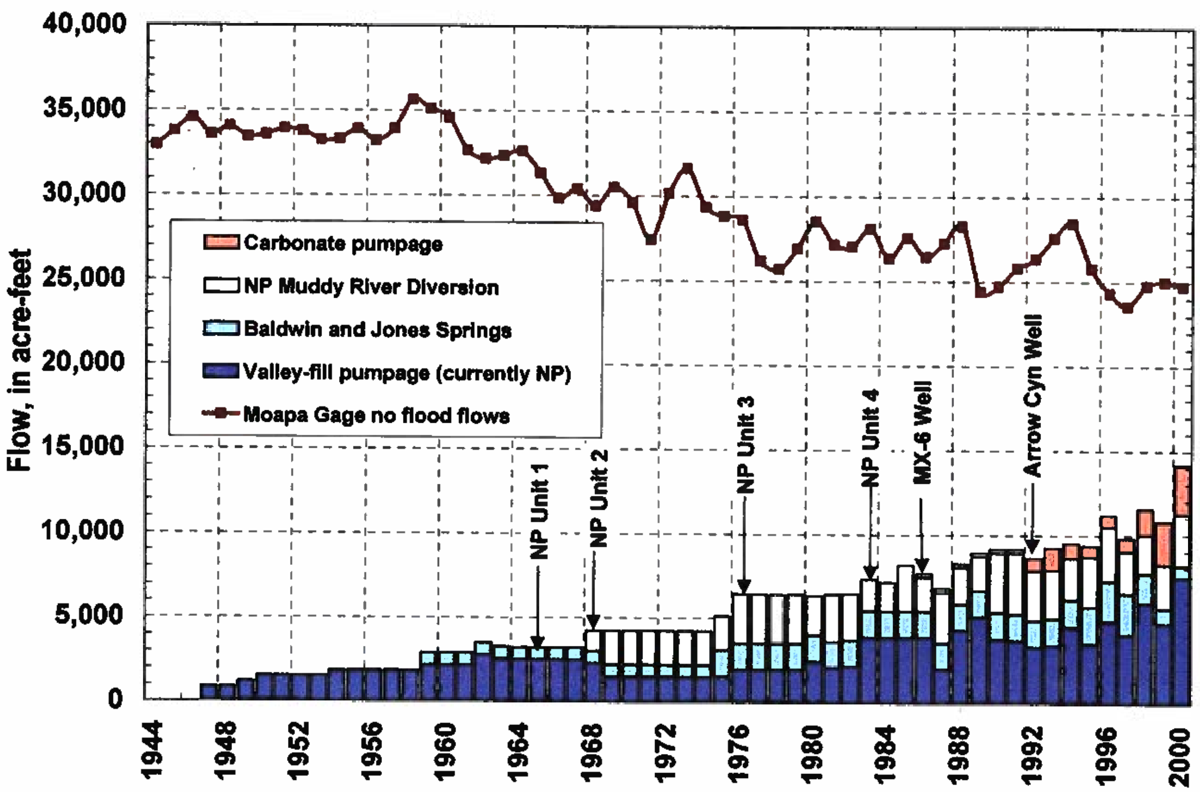

Figure 5-9. Annual flow without flood flows at USGS gaging station *09416000 Muddy River near Moapa, NV,* compared to ground-water pumpage and surface-water diversions. The year key production wells became operational as well as each generating unit at Nevada Power Company's Reid Gardner power generation station is also indicated.

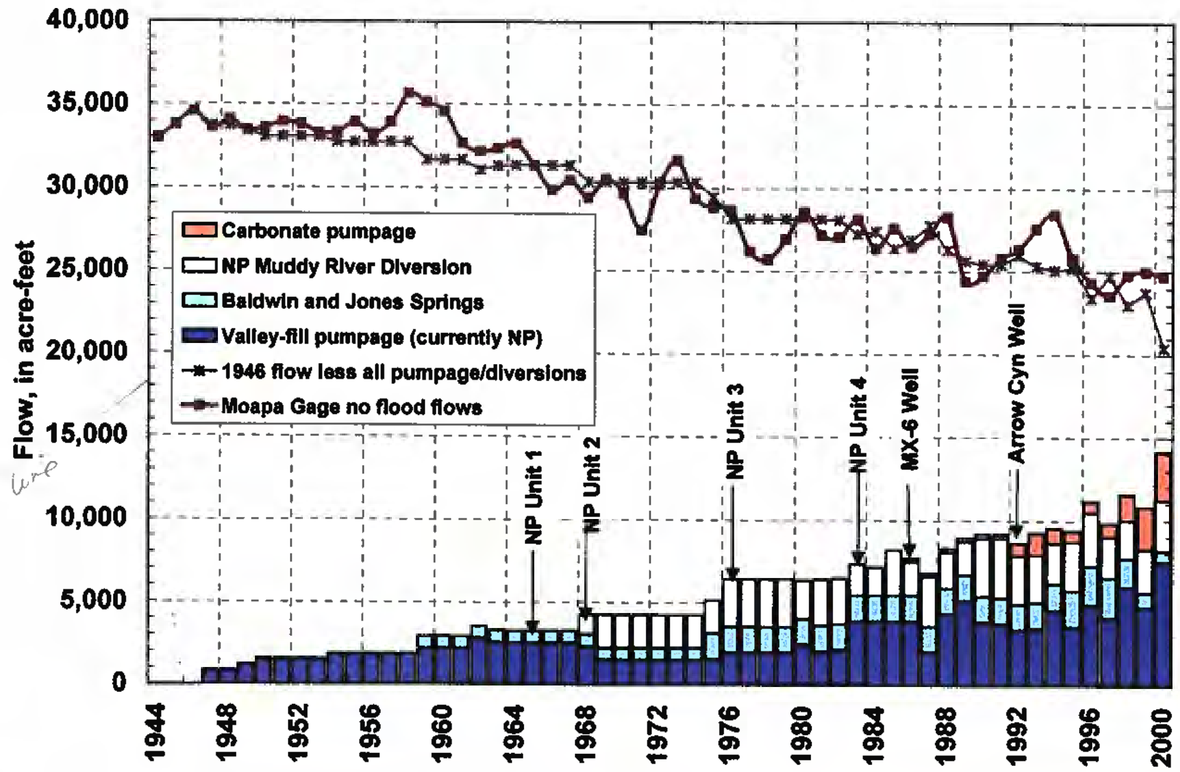

Figure 5-10. Comparison between decline in flow at the Moapa gage and nearby ground-water pumpage and surface-water diversions.

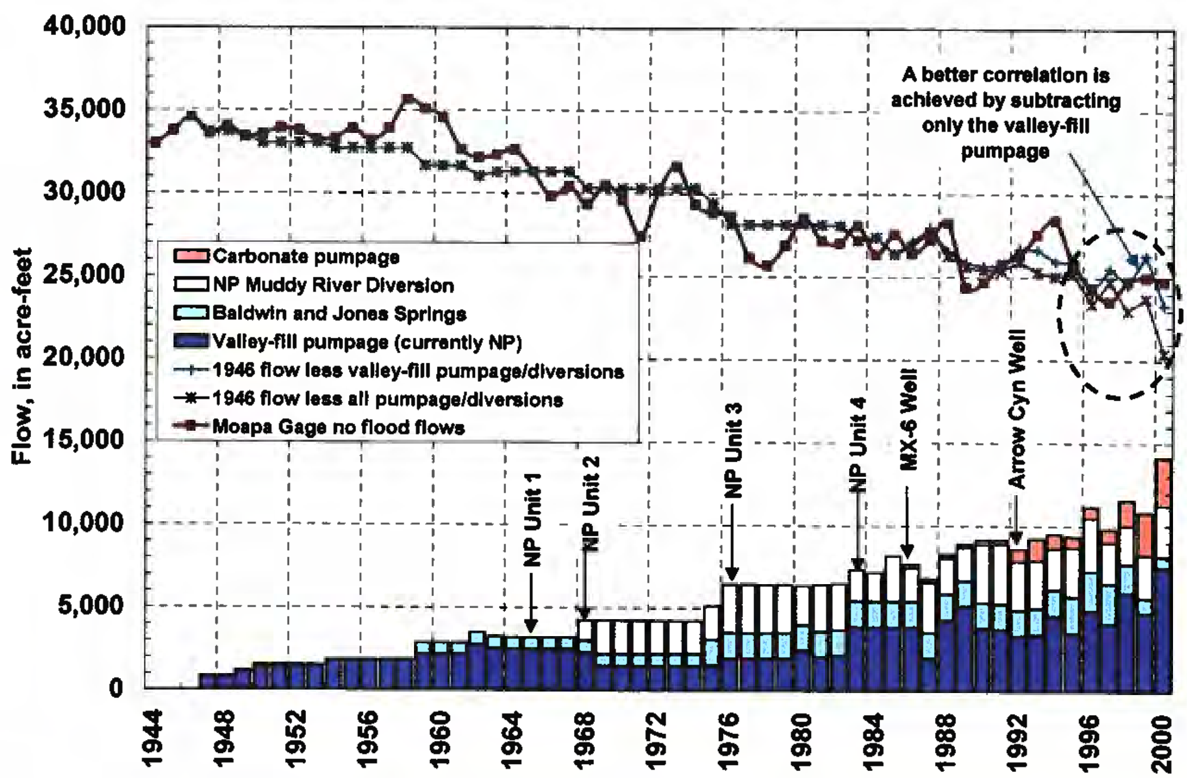

Figure 5-11. Comparison between decline in flow at the Moapa gage and valley-fill vs. carbonate ground-water pumpage and surface-water diversions

Spring discharge at USGS gaging stations: Muddy Springs at LDS Farm near Moapa, NV; Pederson Spring near Moapa, NV; and Warm Springs West near Moapa, NV show a relatively constant flow during the period of record for the gages (**Figure 5-12** and **Figure 5-4**). This spring discharge remains constant when ground-water pumpage and surface-water diversion are at an all time high. This constant flow combined with the observations at the Moapa gage that the valley-fill pumpage has caused the decline in the streamflow at the gage supports Eakin's (1964) conclusion "…ground water in the valley fill, which is a natural reservoir, is recharged largely from the springs." and "In effect, the natural regimen of the springs is one of relatively constant flow year round."

Eakin's (1964) conclusions are also supported by the fact that seasonal valley-fill ground-water pumpage occurring in the Muddy Springs area above the Moapa gage has not caused long-term, declining water levels even though they have been pumped for up to 50 years (See **Appendix C** for hydrographs on Lewis north and Lewis south wells).

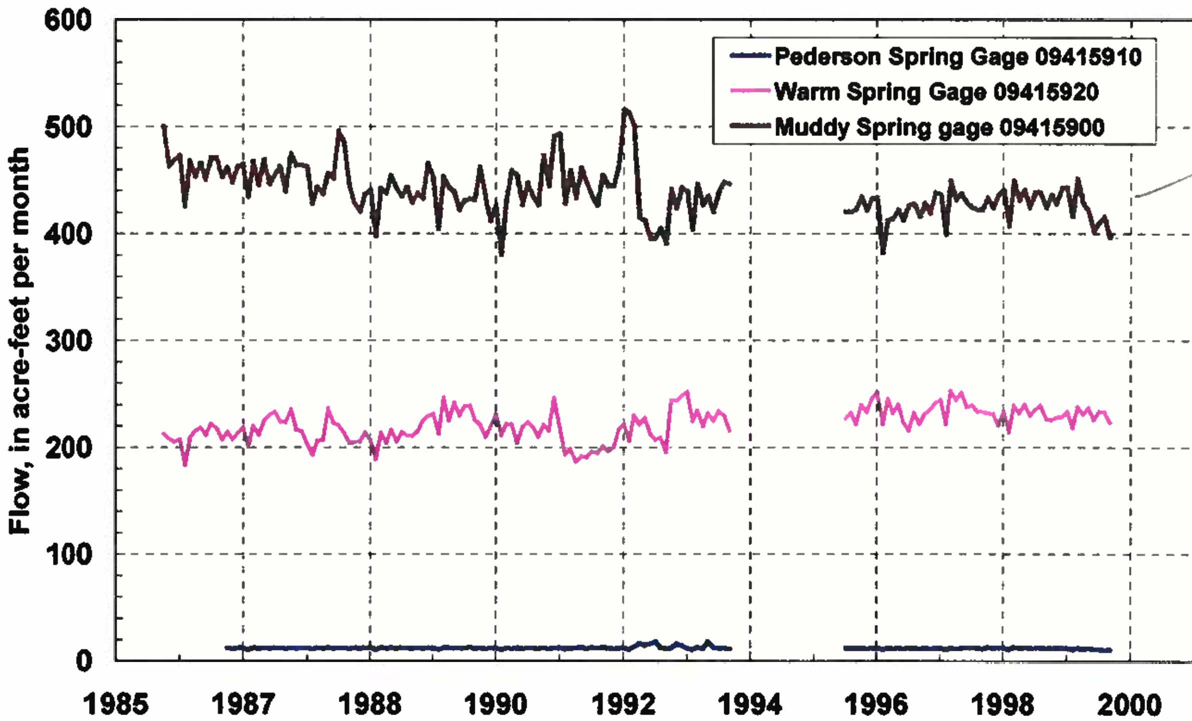

Figure 5-12. Monthly mean spring flow at three USGS gaging stations in the Muddy Springs area.

5.2.2 Moapa Gage to Glendale Gage

Approximately 1,830 acres of phreatophytes existed between the Moapa and Glendale gages under pre-development conditions. Using a consumptive use rate of 5 ft/acre the phreatophytes consume approximately 9,000 afy. Under current conditions the phreatophytes have been replaced with agricultural fields on the Moapa River Indian Reservation and the Hidden Valley

Ranch. Utilizing September 2000 aerial photography, the current estimated consumptive use continues to be approximately 9,000 afy, which is also supported by the Moapa/Glendale gage correlation discussed below.

Flows at the Glendale gage correspond to flows at the Moapa gage and do not show the 9,000 afy loss due to ET **(Figure 5-13)**. Based on the close comparison between the two gages and the calculated losses between the gages, additional inflow from California Wash and/or Lower Meadow Valley Wash is suggested. In this study approximately 9,000 afy of ground-water inflow is estimated to occur between the Moapa and Glendale gages (6,000 afy from California Wash and Upper Moapa Valley below the Moapa gage and 3,000 afy from Lower Meadow Valley Wash), thus matching the historical gage records.

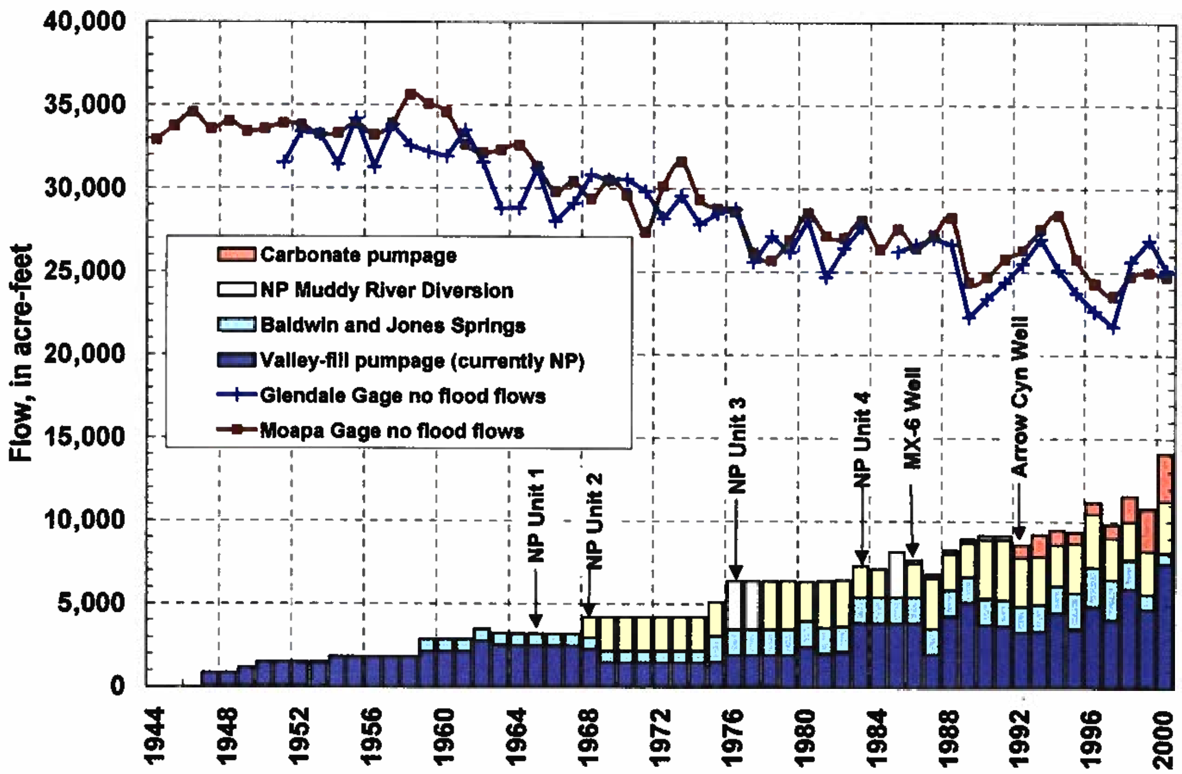

Figure 5-13. Comparison between the measured flow at the Moapa and Glendale gages without flood flows.

5.2.3 Glendale Gage to Overton Gage

The surface-water flow of the Muddy River was decreed under Nevada State Statute in 1920. Virtually all of the decreed surface-water rights in the early 1900's were utilized in Lower Moapa Valley, and based on 1944 and 1974 water right maps (Plan of Muddy River showing decreed water rights, U.S. Dept. of Interior, Office of Indian Affairs and map accompanying proof of beneficial use under permits 21847 and 21873 to 21877 respectively), the entire flood plain of the lower Muddy River was under cultivation. Due to limited availability of information about cropping patterns in Lower Moapa Valley, a detailed analysis of diversions, consumptive uses, and irrigation returns in the flood plain of Lower Moapa Valley was not performed. As stated in Section 5.1.3 the Overton gage is utilized in the development of the water budget and during model calibration only to approximate the magnitude of surface-water flows into Lake Mead since the majority of flow is irrigation returns and a detailed analysis of the current acreage of agricultural in Lower Moapa Valley was not conducted in this study.

6 WATER RESOURCE BUDGET

6.1 WATER RESOURCE BUDGET IN THE STUDY AREA

The water-resources budget for each valley in the study area is an accounting of ground-water inflow and outflow based on the local ground-water recharge, ground-water inflow if it occurs, and the local evapotranspiration. The ground-water outflow is the residual between inflow and evapotranspiration. These values are listed in **Table 6-1** and shown in **Figure 6-1**. Most of the valleys have ground-water inflow and all have ground-water outflow. The ground-water outflow from a valley becomes the inflow to the adjacent down gradient valley. There are some unknowns in this routing of ground water between valleys. We do not know, for instance, if Cave Valley is tributary to White River Valley or to Pahroc. Large structural features in the west-central part of the South Eagan Range may be an avenue for ground-water flow from Cave Valley to White River Valley. Sparse water-level data indicate the flow may be to Pahroc Valley out of the south end of Cave Valley. It makes little difference in the overall project goal, however, it does cause discontinuity between the interpretation in this routing and the geochemistry model by Thomas et al. (2001). The same is true for the ground-water flow from Coal Valley either into Pahroc Valley or Pahranagat Valley. In terms of the ground-water model this is not a problem because the model boundary has a ground-water flux across it that represents the residual ground-water outflow from all the up-gradient valleys.

In the model area for this section there is a lumping of ground- and surface-water flows together as inter-basin flow. As an example, ground-water discharge forms the surface water of the Muddy Springs and the springs become the Muddy River which is considered inter-basin flow from Upper Moapa Valley to California Wash and on into Lower Moapa Valley. Ground-water flow into the model area from Panaca Valley has a surface-water component that is not separated out. In the ground-water model the distinction is made between ground and surface water regardless of where it occurs. **Table 6-2** lists the sum of the budget components for the entire study area. The water-resources budget for the model area is listed in **Table 6-3**. These three budget variations are considered a water-resources budget which is dominated by ground water, based on the values listed in **Table 6-1**.

6.2 GROUND-WATER YIELD

Historically, in the ground-water basins of Nevada, the perennial yield for a ground-water system was based on the amount of discharge by ET that could be reasonably captured and the value varies per basin. The concept of perennial yield can also extend to the capture of ground-water outflow from major flow systems such as the White River and Meadow Valley through deep seated carbonate rocks underneath Lake Mead and the Colorado River. However, the complexity of the relationship between surface and ground-water, recharge and discharge, and geology and hydrology is such that generally the total discharge can never be captured, no matter if the discharge is from ET or ground-water outflow. This is further complicated by the vast amounts of water in storage in the carbonate aquifer and the overlying alluvial aquifers and the long transient time, measured in hundreds to thousands of years (Thomas et al., 1991), for ground water to move from recharge areas to discharge areas.

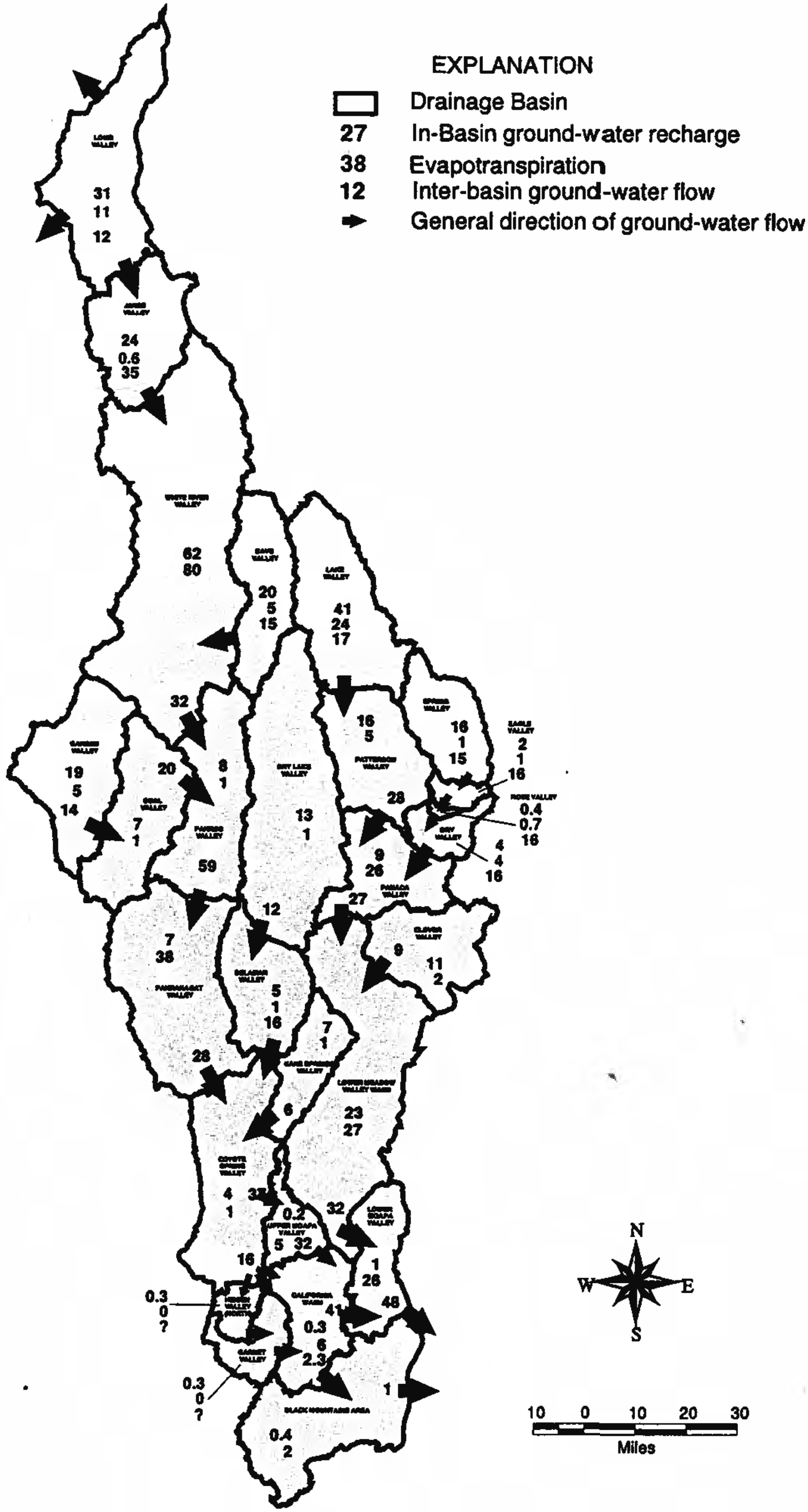

Figure 6-1. Generalized ground-water recharge, evapotranspiration, and inter-basin flow of the White River and Meadow Valley Flow Systems, units in thousands of acre-feet per year.

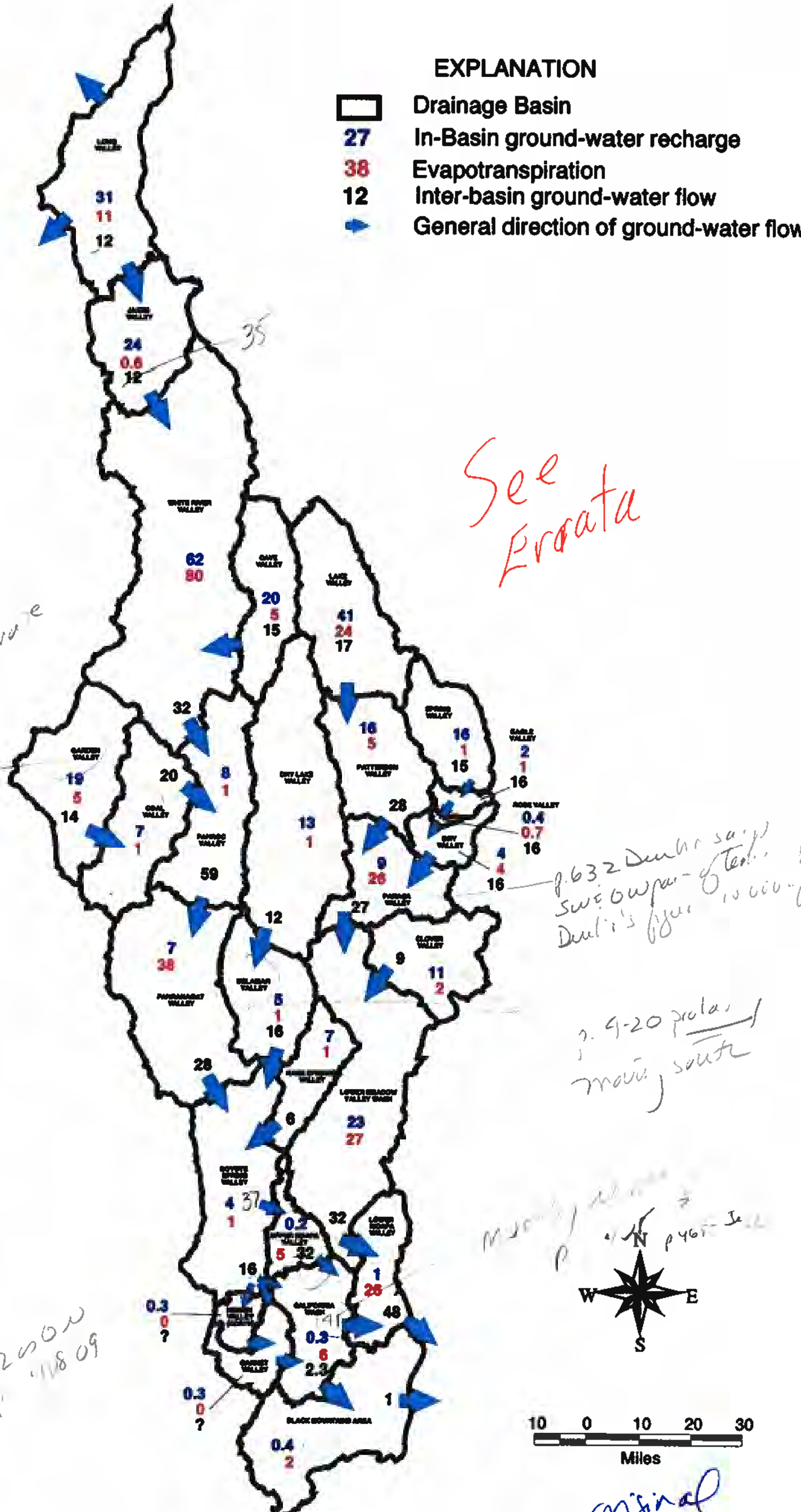

Figure 6-1. Generalized ground-water recharge, evapotranspiration, and inter-basin flow of the White River and Meadow Valley Flow Systems, units in thousands of acre-feet per year.

Table 6-1. Ground-water recharge, discharge, and inter-basin flow for selected Colorado River Basins in Nevada, in thousands of acre-feet/year (rounded).

Valley	Recharge from precipitation	Ground-water inflow	ET	Ground-water outflow	
				To	Volume
WHITE RIVER GROUND-WATER FLOW SYSTEM					
Long	31[a]	0	11	Jakes	12
Jakes	24	12	.6	WRV	35
Cave	20	0	5	WRV	15
WRV	62	50	80	Pahroc	32
Garden	19	0	5	Coal	14
Coal	7	14	1	Pahroc	20
Pahroc	8	52	1	Pahranagat	59
Pahranagat	7	59	38	Coyote	28
Dry Lake	13	0	1	Delamar	12
Delamar	5	12	1	Coyote	16
Kane	7	0	1	Coyote	6
Coyote	4	50	1	U. Muddy	37
				Hidden	16
				Garnet	
Hidden	0.3	16	0	California Wash	17
Garnet	0.3		0		
U. Moapa	0.2	37	5	California Wash	32
California Wash	0.3	49	6	L. Moapa	41
				Black Mtn.	2.3
Black Mountain	0.4	2.3	2	Carbonate outflow	1
Subtotals	200.5		158.6		
MEADOW VALLEY WASH GROUND-WATER FLOW SYSTEM					
Lake	41	0	24	Patterson	17
Patterson	16	17	5	Panaca	28
Spring	16	0	1	Eagle	15
Eagle	2	15	1	Rose	16
Rose	0.4	16	0.7	Dry	16
Dry	4	16	4	Panaca	16
Panaca	9	44	26	LMVW	27
Clover	11	0	2	LMVW	9
LMVW	23	36	27	L. Moapa	32
L. Moapa	1	73	26	Carbonate outflow	48
Subtotals	123		116.7		
Totals	**324**		**275**		

a Only 23,000 acre-feet included in totals, remainder to non-White River flow system valleys (Nichols, 2000).

Table 6-2. Water-resources budget for the White River and Meadow Valley flow systems.

INFLOW	
Precipitation (6,635,741)	
Ground-water recharge	
OUTFLOW	
Evapotranspiration	
Ground water	
Surface water	
Total	**324,000**

modeled area
many reservoirs
south of where
want to take it

Table 6-3. Water-resources budget for the model area.

INFLOW	Volume (afy)
Ground water	80,000
Local Recharge	37,000
Total	**117,000**
OUTFLOW	**Volume (afy)**
Ground water	36,000
Surface water	13,000
Evapotranspiration	68,000
Total	**117,000**

To salvage or capture ground-water that is being discharged through ET requires lowering the water table through ground-water pumping. Once the water table is lowered beyond the depth phreatophytes can reach with their roots then the ground water is considered salvaged. This simple concept is difficult to put into practice. For example in Las Vegas Valley where ground-water pumping has been ongoing for over a hundred years and the water table, at one time and in one area, was drawn down about 300 feet and in other parts of the valley there are still living remnants of phreatophytes, the mesquite forest, that once blanketed much of the valley (Pete Duncombe, horticulturist, LVVWD, oral commun., 2001).

In the Carbonate Rock Province of Nevada the alluvial system, which contains the phreatophytes, is on top of the carbonate rocks. Thus, recharge to the alluvial aquifers is mostly dependent on the recharge in the carbonate rock aquifers, and attempts to capture the perennial yield by developing wells in the carbonate aquifer are difficult. This is particularly true because of the vast distances between areas of large ET volumes, such as Pahranagat and White River Valleys and areas of potential high development of ground water, such as the southern end of the White River Flow System. Thus the concept of the perennial yield regarding phreatophytes has certainly limited application in this instance. This same assumption also applies to the Meadow Valley Flow System. Virtually all of the ET located in the northern valleys such as Lake, Patterson, and Panaca is associated with agriculture. In Lower Meadow Valley Wash, much of the ET is associated with the perennial flow in the wash; for both phreatophytes and agriculture (see **Table 4-8** for a breakdown of ET by phreatophytes and agriculture). This surface flow is the result of ground-water discharge to the wash from the thin narrow strip of alluvium that occupies the canyon bottom.

It may seem simpler to capture ground-water outflow from the numerous basins, but it is not. Ground-water flow in carbonate rocks is probably along preferred pathways caused by fractures, which are related to earth movements and to some extent dissolution of the rock-aquifer. While we generally believe fault systems have a higher probability of being conduits for ground-water flow rather than retarding flow as a barrier it is difficult to define the ground-water flow along these pathways which in turn makes predicting impacts very uncertain. The net discharge from the two ground-water flow systems, White River and Meadow Valley, occurs at great depth through the carbonate rocks underneath Lake Mead and possibly into or underneath the Colorado River and is estimated to be 49,000 acre-feet/year. This outflow includes about 10,000-20,000 afy of surface water from the Muddy River to Lake Mead.

In summary the perennial yield for the entire Colorado River Basin Province in Nevada can not be defined as it has been in the past for individual basins without regard for interbasin flow. Furthermore, capturing or salvaging this outflow is nearly impossible to do simply because of the complexity of the fracture-flow system, the vast amounts of water in transient storage, and the long transient time of ground-water movement.

The "Safe Yield" is also equally difficult to apply and has some commonality with perennial yield. The two yields differ because "Safe Yield" does not depend on estimating "Perennial Yield". This term as indicated by Lohman (1972, p. 61) "....has about as many definitions as the number of people who have defined it." Meinzer (1920, p.330) first defined the term as "....The rate at which the ground water can be withdrawn year after year, for generations to come, without depleting the supply." Todd (1959, p. 200) states "The safe yield of a ground-water basin is the amount of water that can be withdrawn from it annually without producing an undesired result." Lohman (1972, p. 62) offers his own definition as " The amount of ground water one can withdraw without getting into trouble". There are many other definitions for this term that are directed to specific cases, but the one by Lohman (1972, p.62) has the most appeal. "Getting into trouble" is to cause undesirable impacts, which can mean a wide variety of resultant actions and in particular a decrease in discharge of Muddy, Rogers or Blue Point Springs. This is an impact that can be avoided with monitoring and mitigation.

Therefore, we believe an alternative definition for ground-water yield from the Colorado River Basin Province is the *Available Yield*. We define this as the amount of water that potentially is available over hundreds of years from the ground-water system. This term does not recognize economic constraints, but relies entirely on the volume of water in storage, the long transient times, and the annual recharge to the ground-water system. The amount of ground water in transient storage is enormous. If, for example, we consider just that part of the carbonate aquifer in the modeled area **(Table 6-4)** the estimated specific yield as reported by Dettinger et al. (1995, Table 13, p. 72) is 0.01 (dimensionless) so there may be as much as two million acre-feet of water in storage in every 100 feet of saturated carbonate rock. The combined alluvial aquifers of the above valleys are smaller in area and contain over four times as much water as the carbonate rocks, assuming a specific yield of 15 percent (~ 9 million acre-feet). So the amount of available yield as storage in just the top 100 feet of saturated carbonate rock and alluvial aquifer dwarfs the estimated annual recharge of about 117,000 acre-feet to these valleys. We are not advocating allocating the vast amount of water in storage, but we do believe there are sufficient uncertainties in the components of the water budget that cannot be resolved in the short term and there is probably more water available than we have defined. Thus a portion of the transient storage can be used safely, particularly with a monitoring plan in place, to further the economic interests of the state and at the same time provide much needed hydrogeological data.

Table 6-4. Estimated transitional ground-water storage in modeled area.

Valley	Estimate ground-water storage in upper 100 feet of saturated zone, in acre-feet.		Total (~~afy~~) AF
	Alluvial Basin	**Carbonate Rock**	
Kane Springs	529,000	150,000	679,000
Coyote Spring	2,546,000	392,000	2,938,000
Hidden	150,000	52,000	202,000
Garnet	500,000	102,000	602,000
California Wash	1,000,000	206,000	1,206,000
Black Mountain Area	1,113,000	409,000	1,522,000
Lower Meadow Valley Wash	2,800,000	606,000	3,406,000
Upper Moapa	30,000	93,000	123,000
Lower Moapa	800,000	176,000	976,000
TOTAL	**9,468,000**	**2,186,000**	**11,654,000**

~24%

pumping 27512 AF/yr, 100 yr   2,751,200

i.e. AF [illegible] totally deplete all [illegible] in top 100 feet of both alluvial and carbonate aquifer

7 ISOTOPE GEOCHEMISTRY

For this study, Thomas et al. (2001) conducted a reevaluation of the geochemistry of the White River and Meadow Valley ground-water flow systems. The executive summary for this report is provided below:

Deuterium data were used to evaluate new ground-water recharge and discharge (evapotranspiration) rate estimates developed by the Las Vegas Valley Water District (LVVWD, 2001) for the regional ground-water flow systems in southeastern Nevada. A deuterium-calibrated mass-balance model was constructed for the White River, Meadow Valley Wash, and Lake Mead (introduced here) ground-water flow systems. This model was used to evaluate if proposed ground-water recharge rates, evapotranspiration rates, sources, and mixing are possible or not. If model-calculated deuterium values for ground-water in the regional aquifers match measured values (within 2 permil), then proposed recharge rates, evapotranspiration rates, sources, and mixing for these flow systems are possible. However, the deuterium mass-balance model developed for the water budget of these flow systems produces a non-unique solution, because a proportionate decrease or increase in both recharge and ET rates, or a different combination of ground-water sources and mixing, can produce the same results.

Results of the deuterium mass-balance model show that:

> New estimates of ground-water recharge and evapotranspiration rates (Section 4.2), and proposed groundwater sources and mixing for the White River, Meadow Valley Wash, and Lake Mead flow systems are consistent with the results of a deuterium-calibrated mass-balance model.
>
> The White River Flow System acts as one continuous carbonate-rock aquifer from Long Valley in the north to Upper Moapa Valley (Muddy River Springs area) in the south.
>
> The results of the deuterium mass-balance model of the White River Flow System are consistent with 53,000 acre-feet per year (afy) of groundwater flowing out of Coyote Springs Valley to the Muddy River Springs area in Upper Moapa Valley (37,000 afy) and to the south-southeast in the carbonate-rock aquifers (16,000 afy).
>
> The Meadow Valley Flow System acts as a two-layer flow system with a carbonate-rock aquifer flow system to the north and west and a volcanic-rock alluvial-fill aquifer system to the east and south that overlies the carbonate-rock aquifer flow system.
>
> The results of the deuterium mass-balance model of the Meadow Valley Flow System are consistent with measured deuterium values in Panaca Valley for a two-layer regional flow system, but deuterium data are lacking for the underlying carbonate-rock aquifer in Lower Meadow Valley Wash, so the estimated 32,000 afy of groundwater flowing out of Lower Meadow Valley Wash to Upper Moapa Valley cannot be evaluated.
>
> The Lake Mead Flow System is primarily a carbonate-rock aquifer flow system that transports groundwater from the White River and Meadow Valley flow systems to Lake Mead.

The results of the deuterium mass-balance model of the Lake Mead Flow System are consistent with 16,000 afy of groundwater flowing from the Coyote Springs Valley-Upper Moapa Valley area to the Hidden Valley-Garnet Valley-California Wash Valley area.

The deuterium mass-balance model of the Lake Mead Flow System cannot evaluate the inflow of 32,000 afy from Lower Meadow Valley Wash and 8,000 afy from California Wash Valley to Upper Moapa Valley because of the lack of deuterium data for groundwater in the carbonate-rock aquifer in Upper Moapa Valley.

The deuterium mass-balance model of the Lake Mead Flow System indicates that ground-water discharging in the Rogers and Blue Point springs area is mostly regional ground-water flow in the carbonate-rock aquifers with some local recharge. However, on the basis of deuterium data, another water source for the spring area from Upper Moapa Valley cannot be ruled out.

Preliminary analyses of oxygen-18 and geochemical data show that these data are consistent with the deuterium mass-balance model of the regional flow systems.

More work needs to be done to better define deuterium compositions of recharge-area ground-waters (many recharge areas have little or no data) and the variability of deuterium values of springs in recharge areas over time.

8 GROUND-WATER FLOW MODEL

A ground-water model was developed for the southern part of the study area **(Figure 8-1)**. The geographic extent of the model includes Coyote Spring Valley, Kane Springs Valley, Garnet Valley, Hidden Valley, California Wash, Lower Meadow Valley Wash, Upper Moapa Valley, Lower Moapa Valley, and Black Mountains area. This region, which is referred to as the model area, has an area of approximately 3,400 mi^2, and an elevation range of 1,200 to 10,000 ft above sea level.

The model was developed for three purposes: First, to test the hydrogeologic and hydrologic conceptualization of the modeled area; second, to examine the impacts of current and past water use on spring flows and ground-water levels; and third, to identify the effects of future water use on spring flows and ground-water levels. To accomplish these purposes, the model was constructed to represent the 56-year historical period 1945-2000 and the 61-year future period 2001-2061. The model simulates these periods using one-year time steps.

8.1 DESCRIPTION OF CONCEPTUAL MODEL

8.1.1 Hydrogeologic Conceptualization

The hydrogeologic conceptualization of the modeled area includes six hydrogeologic units (described in the Geology section). These include basement rocks of Cambrian and older age, carbonate rocks of Cambrian to upper Paleozoic age, clastic rocks of predominately Mesozoic age, volcanic and intrusive rocks of Tertiary age, and alluvial deposits of upper Tertiary to Quaternary age. The stratigraphic relationships among units are shown on **Figure 8-2**, which diagrammatically shows the presence or absence of each hydrogeologic unit in the modeled area, based on the geographic delineations shown on **Figure 8-3a** through **Figure 8-3d**. The subareas referenced on **Figure 8-2** relate to the structure blocks shown on **Figure 8-4**.

The basement rocks include the Lower Cambrian Prospect Mountain Quartzite, Wood Canyon Formation, and the Proterozoic Vishnu Schist, and Gold Butte Metamorphic Complex. These rocks consist of clastics (quartzite) and metamorphics, and they are non-water-bearing relative to the overlying carbonate rocks. Correspondingly, the top of the basement rocks form the base of the ground-water system.

The carbonate rocks **(Figure 8-3a)** include the Ordovician to Pre-Cambrian Antelope Valley Limestone and Goodwin and Nopah Formations. These rocks are overlain by the Ordovician Eureka Quartzite. The overlying Ordovician to Permian consists of Simonson and Laketown Dolomite, Guilmette Formation, Monte Cristo Group and the Bird Spring Formation. Within the modeled area, these rocks are as much as 27,000 ft in thickness. The carbonate rocks underlie essentially all of the modeled area except in the north where intrusive volcanic rocks penetrate the carbonate rocks, and in the southeast where clastic rocks directly overlie the basement rocks. The carbonate rocks are broadly folded, highly faulted, and fractured. Faulting occurs on both regional and local scales. On the regional scale, large-scale faults **(Figure 8-4)** that are nearly perpendicular to ground-water flow tend to restrict ground-water flow. On the local scale, small-

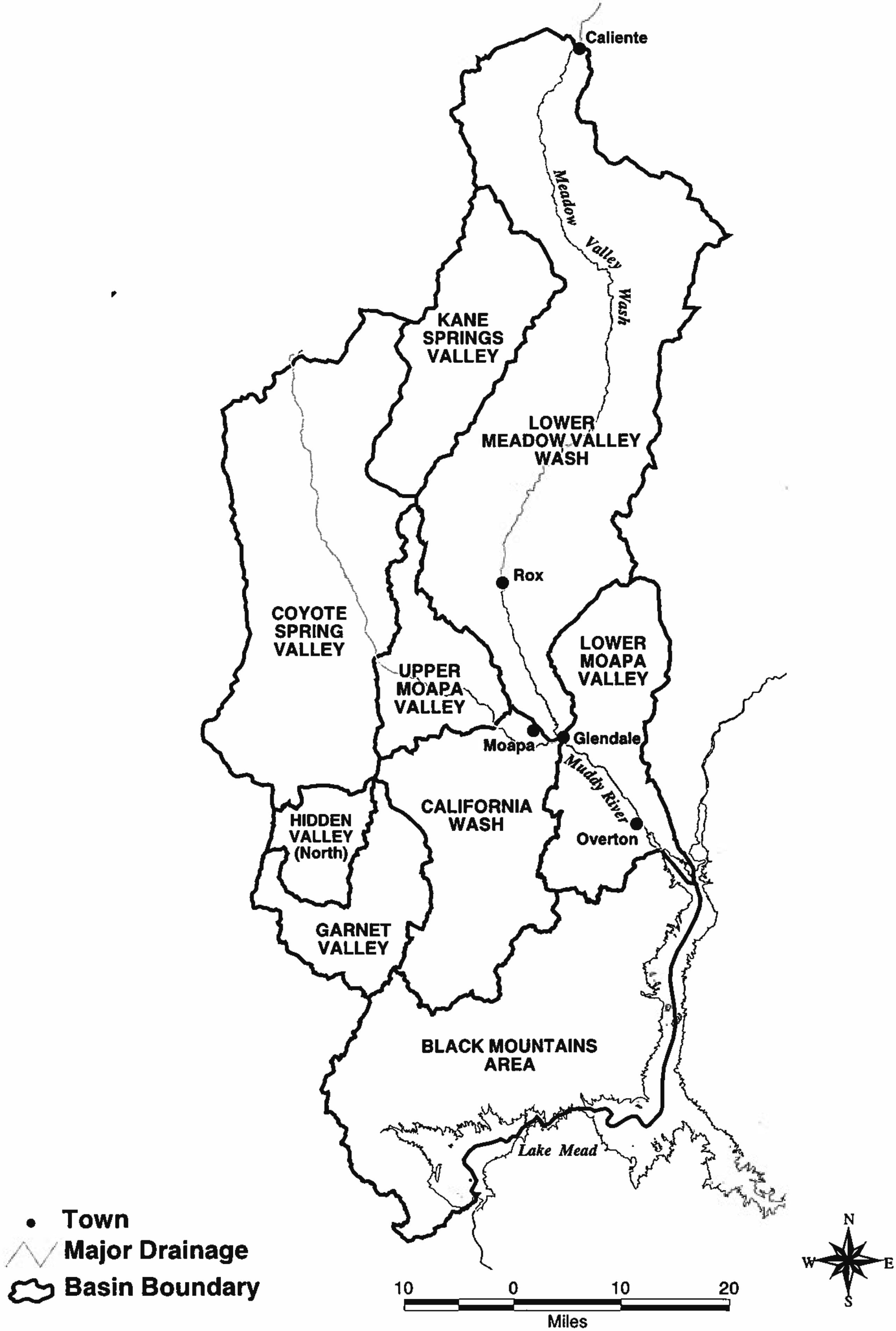

Figure 8-1. Model Area

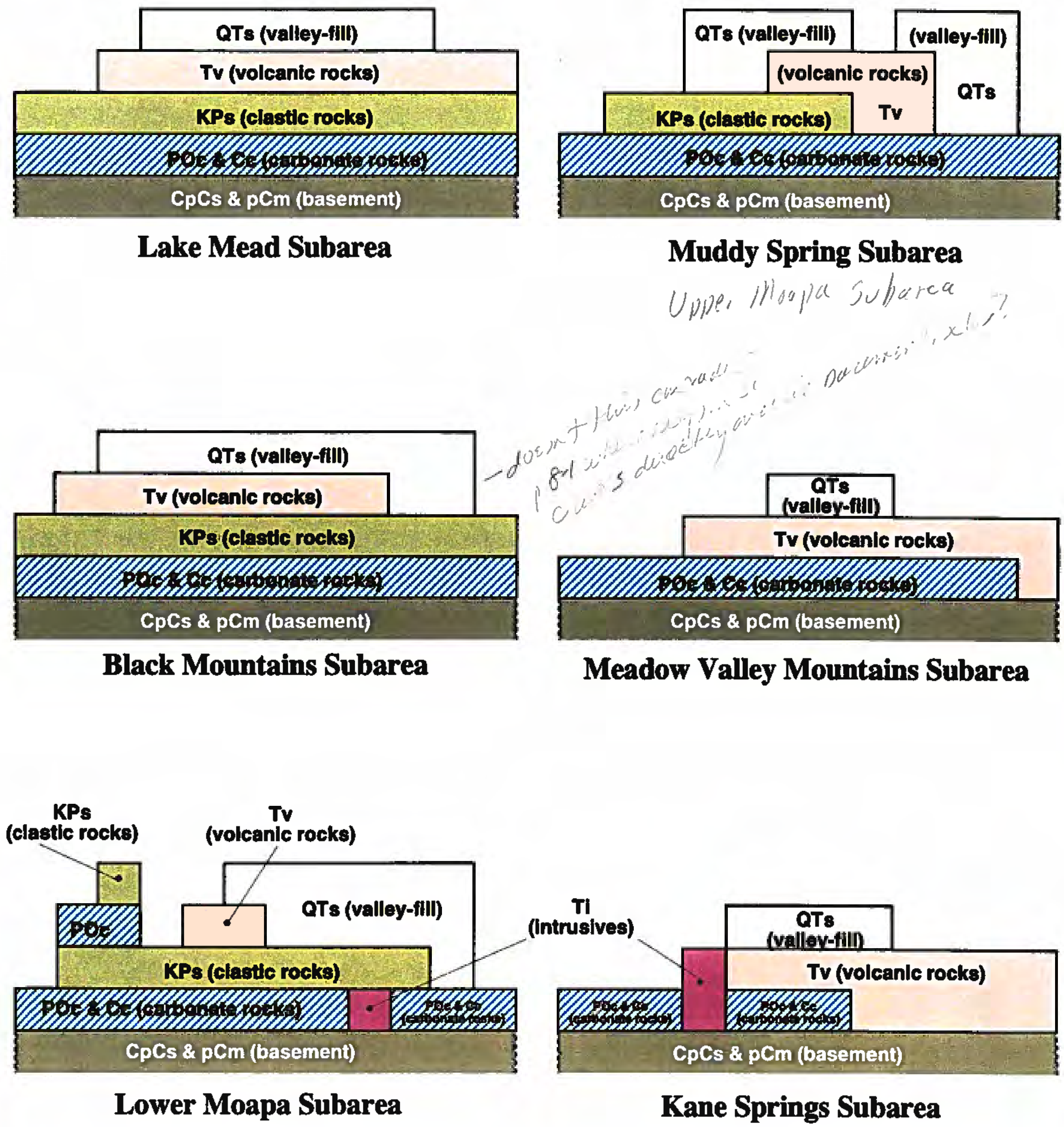

Figure 8-2. Stratigraphic relations within structural blocks.

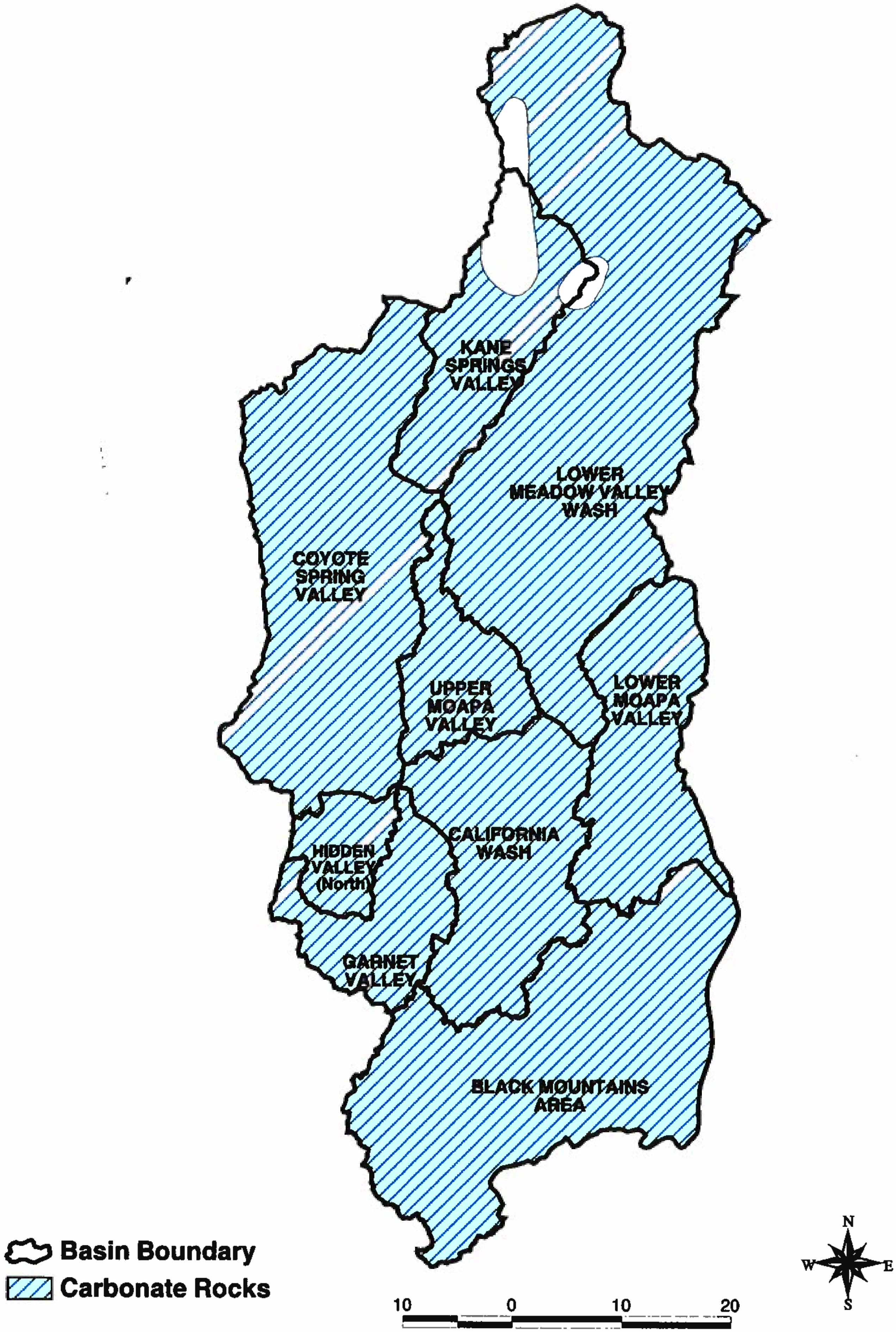

Figure 8-3a. Geographic extent of carbonate rocks.

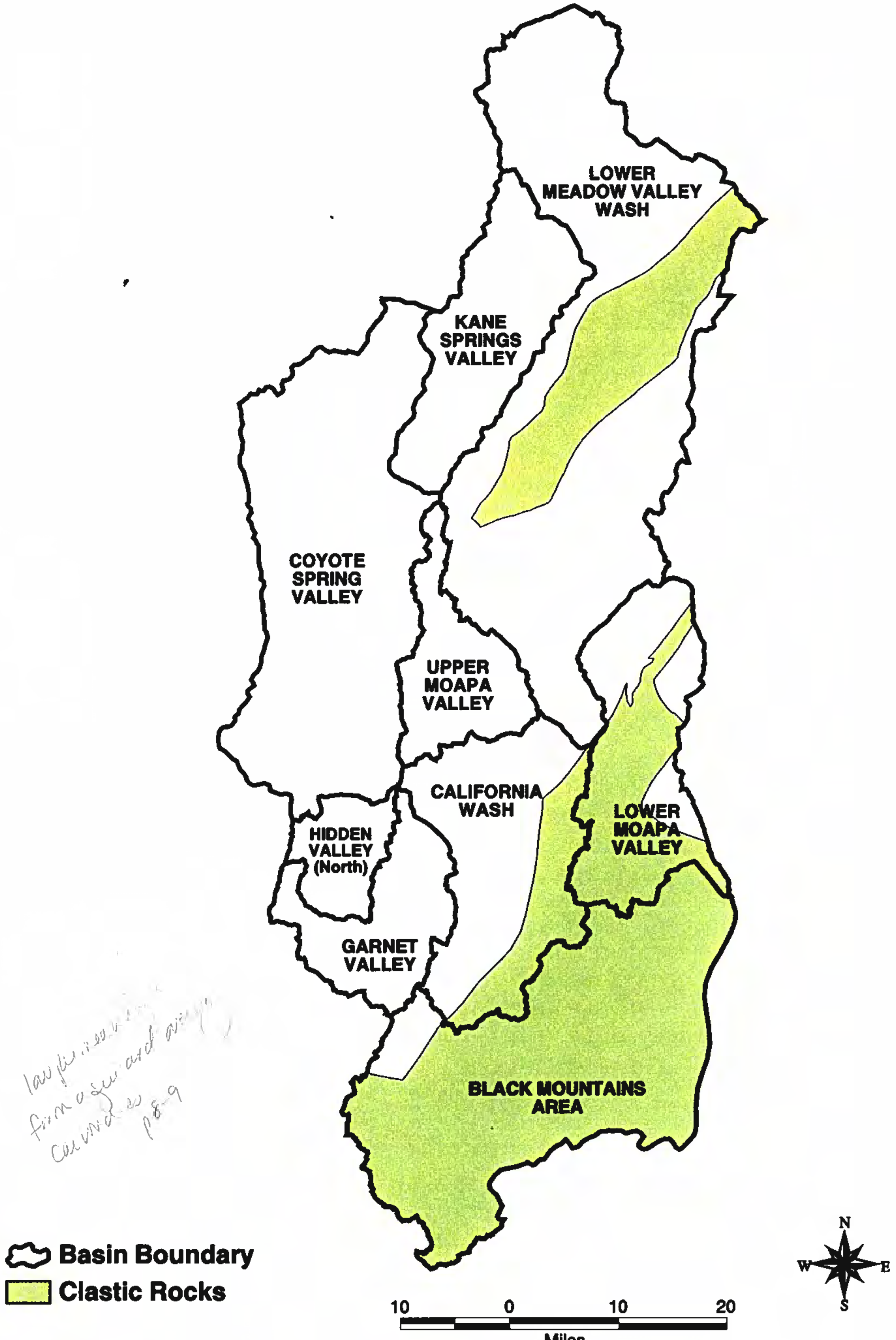

Figure 8-3b. Geographic extent of clastic rocks.

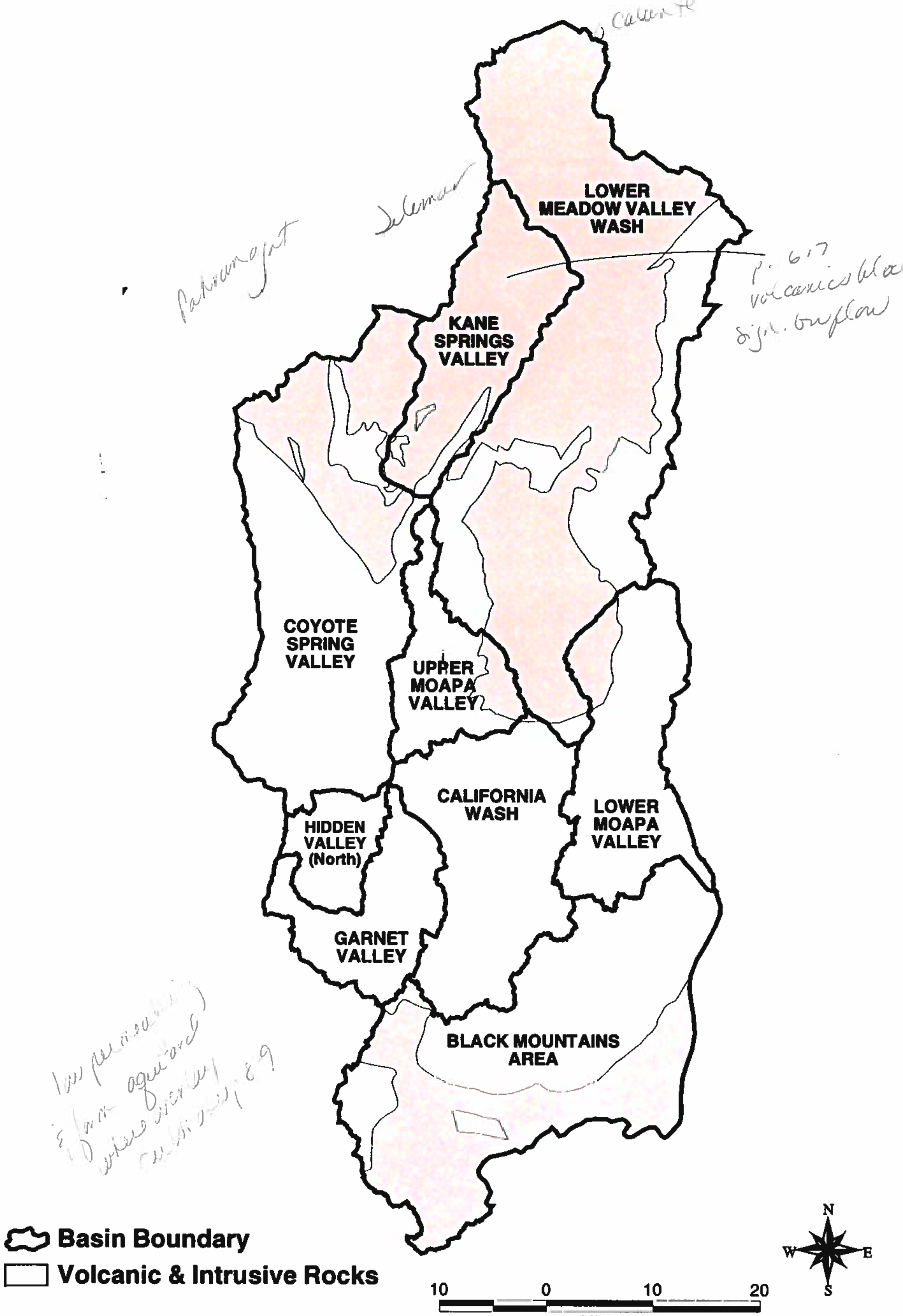

Figure 8-3c. Geographic extent of volcanic and intrusive rocks.

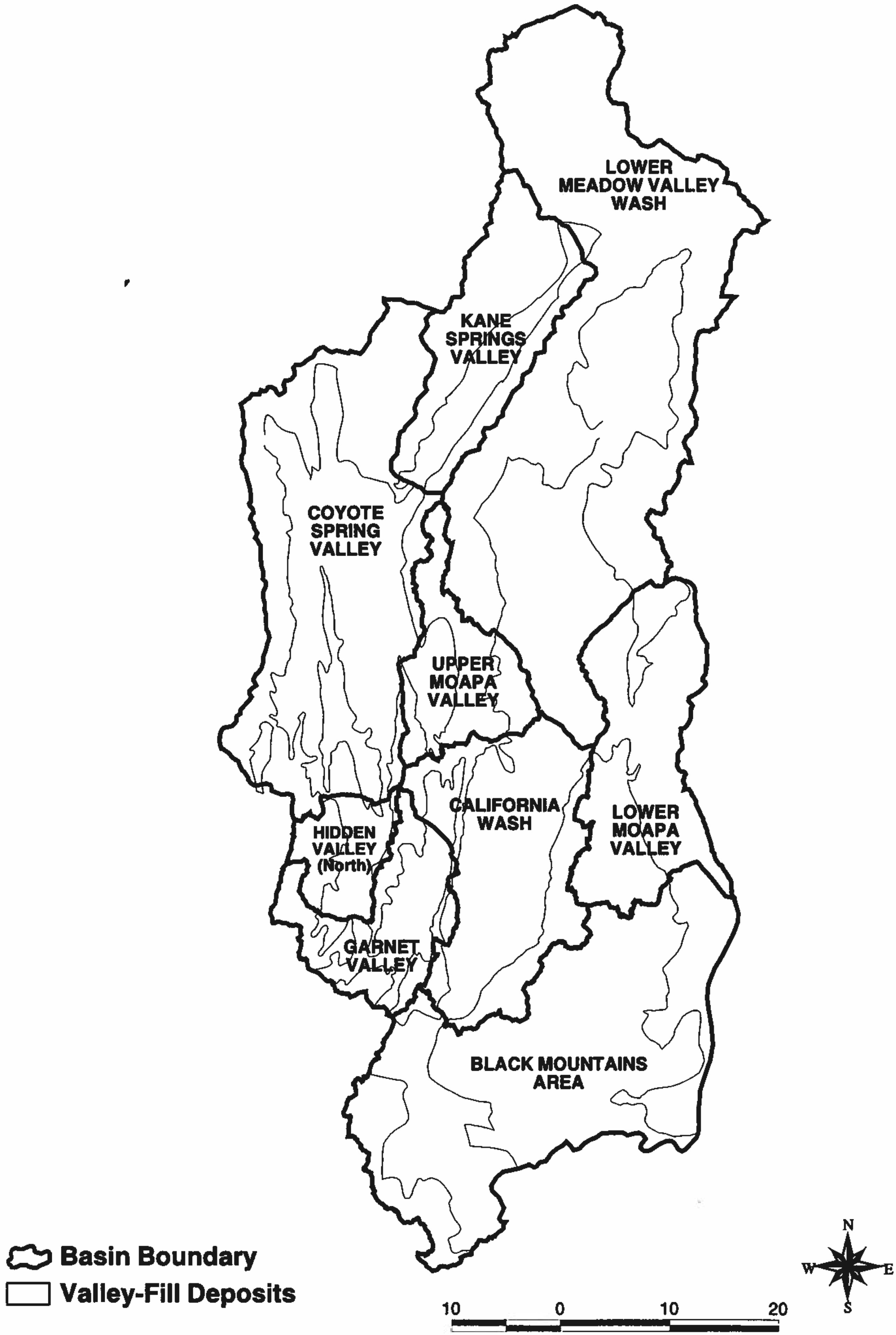

Figure 8-3d. Geographic extent of valley-fill deposits.

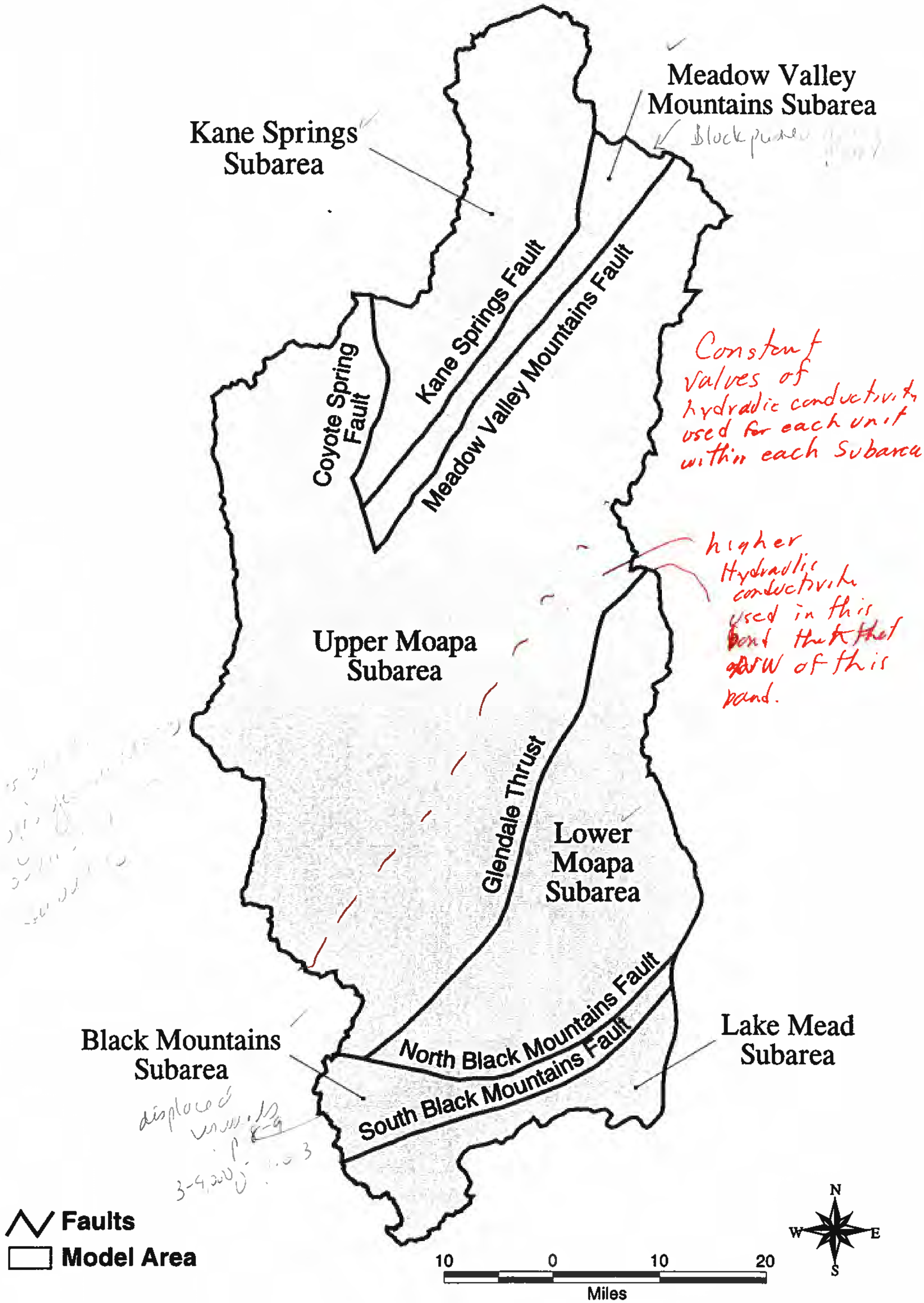

Figure 8-4. Structural blocks within the model area.

scale faults likely produce conduits for ground-water movement. Similarly, fractures likely produce conduits for ground-water flow. Most regional and local ground-water flow within the carbonate rocks occurs within the secondary permeability produced by faults and fracturing, and associated solution channels.

The clastic rocks **(Figure 8-3b)** include the Jurassic Aztec Formation, the Triassic Moenkopi and Chinle Formations and the Lower Permian red bed sequence, Kaibab Limestone and Toroweap Formation. Within the modeled area these rocks are as much as 10,000 ft in thickness. The clastic rocks underlie only a portion of the modeled area in the central and southern area. The clastic rocks have low permeability and form an aquitard overlying the carbonate rocks. While the clastic rocks are fractured, the fracturing has not produced significant secondary permeability vertically through these rocks.

The volcanic rocks **(Figure 8-3c)** include both intrusive and volcanic-flow units. Intrusive rocks occur principally in the northern part of the modeled area. The volcanic rocks occur principally in the northern and to a lesser extent, in the southern part of the modeled area. Within the modeled area, volcanic rocks are as much as 10,000 ft in thickness. The volcanic rocks have low permeability and tend to form an aquitard where they overlay the carbonate rock. Additionally, the volcanic rocks retard vertical ground-water flow where they overlay the clastic rocks, which also have low permeability.

The valley-fill deposits **(Figure 8-3d)** include Quaternary alluvial deposits, the Muddy Creek Formation, and the Horse Spring Formation. The alluvial deposits consist of unconsolidated sediments, the Muddy Creek Formation consists of fine-grained clastic and lacustrine sediments, and the Horse Springs Formation consists primarily of conglomerate. The valley-fill deposits overall are moderately permeable; however, the alluvial deposits tend to be more permeable than the Muddy Creek Formation. The valley-fill deposits tend to be thin relative to underlying units, but locally they are as much as 4,000 ft in thickness.

Regional faults partition the modeled area into hydrogeologic subareas **(Figure 8-4)**. The faults retard ground-water movement between the subareas. While local faulting has enhanced the secondary permeability of the carbonate rocks and perhaps other rocks, extensive lateral and vertical displacements on regional faults have had an opposite effect. This occurs because faulting has juxtaposed low-permeability beds opposite higher-permeability beds so as to block ground-water flow within higher-permeability beds. Additionally, the extensive displacements tend to be correlated with the formation of fault gouge or secondary mineralization along the fault plane. Both of these occurrences tend to restrict ground-water flow within the fault plane and transverse to the fault plane.

The regional faults partition the modeled area into six subareas **(Figure 8-4)**. The north Black Mountains Fault and south Black Mountains Fault divide the southern part of the modeled area into three subareas. South of the southern fault is the Lake Mead subarea, between the faults is the Black Mountains subarea, and north of the northern fault is the Lower Moapa subarea, where the Black Mountain subarea is displaced upward relative to the Lake Mead and Lower Moapa subareas. The vertical displacements are up to 2,000 to 3,000 ft on both faults. The Glendale Thrust separates the Lower Moapa subarea from the Upper Moapa Valley subarea (Muddy Springs). The horizontal displacement along the thrust is about 30,000 ft. The Kane Springs Fault and Meadow Valley Mountains Fault divide the modeled area into two additional subareas.

The vertical displacements are 500 to 1,000 ft on the Kane Springs Fault and 2,000 to 3,000 ft on the Meadow Valley Mountains Fault. The Meadow Valley Mountains Fault separates the Upper Moapa Valley subarea from the Meadow Valley Mountains subarea, and the Kane Springs Fault separates the Meadow Valley Mountains subarea from the Kane Springs subarea. Additionally, the Coyote Spring Fault separates the Upper Moapa subarea from the Kane Springs subarea. The Meadow Valley Mountains subarea is displaced upward relative to the Upper Moapa and Kane Springs subareas.

8.1.2 Hydrologic Conceptualization

The hydrologic system within the model area includes ground water and surface water as shown on **Figure 8-5**. This system is conceptualized into the regional ground-water system and local streams and riparian ground water. The sources of ground-water include underflow from adjacent areas and precipitation within the modeled area. The discharges of ground-water include spring discharges, consumption of diverted streamflow and riparian ground water, seepage to stream channels, pumping, and underflow to the Colorado River. The sources of surface water include spring discharges and seepage to stream channels. The discharges include consumption of diverted streamflow and riparian ground water and surface water outflow to the Colorado River.

Ground-water enters the modeled area as underflow within the carbonate rocks from valleys upgradient **(Table 8-1)**. Underflow enters Coyote Spring Valley **(Figure 8-5a)** from Pahranagat and Delamar Valleys. These underflows are 28,000 afy from Pahranagat and 16,000 afy from Delamar Valley. Underflow enters the Lower Meadow Valley Wash basin from Panaca and Clover Valleys. These underflows are 17,000 afy from Panaca Valley and 9,000 afy from Clover Valley. Additionally, streamflow from the Meadow Valley Wash enters the model area from Panaca Valley and is estimated at 10,000 afy. The cumulative estimated underflow and streamflow into to the modeled area is 80,000 afy **(Table 8-1)**.

Ground-water recharge occurs within the modeled area from precipitation **(Table 8-1)**. Most of that recharge occurs in the mountain areas, but some recharge occurs from ephemeral streamflow on alluvial fans and valley floors. Snowmelt and rainfall in mountain areas infiltrates rocks or seeps into fractures. Much of that water is consumed by native vegetation. However, part of the snowmelt and rainfall percolates downward past the root zone and eventually becomes ground-water recharge within the mountain area. When the snowmelt rate or precipitation rate exceeds the infiltration capacity of soils or fractured rocks, streamflow occurs. Within alluvial-fan or valley-fill areas, streamflow infiltrates into channel beds. Part of the infiltrated water percolates downward to become ground-water recharge. These processes act such that the ground-water recharge from precipitation on the modeled area is about 37,000 afy.

Ground-water discharges from the modeled area as spring discharges, ground-water seepage to channels, and pumping **(Table 8-1)**. The principal spring discharge occurs at the Muddy Springs. The discharge from the springs is about 37,000 afy, including ground-water seepage to the

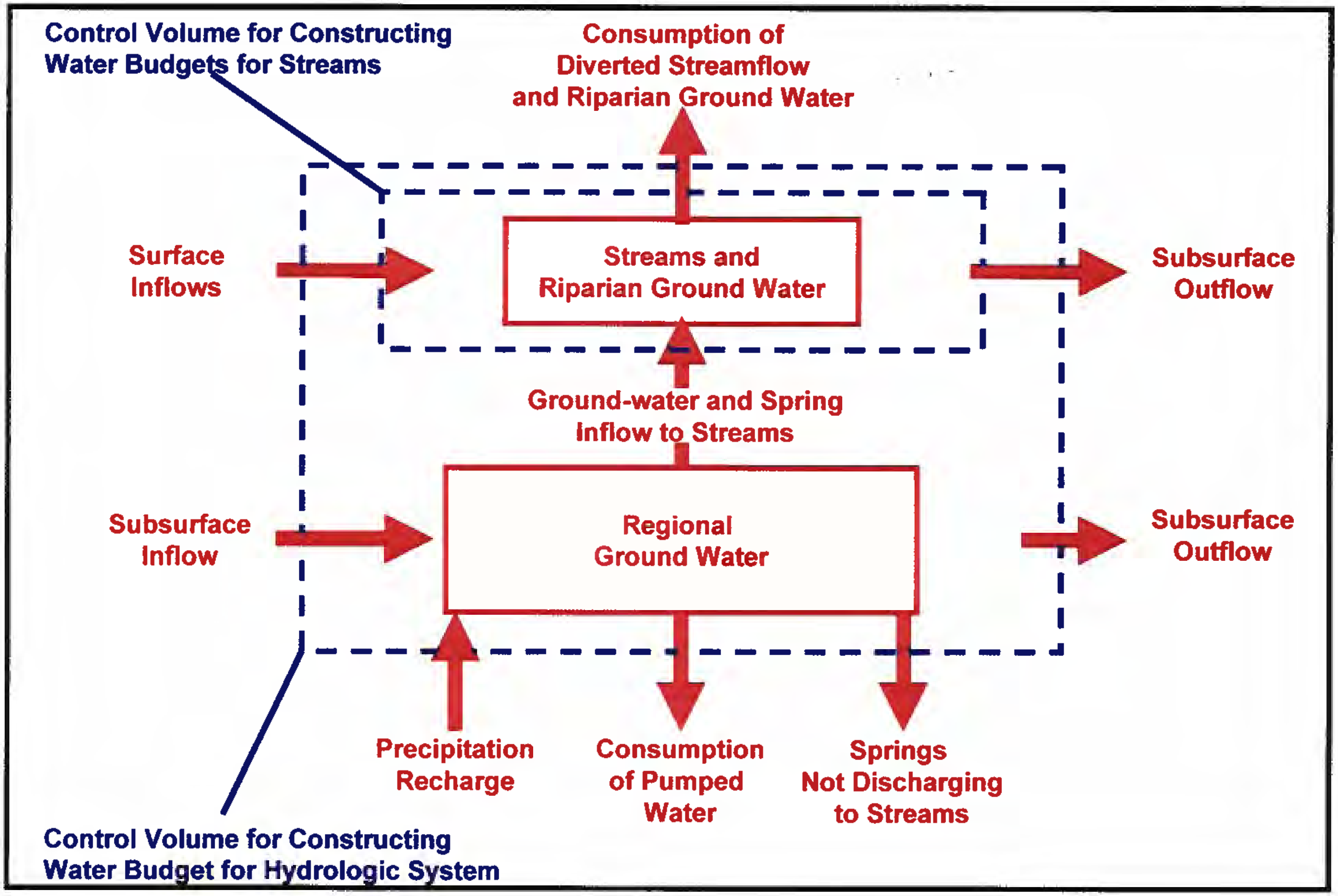

Figure 8-5 Conceptualization of hydrologic system.

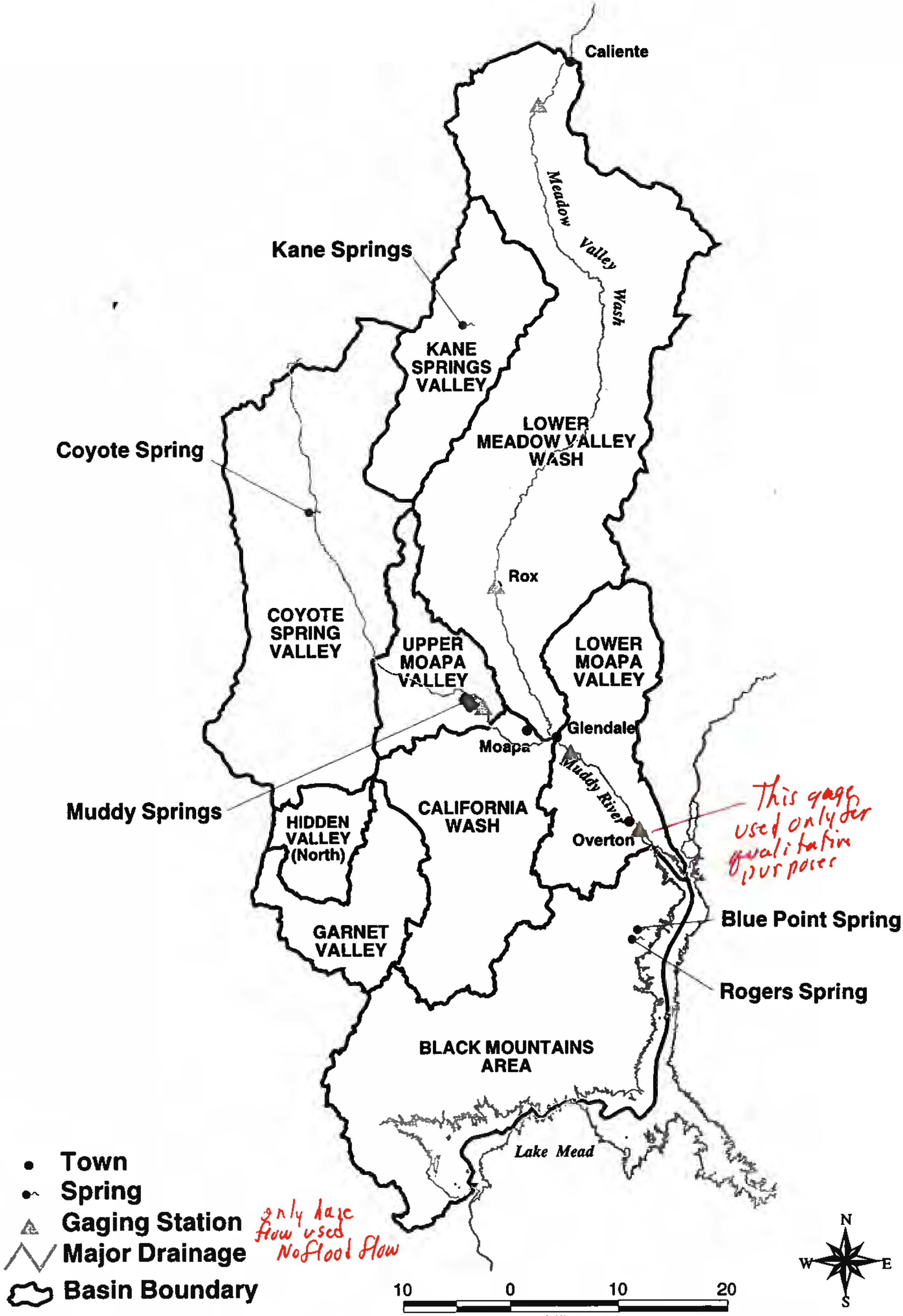

Figure 8-5a. Hydrologic features within the model area.

Table 8-1. Water budgets for streams and hydrologic systems; historical pumping and diversions in 1945 and 2000[1].

Budget Component	Historical Pumping / Diversions 1945	Historical Pumping / Diversions 2000
WATER BUDGETS FOR MEADOW VALLEY WASH AND MUDDY RIVER		
Inflows – Meadow Valley Wash		
• Streamflow at model boundary	10,000	10,000
• Ground-water inflows above Rox	11,000	9,000
• Ground-water inflows Rox to mouth	4,000	3,000
Total	**25,000**	**22,000**
Outflows – Meadow Valley Wash		
• ET above Rox[2]	21,000	20,000
• ET from Rox to mouth[2]	2,000	0
• Streamflow at mouth	2,000	2,000
Total	**25,000**	**22,000**
Inflows – Muddy River		
• Meadow Valley Wash streamflow at mouth	2,000	2,000
• Ground-water inflows above Moapa	38,000	31,000[3]
• Ground-water inflows Moapa to Glendale	6,000	6,000
• Ground-water inflows Glendale to Overton	7,000	7,000
Total	**53,000**	**46,000**
Outflows – Muddy River		
• ET above Moapa[2]	3,000	5,000
• ET Moapa to Glendale[2]	9,000	9,000
• ET Glendale to Overton[2]	25,000	25,000
• Streamflow at Overton	16,000	8,000
Total	**53,000**	**47,000**
HYDROLOGIC SYSTEM		
Inflows		
Ground-water underflow - Pahranagat Valley	28,000	28,000
Ground-water underflow - Delemar Valley	16,000	16,000
Ground-water underflow - Panaca Valley	17,000	17,000
Ground-water underflow - Clover Valley	9,000	9,000
Meadow Valley Wash streamflow at boundary	10,000	10,000
Boundary underflows	0	0
Precipitation recharge	37,000	37,000
Total	**117,000**	**117,000**
Outflows		
Ground-water pumpage	0	18,000
Surface-water outflow - Muddy River	16,000	8,000
Ground-water discharge to Colorado River	37,000	37,000
ET – Coyote Springs	1,000	1,000
ET – Kane Springs	1,000	1,000
ET – Rogers Springs	1,000	1,000
ET – Blue Point Springs	1,000	1,000
ET – Meadow Valley Wash above Rox	21,000	20,000
ET – Meadow Valley Wash below Rox	2,000	0
ET – Muddy River above Moapa	3,000	5,000
ET – Muddy River – Moapa to Glendale	9,000	9,000
ET – Muddy River – Glendale to Overton	25,000	25,000
Total	**117,000**	**126,000**
STORAGE CHANGE	**0**	**-9,000**

[1] *See Figure 8-5 for definition of control volumes.*
[2] *ET includes consumption of diverted streamflow and riparian ground water.*
[3] *After-effects of diversions and ground-water pumping above Muddy River streamgaging station near Moapa.*

Muddy River along the reach from the springs to the Moapa gage **(Figure 8-5)**. The cumulative discharge from other springs within the modeled area is about 4,000 afy. The individual discharges are 1,000 afy for Blue Point Spring, 1,000 afy for Rogers Spring (representing 2,000 afy for the North Shore Spring Complex), 1,400 afy from Coyote Spring, and 600 afy from Kane Springs. The discharge at the Muddy Springs, Blue Point Spring, and Rogers Spring is from deep carbonate rocks where fault intersections facilitate the discharge. The discharge at Kane Springs is from volcanic rocks, and the discharge from Coyote Spring is from valley-fill deposits. Ground-water discharges to the Muddy River channel from below the Muddy Springs to Lake Mead. Ground-water discharges toward the lower Virgin River channel in the vicinity of Fisherman's Cove and may actually not surface until it is constrained by the fault structure that defines the Colorado River. Finally, ground-water discharges to the Meadow Valley Wash along discontinuous reaches from Caliente to near Rox **(Figure 8-5)**. Additional discharge occurs near the confluence of Meadow Valley Wash with the Muddy River. The cumulative discharge to the Muddy River between Muddy Springs and the Overton gage is about 13,000 afy, which is in addition to the Muddy Springs discharge above the Moapa gage. The cumulative discharge to the Meadow Valley Wash between the Caliente gage to near the Rox gage is about 9,000 afy. The additional discharge to Meadow Valley Wash near its confluence with the Muddy River is 3,000 afy.

Ground-water is pumped within the modeled area for agricultural, industrial, and municipal uses **(Table 8-1)**. Additionally, minor ground-water is pumped at various locations for residential and commercial purposes. The agricultural and industrial pumping is located along the Muddy River from near the Muddy Springs to Overton. About 35 active wells occur along this reach, and the current consumptive pumpage is about 11,000 afy. Ground-water pumping along the Muddy River started in 1947 for irrigation. During 1947-2000 pumping tended to increase from year to year, but during the middle of this period, most agricultural pumping was replaced with industrial pumping. The industrial pumping is mostly for cooling at Nevada Power's Reid Gardner Station. The current consumptive industrial pumping is about 7,500 afy. Additional pumping for export to Lower Moapa Valley municipal and industrial uses began in the early 1990s, and has increased steadily to a current export of approximately 3,000 afy.

Spring discharges and ground-water seepage to streams are used consumptively within the modeled area **(Table 8-1)**. Consumption results from irrigation diversions or direct ground-water use by phreatophytes. Along Meadow Valley Wash, streamflow resulting from ground-water discharges is consumed. Streamflow enters the modeled area at Caliente, and is diverted for irrigation and consumed within the modeled area. The water use along the Meadow Valley Wash in year 2000 is such that streamflow almost ceases near Rox, except for occasional flood flows. The consumption along the wash is about 20,000 afy. Along the Muddy River, streamflow resulting from ground-water discharges is diverted for irrigation or industrial uses and consumed. The water use along the Muddy River is such that a substantial amount of the streamflow is consumed above the Overton gage. Nevertheless, some streamflow reaches Lake Mead. The consumption along the river is about 39,000 afy.

Ground-water discharges to Lake Mead and the Virgin River as upward ground-water flow to the lake or stream channel **(Table 8-1)**. The carbonate rocks within the modeled area terminate in the vicinity of Lake Mead where they transition into rocks of the Colorado Plateau series. The carbonate rocks are juxtaposed against low permeability rocks at that boundary, and ground-water flow in the carbonate rocks is forced upward. Prior to the construction of Hoover Dam in

1935, the current ground-water discharge to the Colorado River. With the dam and Lake Mead constructed, the current ground-water discharge to Lake Mead on the lower Virgin River is about 37,000 afy.

8.2 DEVELOPMENT OF NUMERICAL MODEL

A three-dimensional model was developed based on the hydrogeologic and hydrologic conceptualizations described above. The model was constructed using the U.S. Geological Survey computer program FEMFLOW3D (Durbin and Bond 1998). This program solves the governing equations of ground-water flow using the finite-element method, which is one of several mathematical techniques used in ground-water models. The program consists of modules for simulating inflows and outflows for a ground-water system. Those utilized within the current model include the specified-flux module, specified-head module, stream-aquifer module, and variable-flux module (Durbin and Bond, 1998). Additionally, the model utilizes the flexible-grid module (Durbin and Berenbrock, 1985).

The model utilizes a three-dimensional mesh that is specified as an assemblage of nodes and elements, and the modules for simulating ground-water inflows and outflows relate those quantities to nodes within the model mesh. The specified-flux module assigns recharge and discharge rates to specified mesh nodes. The specified-head module specifies a relation for a mesh node between discharge and the simulated ground-water level for the node. The stream-aquifer module specifies a relation for a mesh node between ground-water discharge to a stream and the simulated ground-water level at the stream. The variable-flux module specifies a relation for a mesh-boundary node between the boundary discharge and ground-water conditions outside the model area.

The flexible-grid module adjusts the grid geometry to account for the position of the ground-water table. As the water-table elevation changes during a simulation, the module adjusts mesh nodes upward or downward such that the node elevation equals the water-table elevation (Durbin and Berenbrock, 1985).

8.2.1 Representation of Hydrogeology

The ground-water model represents five hydrogeologic units **(Figure 8-6)**. These include the carbonate rocks, clastic rocks, intrusive rocks, volcanic rocks, and valley-fill deposits. The geographic extents and thickness of these units were derived from the geologic cross sections **(Figure 3-2** through **Figure 3-4** in Section 3**)**. **Figure 8-3a** through **Figure 8-3d** show the geographic extent of each unit.

The hydrogeologic units and structural features within the model area are represented in the ground-water model using a three-dimensional mesh. The mesh is an assemblage of vertically oriented prismatic elements. A typical element is shown on **Figure 8-7**. The elements project a triangle on a horizontal cross-section, which is represented by the top and bottom faces shown on the figure. The elements project a trapezoid on a vertical plane, which is represented by the

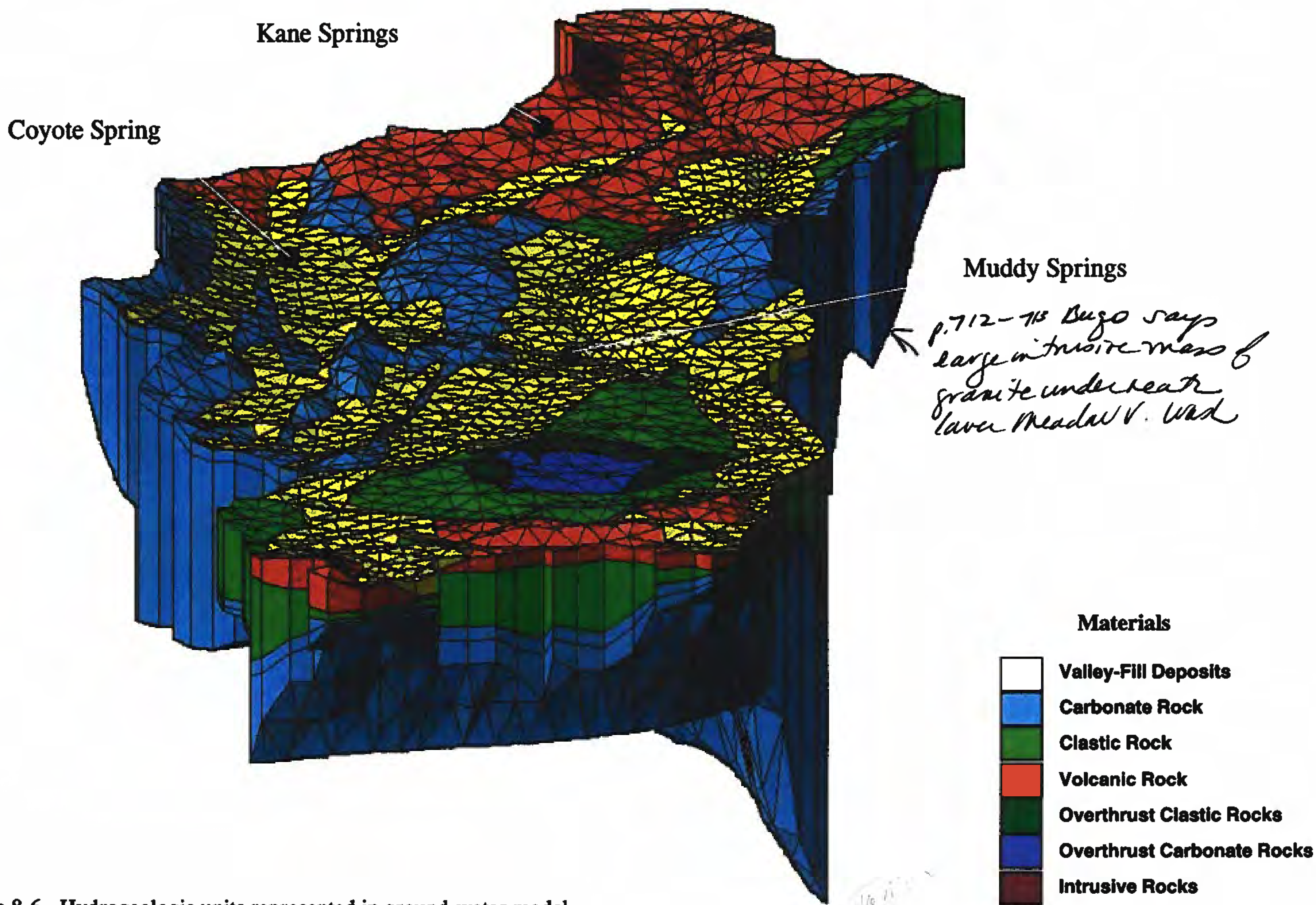

Figure 8-6. Hydrogeologic units represented in ground-water model.

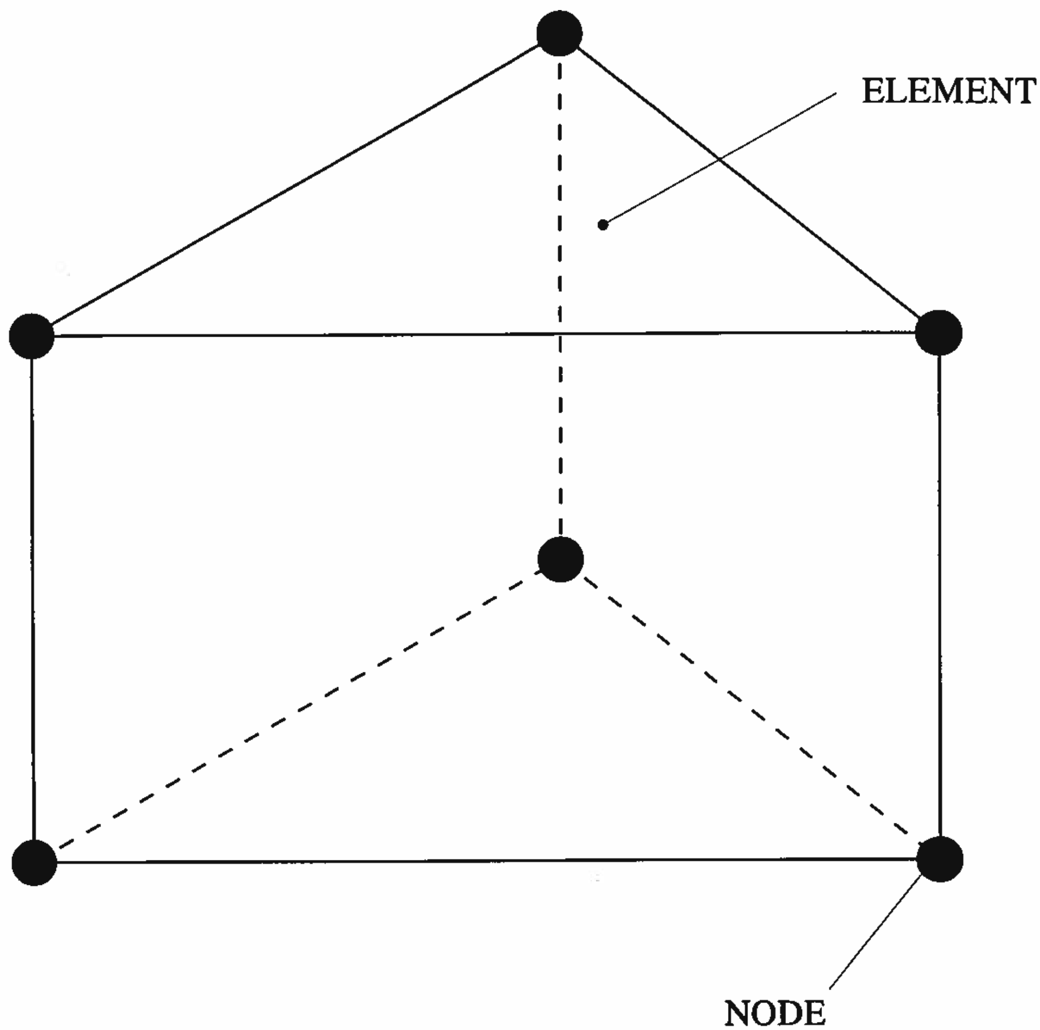

Figure 8-7. Typical element within finite-element mesh.

vertical faces shown on the figure. The particular size and spatial position of an element is specified by the three-dimensional coordinates representing the vertices of the prism, which are referred to as nodes. Laterally and vertically adjacent elements share nodes, which establish the continuity of the ground-water system within the modeled area.

The finite element mesh is shown on **Figure 8-8,** and **Figure 8-9a** through **Figure 8-9e**. **Figure 8-8** shows the geographic layout of the mesh. The mesh is constructed geographically to define the extents to the hydrogeologic units. As shown on **Figure 8-8**, element top or bottom faces define surface contacts between units. The mesh is constructed vertically to define the thickness and elevations of the hydrogeologic units. The layering of elements within the three-dimensional mesh represents the layering of the hydrogeologic units. Additionally, the mesh is constructed to represent location of regional faults. As shown on **Figure 8-8**, faults are represented in the mesh as linear assemblage of narrow elements.

Using the flexing-grid module of FEMFLOW3D, the mesh adjusts so that the top of the surface represents the ground-water table. The top surface of the mesh initially is the land surface, and nodes in the top surface are assigned an elevation equal to the land-surface elevation. If the ground-water table fluctuates during a transient-state simulation, the top surface of the finite-element mesh correspondingly fluctuates. This is accomplished by appropriately expanding or contracting the mesh. If the ground-water table rises or falls during a simulation, the top surface of the mesh rises or falls so that the local elevation of the top surface always equals the local computed elevation for the ground-water table.

While the mesh itself defines spatial relationships within the ground-water system, the assignment of material properties to elements defines the hydraulic characteristics of the ground-water system. Each element is assigned values for horizontal permeability, vertical permeability, and specific storage. Elements forming the top surface of the mesh also are assigned a value for specific yield. The collection of elements representing a particular hydrologic unit or fault is assigned material properties characterizing the unit or fault. In the model inputs, each element is assigned a material type taken from a list of materials. Each material is assigned a horizontal permeability, vertical permeability, specific storage, and specific yield, and material-type assignment correspondingly assigns values to elements. Elements are assigned hydraulic properties from a list of thirty-nine materials **(Table 8-X)**. The list contains material properties for each hydrogeologic unit and each subarea. Additionally, the list contains material properties for each fault. The specification of values for material properties was derived from a model calibration, which is a process for selecting material properties so that the ground-water model best fits historical conditions. That process is described later.

8.2.2 Representation of Natural Recharge

Using the specified-flux module of FEMFLOW3D, the model replicates natural recharge to the ground-water system, where the total recharge to the model area is about 107,000 afy groundwater and 10,000 afy surface-water **(Table 8-1)**. Natural ground-water recharge to the ground-water system includes precipitation recharge and subsurface inflows. Recharge from precipitation within the modeled area is based on a modified Maxey-Eakin method as described

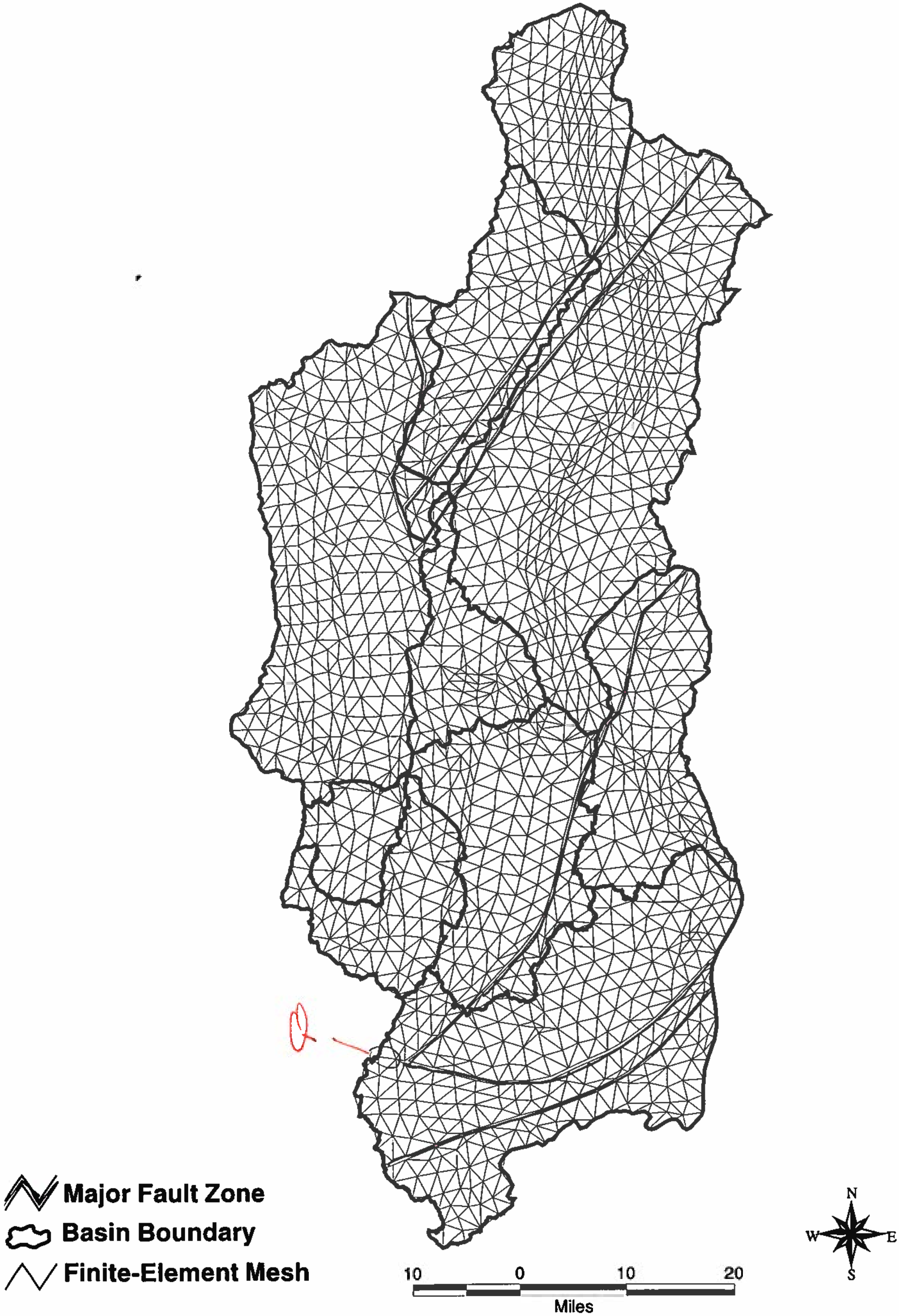

Figure 8-8. Finite-element mesh.

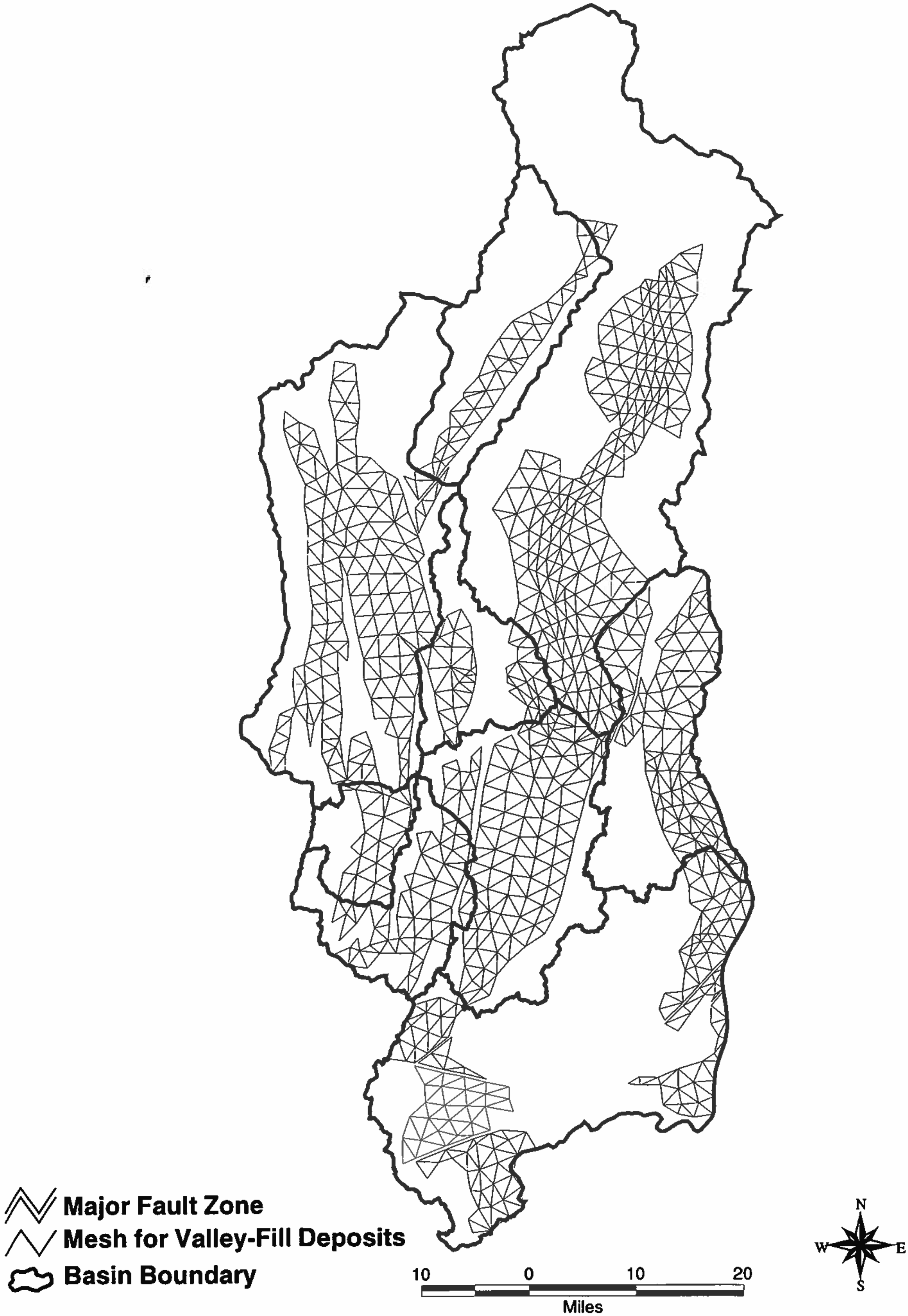

Figure 8-9a. Geographic extent of valley-fill deposits within finite-element mesh, layer one.

SE ROA 40172

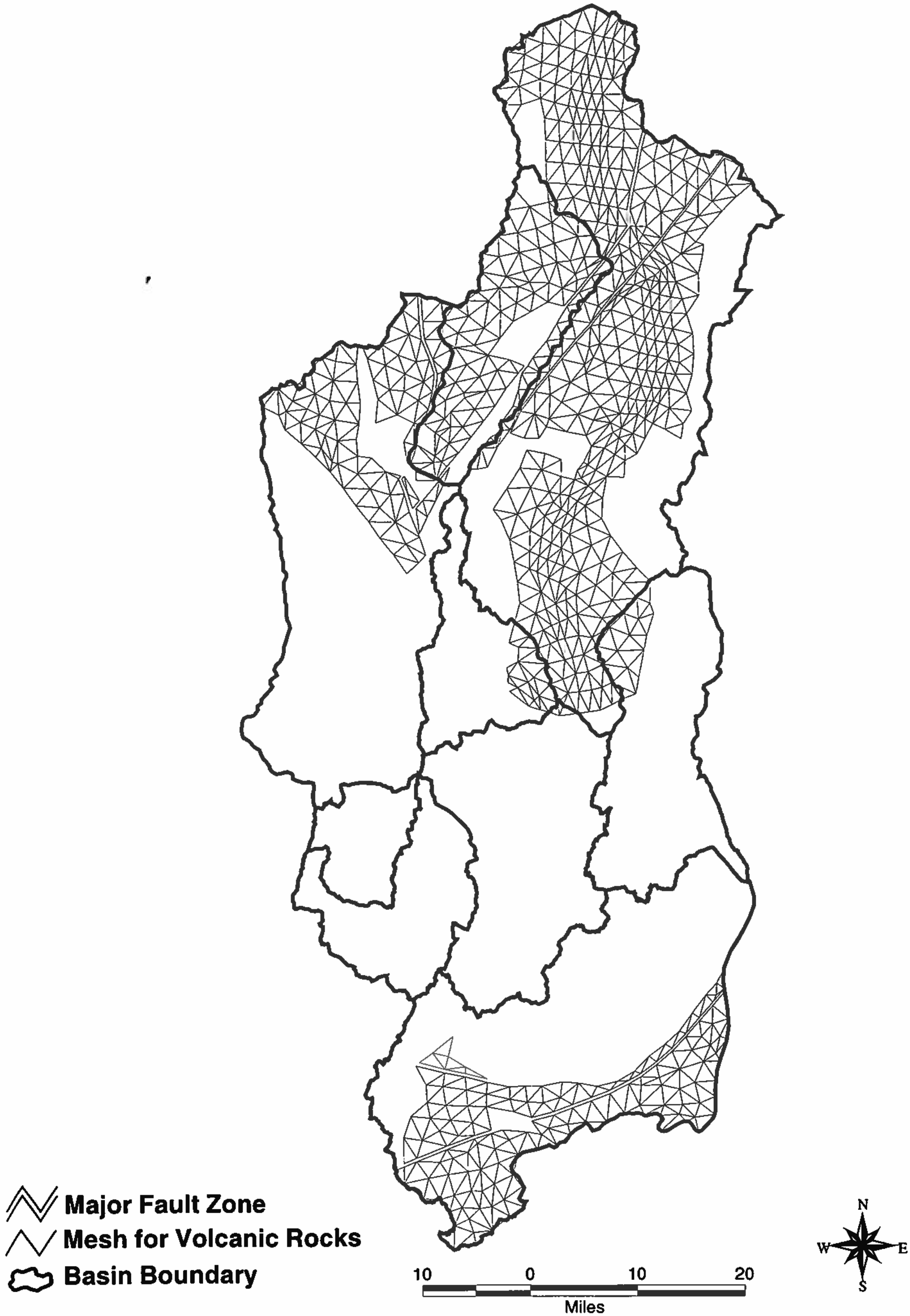

Figure 8-9b. Geographic extent of volcanic rocks within finite-element mesh, layer two.

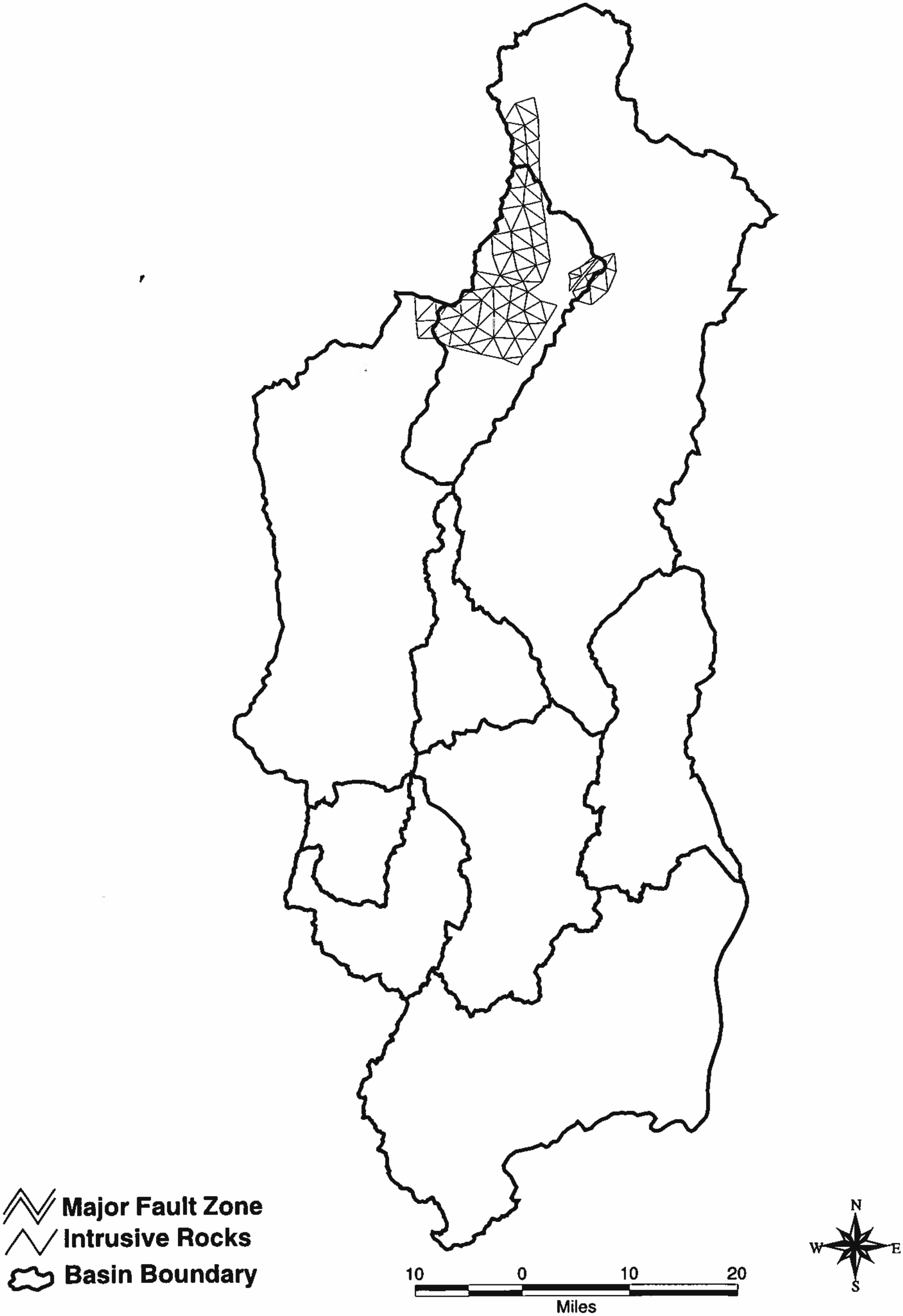

Figure 8-9c. Geographic extent of intrusive rocks within finite-element mesh, layer three.

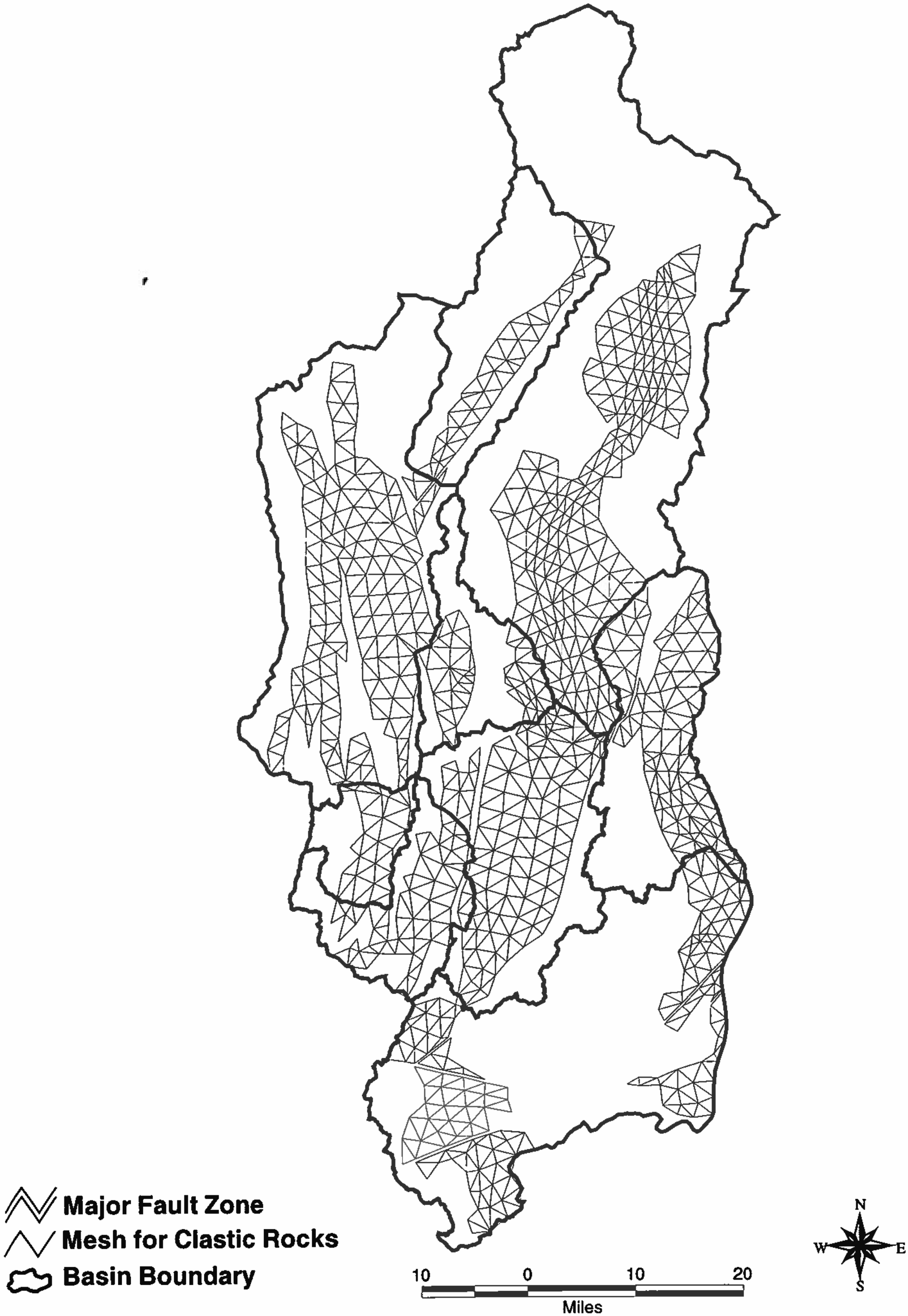

Figure 8-9d. Geographic extent of clastic rocks within finite-element mesh, layer four.

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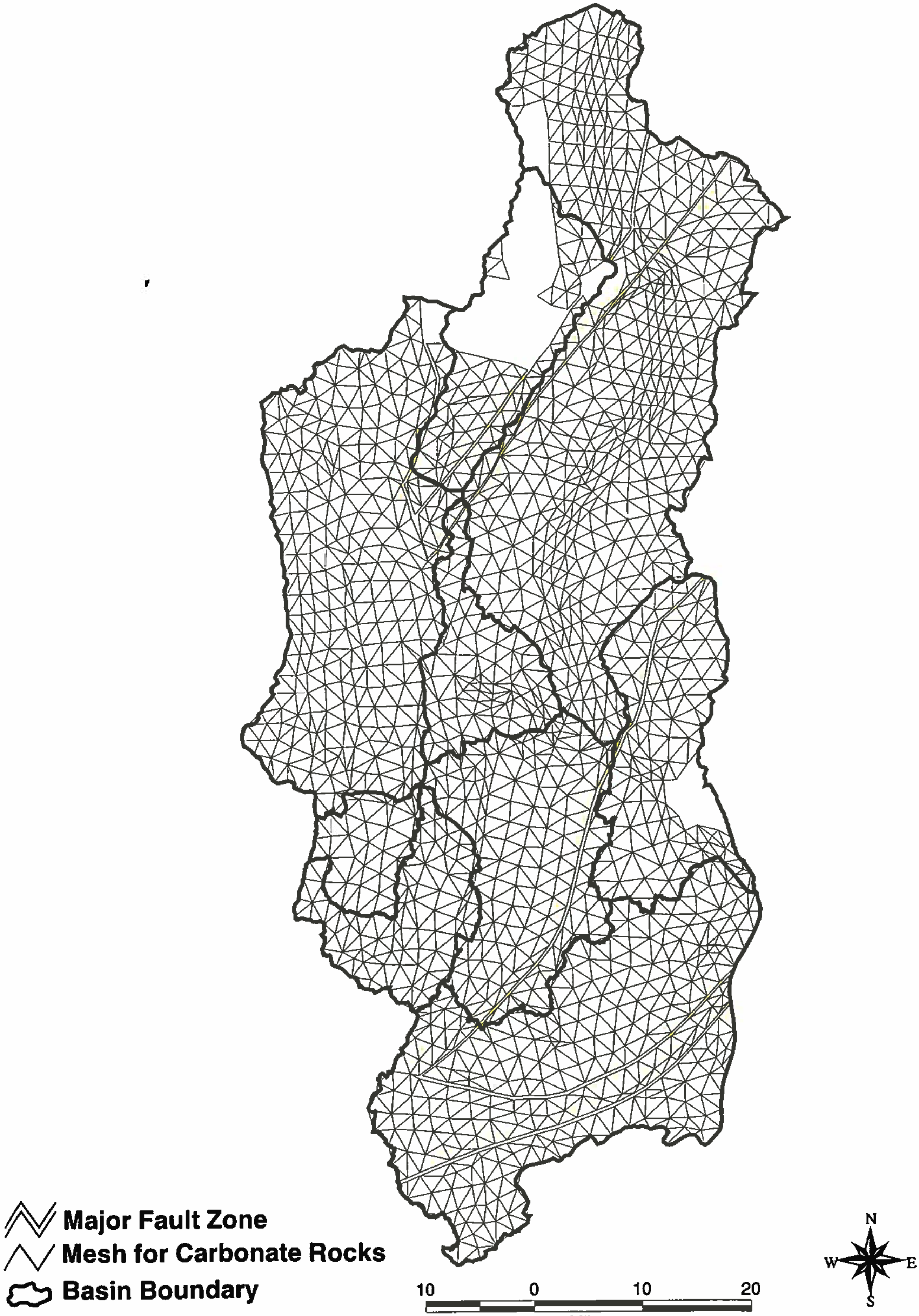

Figure 8-9e. Geographic extent of carbonate rocks within finite-element mesh, layer five.

in Section 4.4. Likewise, the subsurface inflows to the modeled area are based in part on the application of this modified Maxey-Eakin method to the source area, which is the study area upgradient from the modeled area. The resulting subsurface inflows represent the precipitation recharge within the source area less the consumption within that area.

Natural recharge is incorporated in the model by assigning recharge values to nodes within the model mesh that correspond to areas where recharge occurs. Precipitation recharge within the model area is assigned to nodes in the top surface of the model mesh. The recharge value assigned to a particular node represents the integration of the local recharge per unit area over the local area associated with the node. The integration translates local recharge expressed as depth per unit time to a nodal recharge expressed as a volume per unit time. The sum of the volumetric values for all nodes equals the total precipitation recharge for the model area. The subsurface inflows to the modeled area are assigned to nodes in the vertical surface of the model mesh at the boundary of the modeled area. Where mesh nodes occur on that vertical surface, a set of nodes occur as a column. The bottom three nodes in the column represent the carbonate rocks, and the subsurface inflows are assigned to the carbonate rocks at the bottom two nodes. **Figure 8-10** shows the locations where subsurface inflows are assigned to the model mesh.

8.2.3 Representation of Natural Discharge

Using the specified-head, stream-aquifer, and specified-flux modules of FEMFLOW3D, the model represents natural discharge from the ground-water system, where the total natural discharge from the model area is about 117,000 afy **(Table 8-1)**. Natural ground-water discharge includes spring discharges, ground-water seepage to streams, and subsurface outflows. Spring discharges and ground-water seepage are calculated internally within the model based on the simulated ground-water levels, except that valley-fill springs are simulated in the model as a specified discharge. Subsurface outflows are represented either as a head-dependent condition or a specified discharge.

For a carbonate spring, when the hydraulic head within the source aquifer for the spring is above the spring-orifice elevation, the spring discharge in the model is proportional to the difference between the spring-orifice elevation and the source-aquifer head. Otherwise, the spring discharge equals zero. The coefficient of proportionality is the spring leakance. For a stream, when the ground-water level in the underlying aquifer for the stream is above the stream-surface elevation **(Figure 8-11a** and **Figure 8-11b)**, the ground-water seepage to the stream in the model is proportional to the difference between the stream-surface elevation and the underlying ground-water level. Otherwise, streamflow is lost from the channel. The constant of proportionality is the stream leakance, which is related in the model to streamflow depth **(Figure 8-12)**, streamflow width **(Figure 8-13)**, streambed permeability, streambed thickness, and reach length.

Ground-water discharge to carbonate springs and streams is incorporated in the model by identifying the spring and stream nodes. For the spring nodes **(Figure 8-14)**, the spring-orifice elevation and spring leakance are assigned. For the stream nodes **(Figure 8-15)**, the streambed elevation, thickness, and permeability are assigned. Additionally, a channel network is specified in order to link the nodes **(Figure 8-15)**, and channel-geometry relations are specified. Those

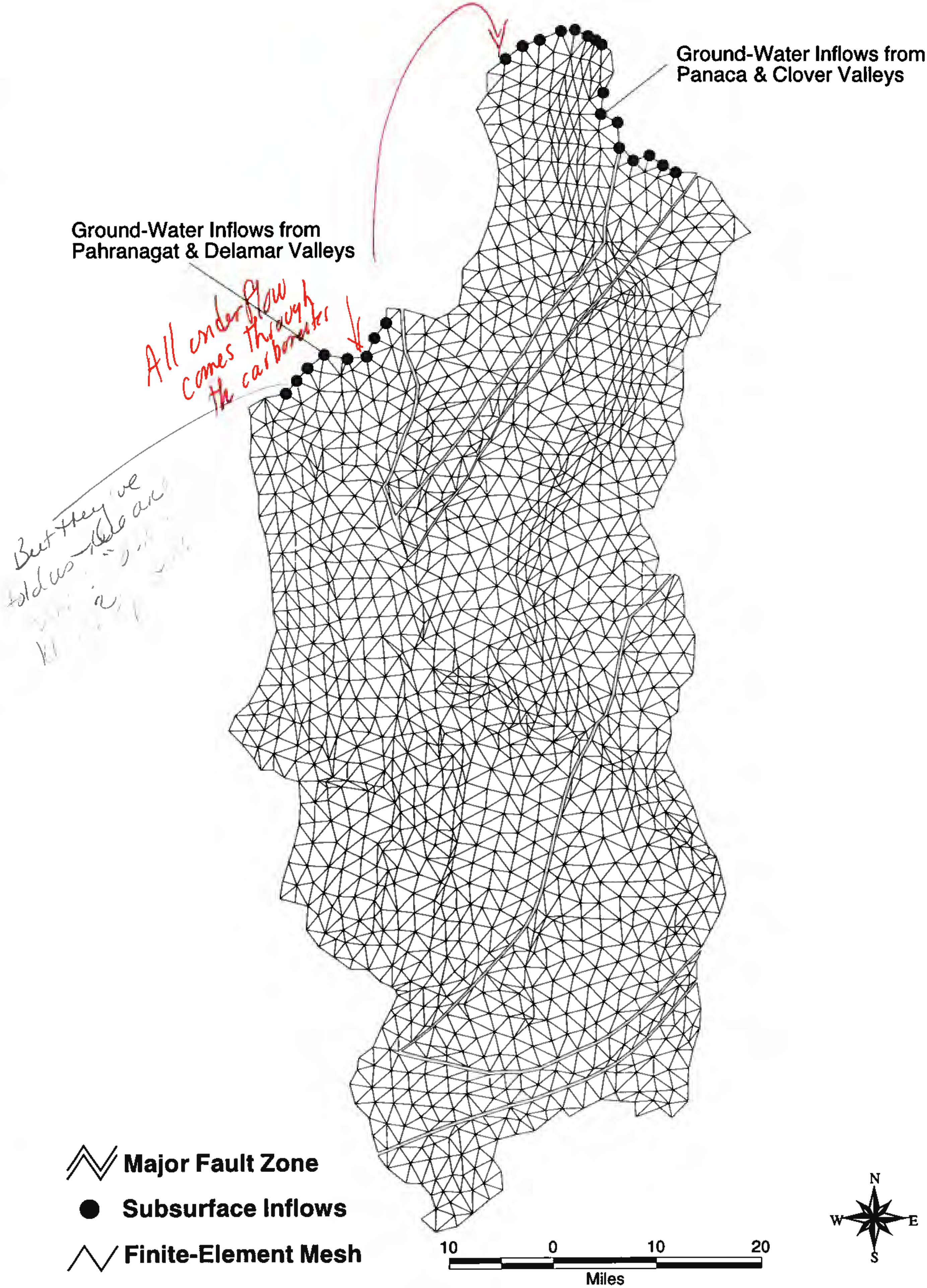

Figure 8-10. Location of subsurface inflows represented in model.

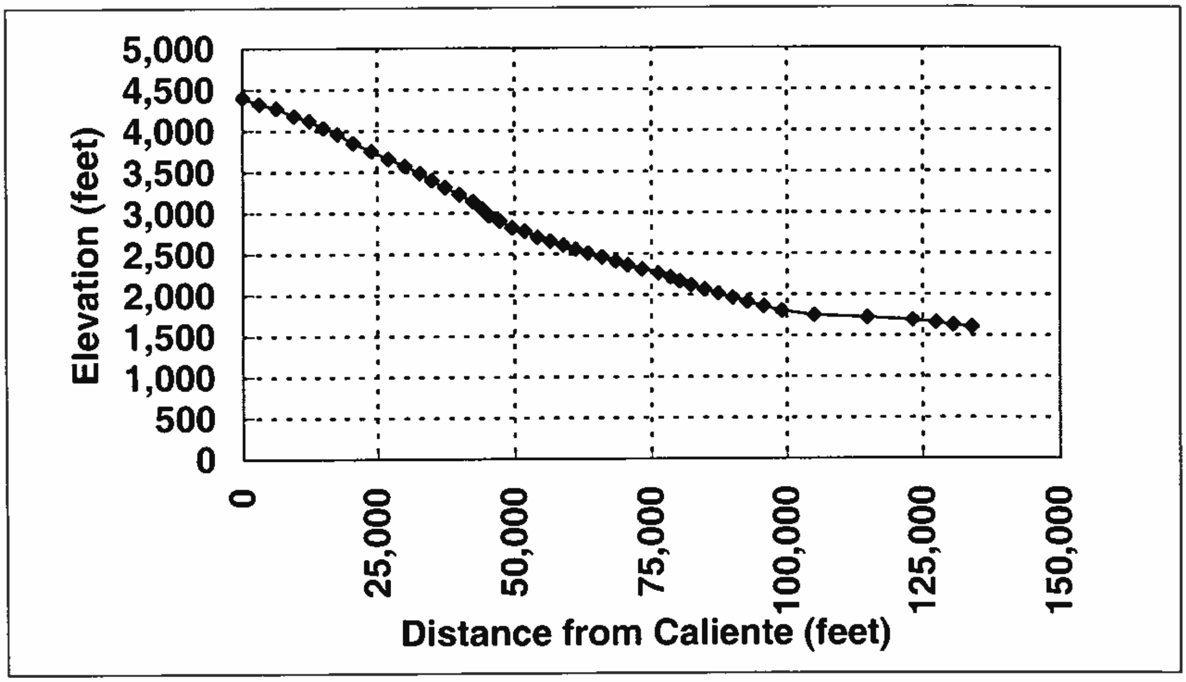

Figure 8-11a Lower Meadow Valley Wash Elevation.

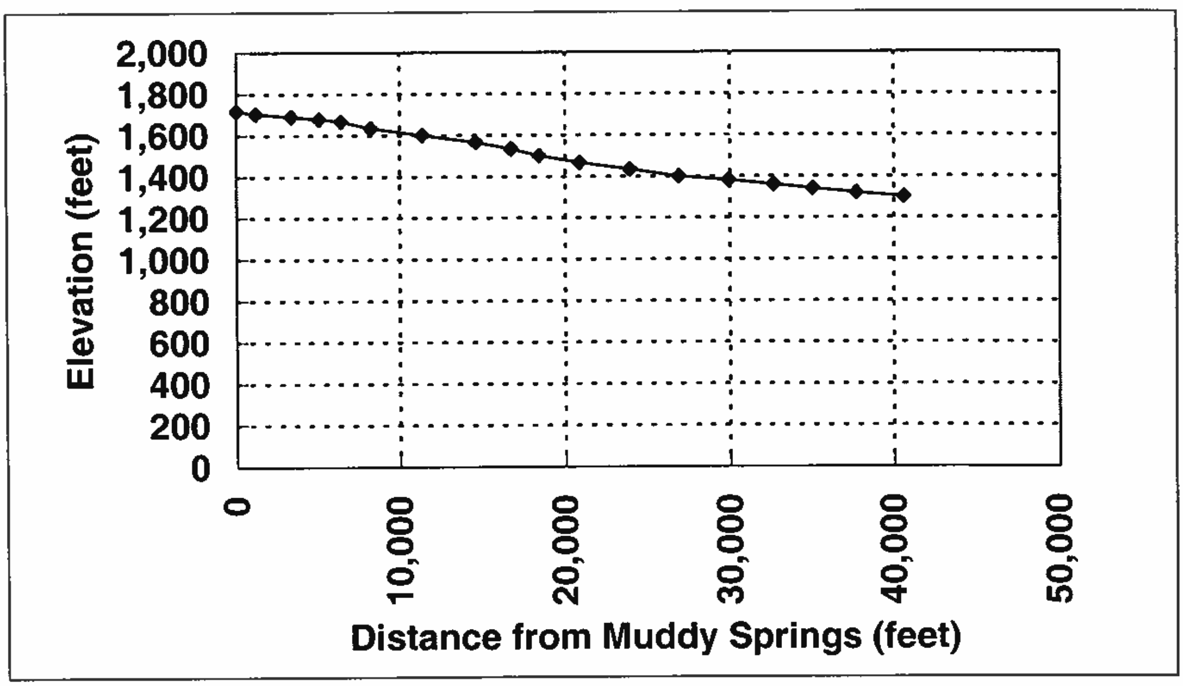

Figure 8-11b Muddy River Elevation.

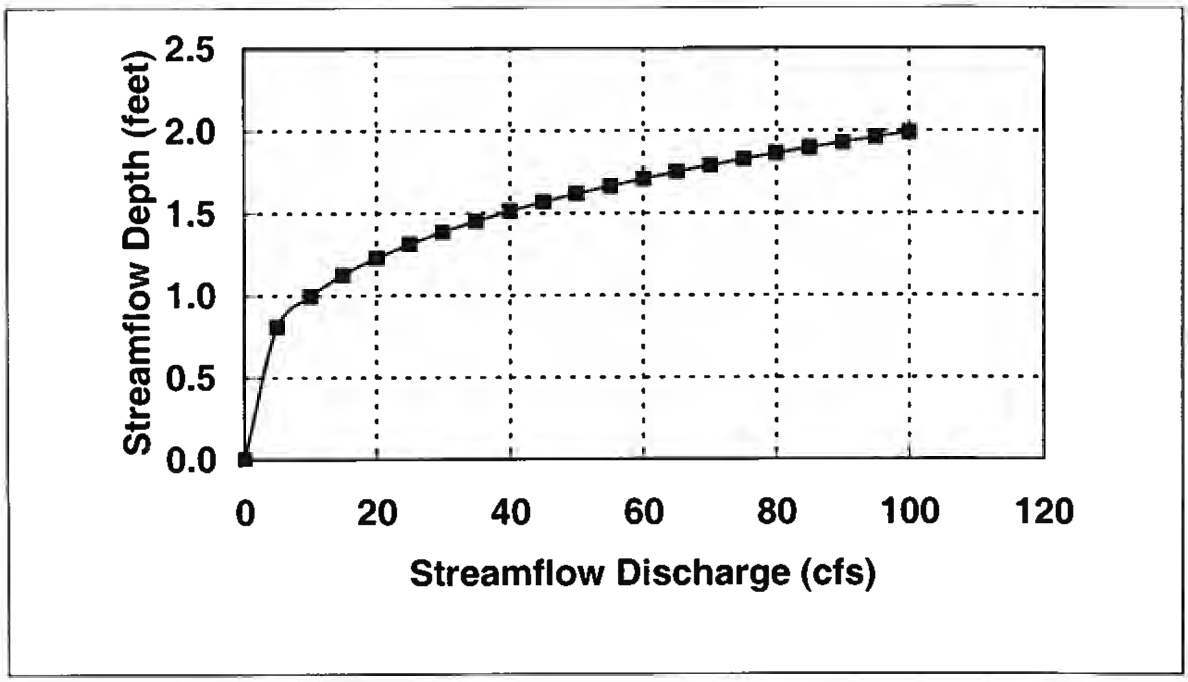

Figure 8-12 Streamflow Depth as a Function of Streamflow Discharge.

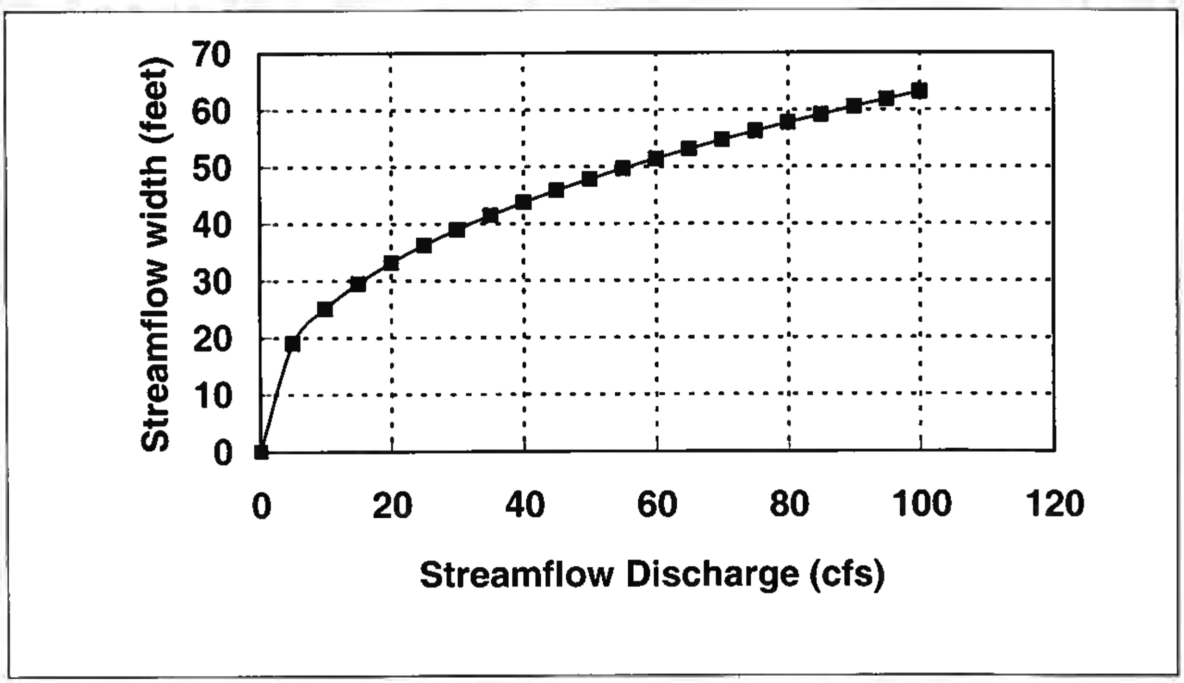

Figure 8-13 Streamflow Width as a Function of Streamflow Discharge.

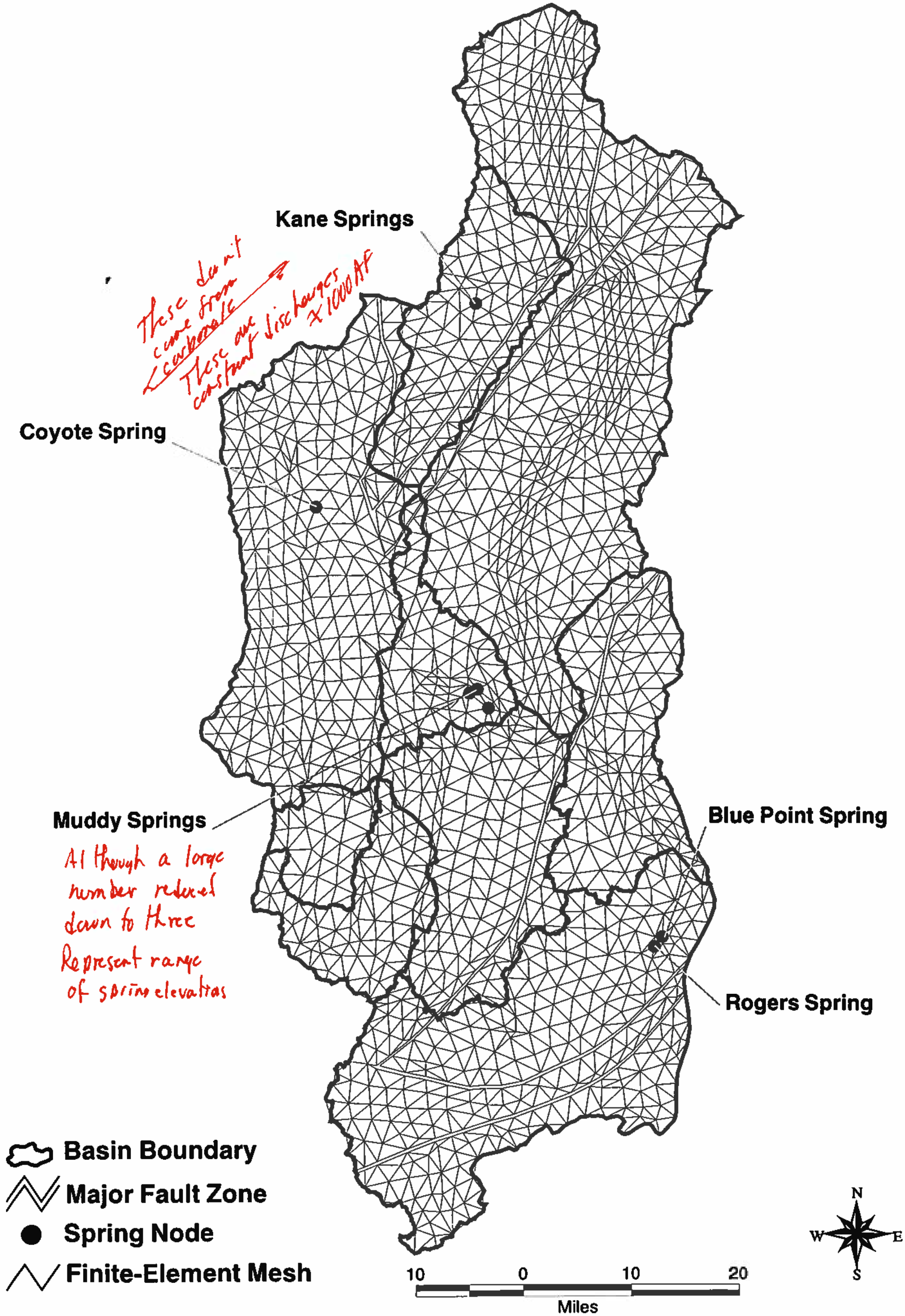

Figure 8-14. Location of spring nodes represented in model.

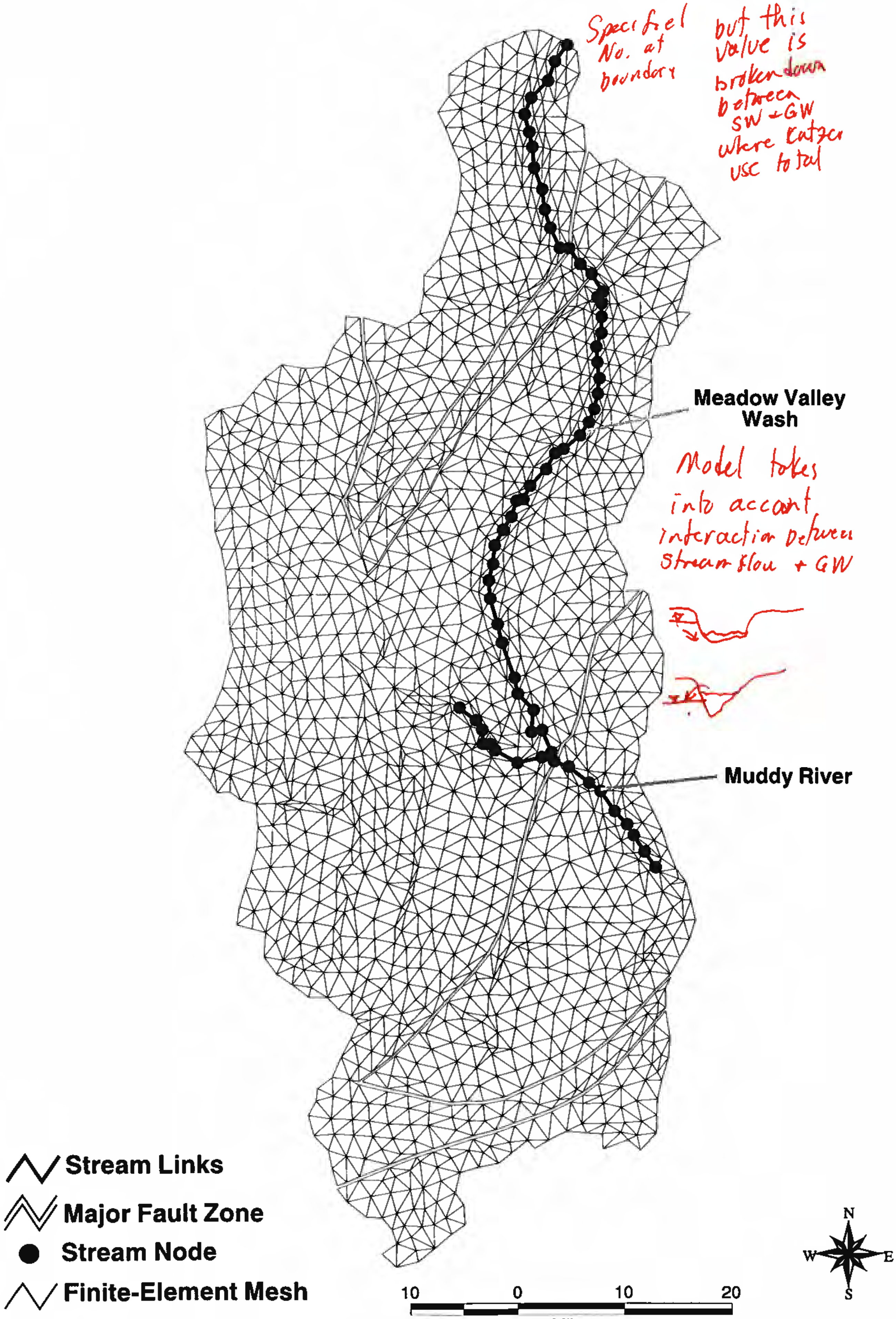

Figure 8-15. Location of stream nodes represented in model.

relations define the streamflow depth and width as functions of streamflow discharge **(Figure 8-12** and **Figure 8-13)**.

Ground-water discharge to Lake Mead is represented as a specified-head boundary condition, and subsurface outflow from the modeled area toward the Virgin River is represented as a specified discharge. Ground-water discharge to Lake Mead is represented by specified-head nodes on the top surface of the model mesh at the locations shown on **Figure 8-16**. Subsurface discharge toward the Virgin River is represented in the model as specified-discharge nodes within the carbonate aquifer at the locations shown on **Figure 8-17.** The discharge at a particular geographic location is assigned to the carbonate rocks at the bottom two nodes within the local model mesh.

8.2.4 Representation of Pumpage

The model represents pumping from the ground-water system, where the total pumping from the model area is about 18,000 afy in year 2000 **(Table 8-1)**. Ground-water pumping includes agricultural, industrial, and municipal pumping. Minor residential and commercial pumping within the model area is not represented in the model.

Pumping from a well is represented in the model by assigning a discharge to a node within the model mesh. The location of a well is represented by assigning the well to the geographically nearest node column. The depth of a well is represented by assigning the well to an appropriate node within a node column. Valley-fill wells are assigned to the top node within the node column, and carbonate wells are assigned to the second node from the bottom of the node column.

Pumping from 60 valley-fill wells and 11 carbonate wells is represented in the model in year 2000. The location of pumping-wells is shown on **Figure 8-18**. The total annual pumping from valley-fill wells is shown on **Figure 8-19** for 1945-2000, and the total annual pumping from carbonate wells is shown on **Figure 8-20**. The annual pumping for individual wells is listed in Appendix B.

Historically, ground-water development within the model boundary has been limited to areas located within the flood plains of the Muddy River and Meadow Valley Wash in Lower Moapa Valley, Lower Meadow Valley Wash, and the Upper Moapa Valley near the southeast portion of the modeled area. Ground water has principally been developed to supply water for agriculture in these areas, but has also been developed in the Upper Moapa Valley to supply water to the Reid Gardner facility located in California Wash and owned and operated by NPC. Until recently, there has been little to no ground-water development in the other basins comprising the remainder of the modeled area (Black Mountains, California Wash, Garnet Valley, Hidden Valley). However, since 1990, various commercial enterprises have been granted ground-water withdrawal permits within the Black Mountains Area and Garnet Valley, of which, only a few have been certified.

Records of ground-water production for each basin within the model boundary were developed for the period 1945 to 2000 based on data and information acquired from DRI, MVWD, NDWR,

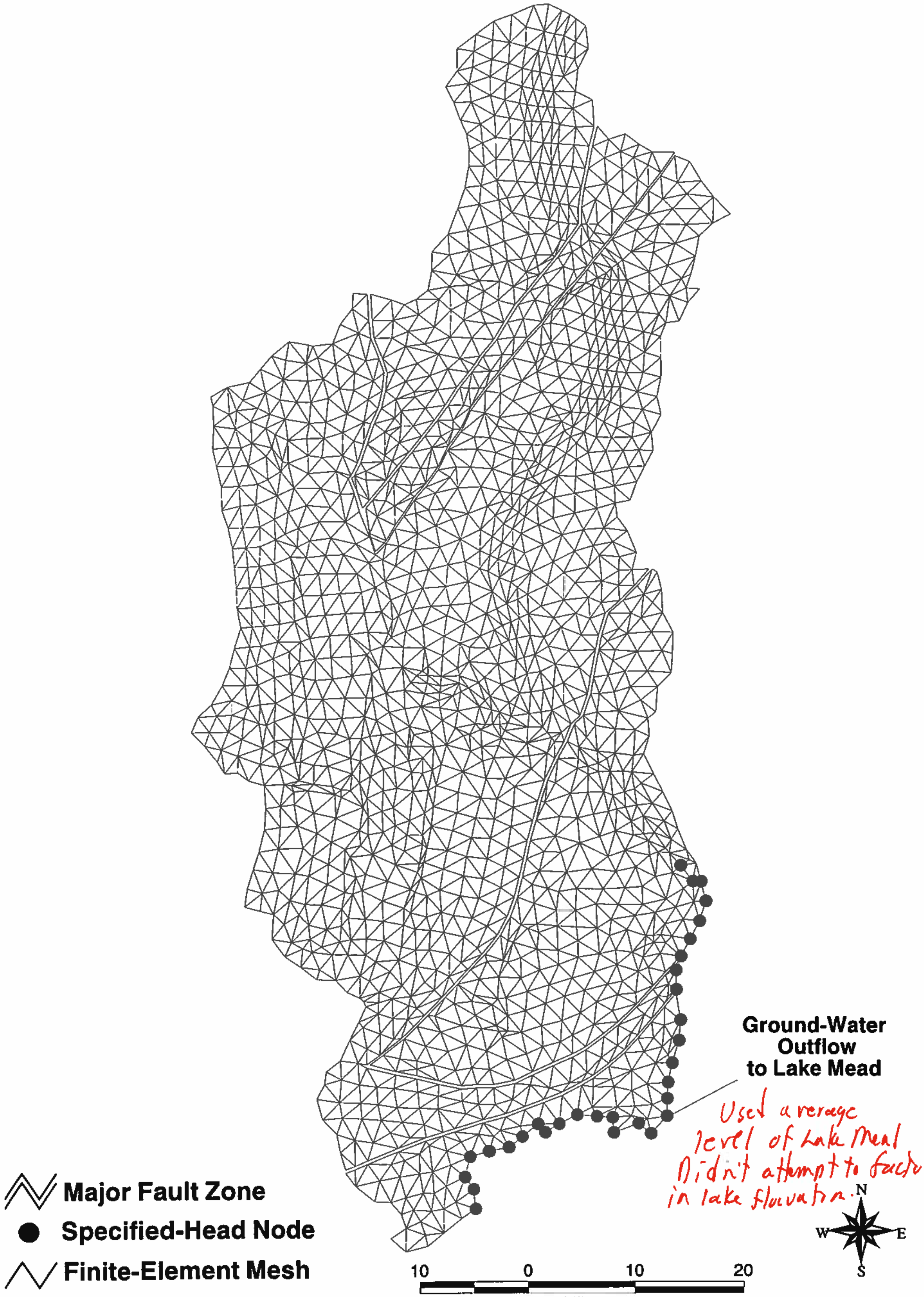

Figure 8-16. Location of specified-head nodes represented in model.

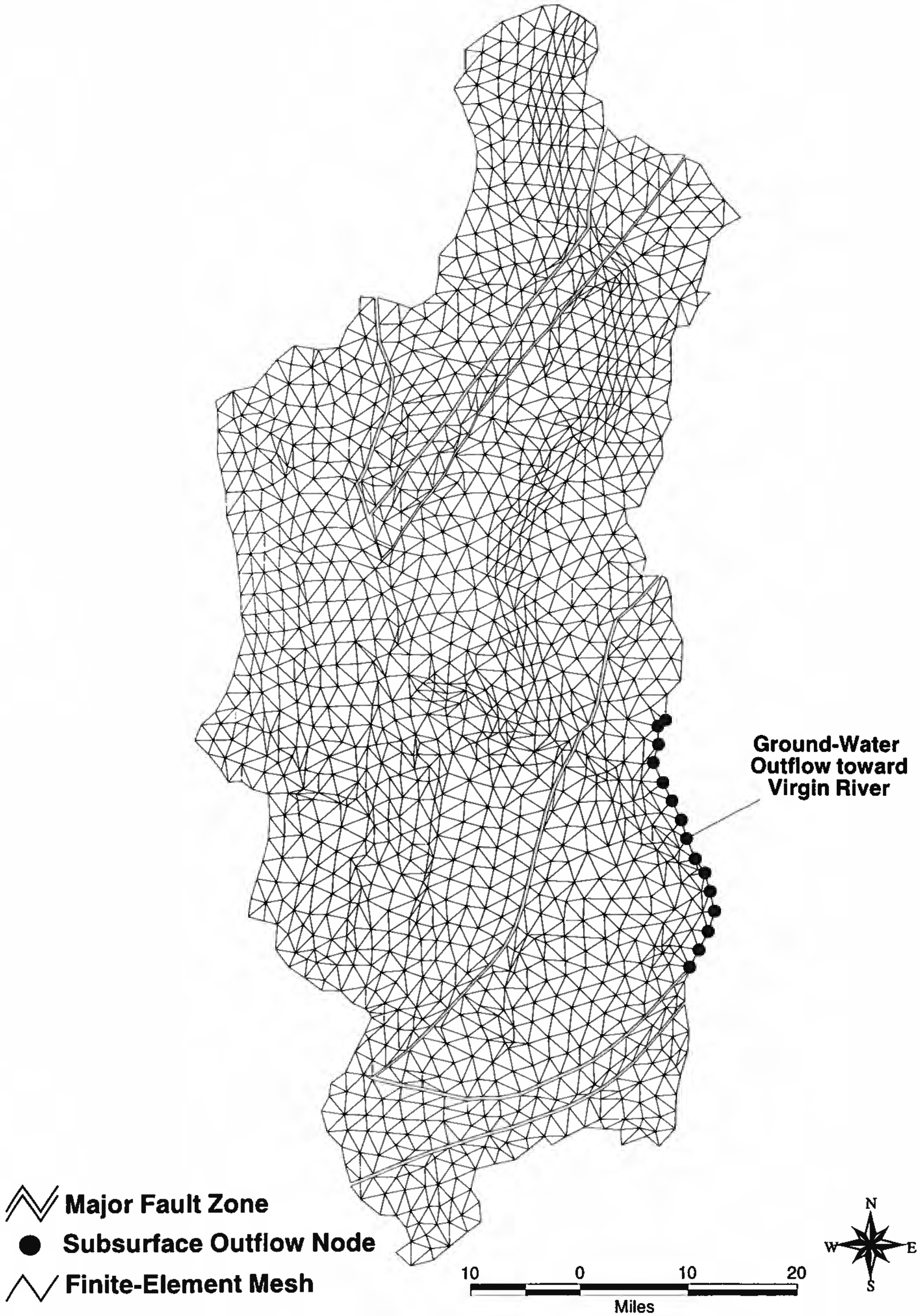

Figure 8-17. Location of subsurface outflow nodes represented in model.

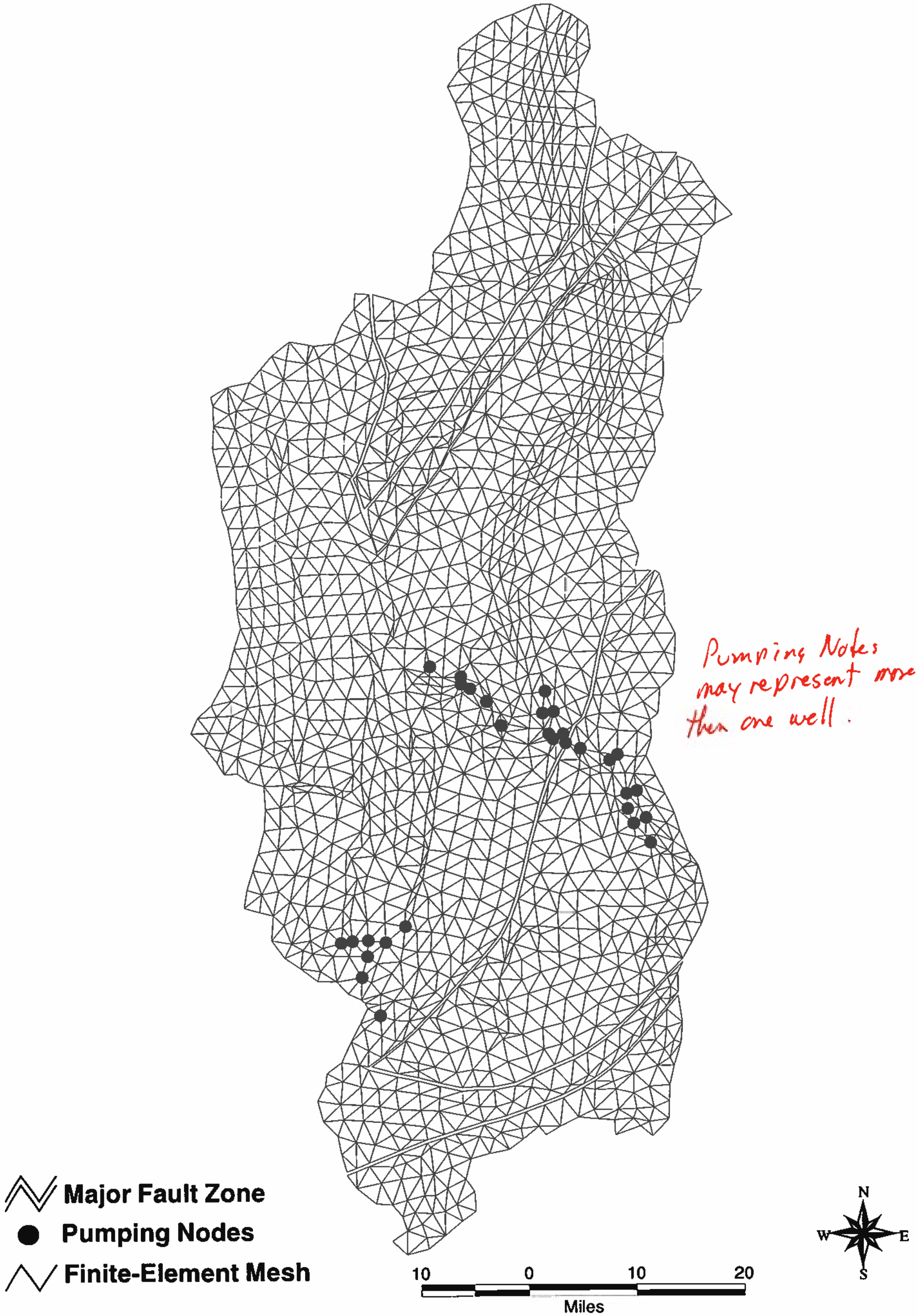

Figure 8-18. Location of pumping nodes represented in model.

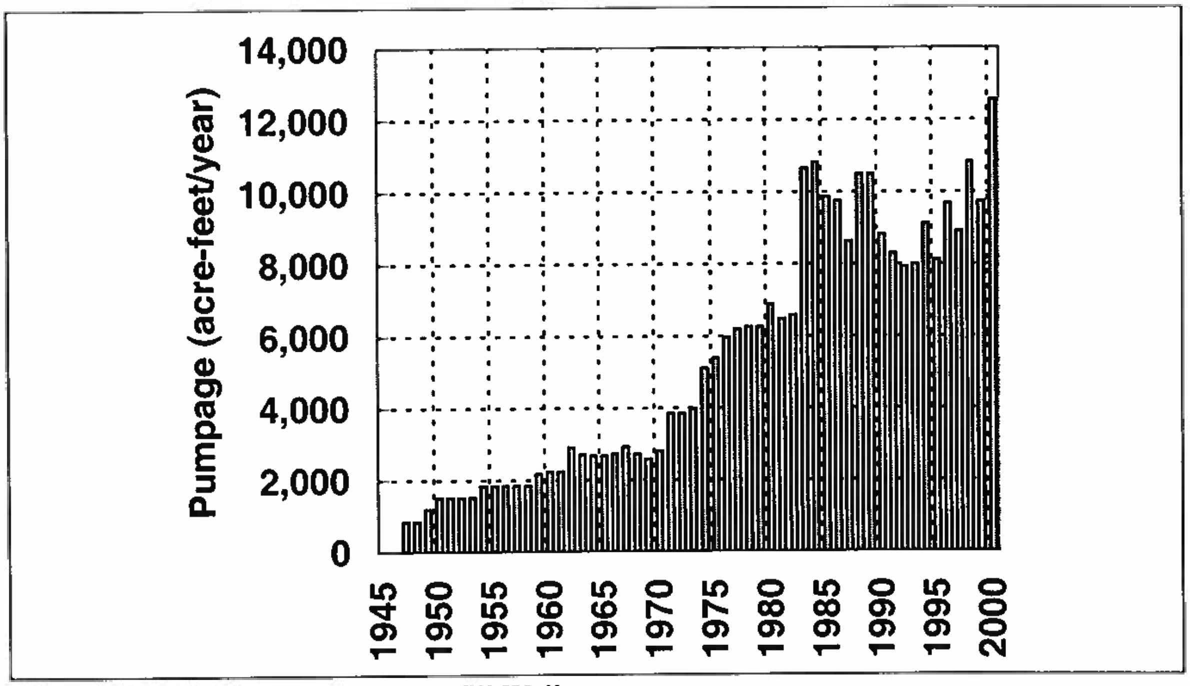

Figure 8-19 Pumping from Valley-fill Wells.

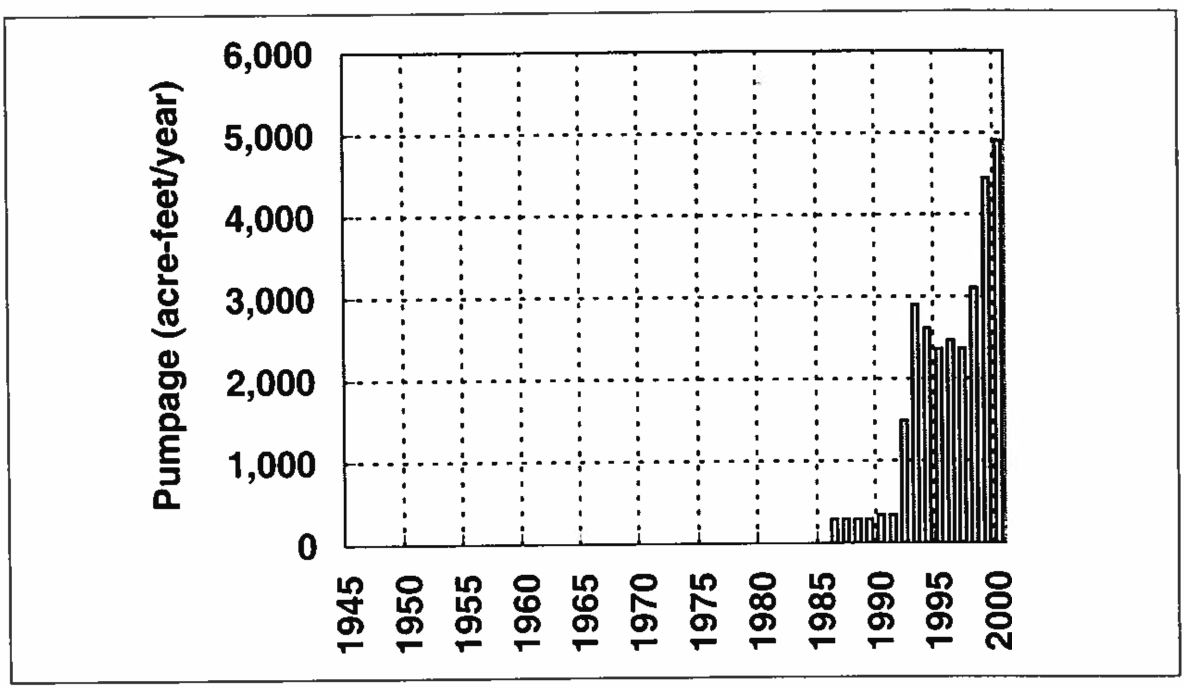

Figure 8-20 Pumping from Carbonate Wells.

NPC, and the USGS. **Figure 8-21** depicts the location of pumping wells used to simulate transient conditions during calibration of the ground-water flow model. Data and information for these wells were acquired in the form of published and unpublished documents and data sets. In addition, numerous interviews were conducted with representatives of MVIC, MVWD, NDWR, and various consultants working within the boundary of the modeled area to assist in the development of the records.

Few recorded data are available for years prior to 1987; therefore, information garnered from literature review and the interview process, water-right abstracts, land-use maps, aerial photography, and satellite imagery was relied upon to construct estimates of ground-water development for each basin for the period 1945 to 1986. Although all available data and information were used to develop the estimates, the fact that records do not exist or are unavailable for this period lend uncertainty to these estimates. Conversely, relatively complete records of ground-water production for the Black Mountains Area, Garnet Valley, and Upper Moapa Valley exist for the period 1987 to 2000. The Upper Moapa Valley has the most complete record due to monitoring programs established by DRI, MVWD, and NPC, and hydrologic investigations conducted by DRI and the USGS. Estimated totals of annual ground-water production for selected basins within the model boundary are listed in **Table 8-2.** A summary of ground-water development by MVWD and NPC in the Muddy River Springs Area for the period 1987 to 2000 is provided in **Table 8-3.**

Table 8-2. Estimates of ground-water production for selected sub-basins within the model boundary, in acre-feet.

	Estimated annual ground-water production					
Sub-basin	1950	1960	1970	1980	1990	2000
Black Mountains Area	0	0	0	0	0	1,693
Garnet Valley	0	0	50	150	496	952
Lower Moapa Valley	0	63	378	1,197	881	462
Meadow Valley Wash	0	0	880	3,080	3,740	3,960
Muddy River Springs Area	1,513	2,171	1,495	2,455	4,056	10,393

Table 8-3. Ground-water development in the Upper Moapa Valley since 1987 by MVWD and NPC, in acre-feet.

Year	MVWD	NPC
1987	245	2,304
1988	245	4,309
1989	245	7,126
1990	245	7,337
1991	245	7,342
1992	758	6,293
1993	1,345	6,287
1994	894	6,890
1995	678	6,414
1996	705	7,972
1997	808	6,589
1998	1,557	8,262
1999	2,579	7,333
2000	2,908	10,548

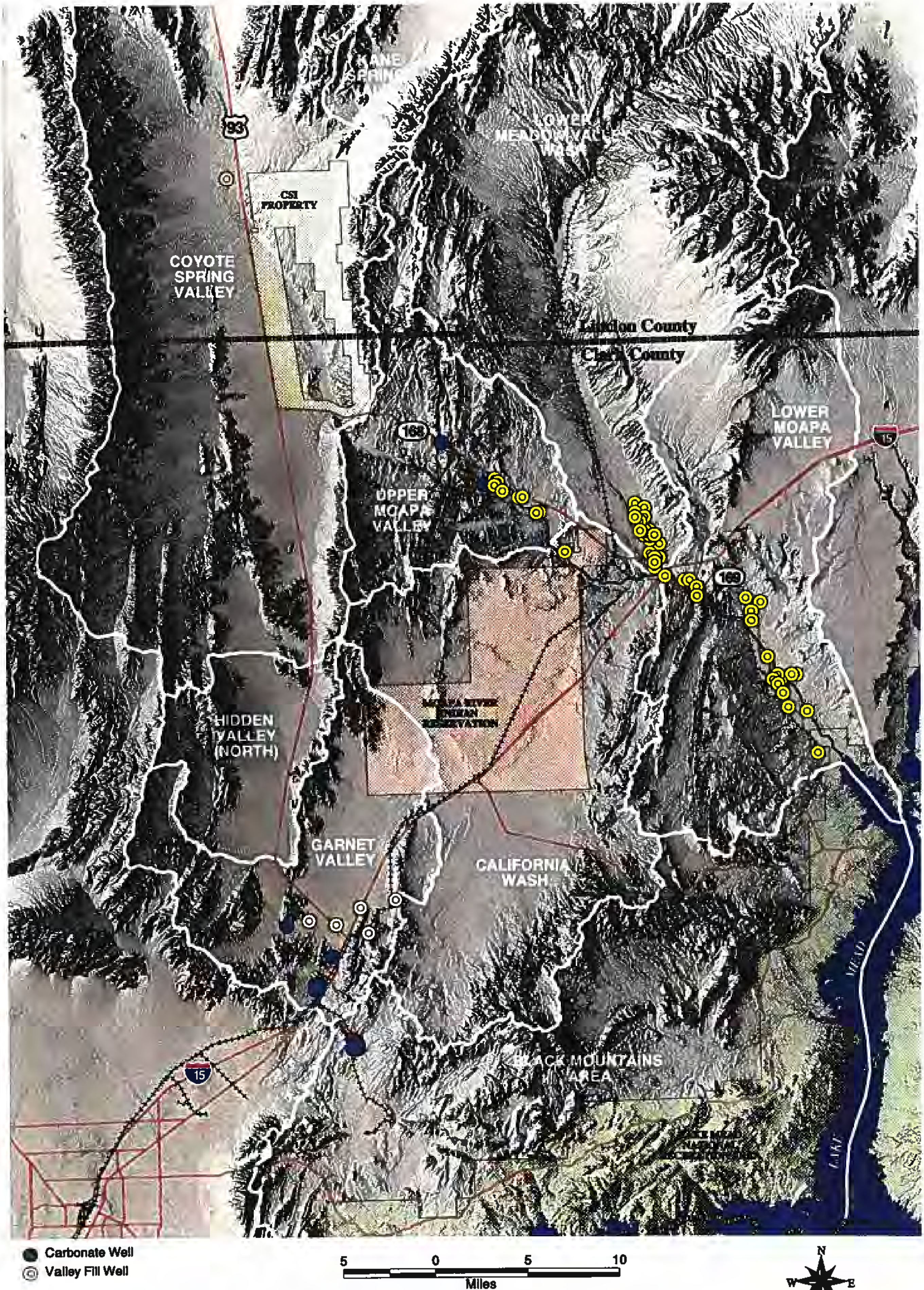

Figure 8-21. Location of pumping wells within the model area, historical 1945-2000.

SE ROA 40189

Appendix B provides a detailed discussion of the methods used to estimate and distribute ground-water pumping in each basin within the model boundary for the period 1945 to 2000. Included, are annual ground-water production totals for MVWD and NPC as reported by MVWD, DRI, and NPC, as well as, recent data submitted to NDWR by various water users in the Black Mountains Area and Garnet Valley.

8.2.5 Representation of Consumptive Use

The model represents the consumption of surface water and ground water, which results from vegetation and municipal and industrial use.

Vegetative consumption occurs where soils are moist owing to irrigation or shallow ground-water. About 5,000 acres produce consumption along Meadow Valley Wash from Caliente to its confluence with the Muddy River. About 4,000 acres occurs above the Rox gage, and about 1,000 acres occurs near the confluence with the Muddy River. About 7,400 acres produce consumption along the Muddy River from Muddy Springs to Lake Mead. Along the Muddy River, about 600 acres occurs along the river above the Moapa gage, about 1,800 acres occurs along the river from the Moapa gage to the Glendale gage, and about 5,000 acres occurs along the river from the Glendale gage to Lake Mead.

The annual consumption within the model area is about 5 ft per acre. Correspondingly, the consumption along Meadow Valley Wash is about 23,000 afy, and the consumption along the Muddy River from Muddy Springs to Lake Mead is about 37,000 afy. Along Meadow Valley Wash, the consumption is 20,000 afy above the Rox gage and 4,000 afy near the confluence with the Muddy River. Along the Muddy River, the consumption is 3,000 afy along the river above the Moapa gage, about 9,000 afy along the river from the Moapa gage to the Glendale gage, and about 25,000 afy along the river from the Glendale gage to Lake Mead.

This consumption most likely has remained essentially constant over a long period. This is the case even though water-use patterns have changed. Prior to the introduction of agriculture, the consumption resulted from water use by native phreatophytes. With the introduction of agriculture, the phreatophytes were replaced with forage and other crops, which have been irrigated from shallow ground water, streamflow diversions, and pumping. The acreage has remained essentially unchanged, the consumption per unit area has remained unchanged, and the total consumption has remained unchanged. This is the case except for lands along Meadow Valley Wash near its confluence with the Muddy River, which presently are irrigated with ground-water. Prior to the agricultural development of those lands, about 400 acres were covered with phreatophytes. Currently, about 1,000 acres are irrigated or covered with phreatophytes.

These conditions are represented in the model using the stream-aquifer module of FEMFLOW3D. The module simulates stream-aquifer interactions and the accretion or depletion of streamflow along a channel owing to the stream-aquifer interactions and upstream inflows. Consumption is represented by diversions from streamflow. Where irrigation occurs from actual diversions, the specified local diversion is the net diversions, which is the diversion less ground-water returns and surface-water returns. Where irrigation occurs from shallow ground-water, the specified local diversion is the net consumption, which is the vegetation ET. By this representation, the streamflow diversion is a surrogate in the model for the consumption of ground water **(Figure 8-5)**. **Figure 8-22** shows the location where consumptive diversions are represented in the model.

Ground water is pumped for supplemental irrigation along the Muddy River and Meadow Valley Wash. That pumping is represented in the model as the net pumping, which is the consumption of the pumped water. Where supplemental ground-water is used, the local streamflow diversion expressed in the model is reduced by the local net pumping. Correspondingly, supplemental pumping replaces diversions such that the total consumption is unchanged. The supplemental pumping and reduced diversions are shown on **Figure 8-23a** through **Figure 8-23c**, which are the values represented in the model. **Figure 8-23a** shows in particular the pumping and reduced diversions for the Meadow Valley Wash below the Rox stream gaging station. As shown on the figure, the supplemental pumping exceeds the initial local diversion after 1970. This represents a case where the total vegetative consumption is not unchanged, but it increases owing to supplemental pumping that exceeds the consumption prior to any pumping.

8.2.6 Representation of Boundary Shifts

While the boundaries of the modeled area follow drainage divides, pumping causes the boundary location to shift. Under the 1945 steady-state conditions, the model boundaries correspond to the boundaries of the modeled area, which follow drainage divides. Topographic divides correspond with ground-water boundaries owing to the higher recharge beneath mountain areas. Post-1945 pumping has induced ground-water flow across the prior steady-state boundaries such that the boundaries moved outward. However, because post-1945 carbonate aquifer pumping has had little effect on Muddy River flows, the regional water-level declines have been small and the boundary shift has been slight. Nevertheless, the proposed future pumping is sufficient to shift this boundary further outward.

To account for this phenomenon, the variable-flux module of FEMLOW3D is utilized in the model. That module specifies a boundary condition that in effect extends the model area by attaching an analytical solution representing a one-dimensional aquifer to mesh nodes at the model boundary (Durbin and Bond, 1998). The extension occurs when pumping within the modeled area causes a water-level decline at the boundary of the modeled area. The module simulates subsurface flows at the boundary that occur in response to a water-level decline at the boundary. This approach has some similarities to the general-head boundary utilized in the modeling program MODFLOW (McDonald and Harbaugh, 1988), but it differs in that the variable-flux boundary incorporates the changes in ground-water storage outside the model area.

Figure 8-24 shows the geographic locations where a variable-flux boundary is assigned to mesh nodes. That boundary condition is assigned to the carbonate aquifer using the second from the bottom node in the model mesh. At that vertical position, the aquifer thickness specified for the boundary condition is the overall thickness of the carbonate aquifer.

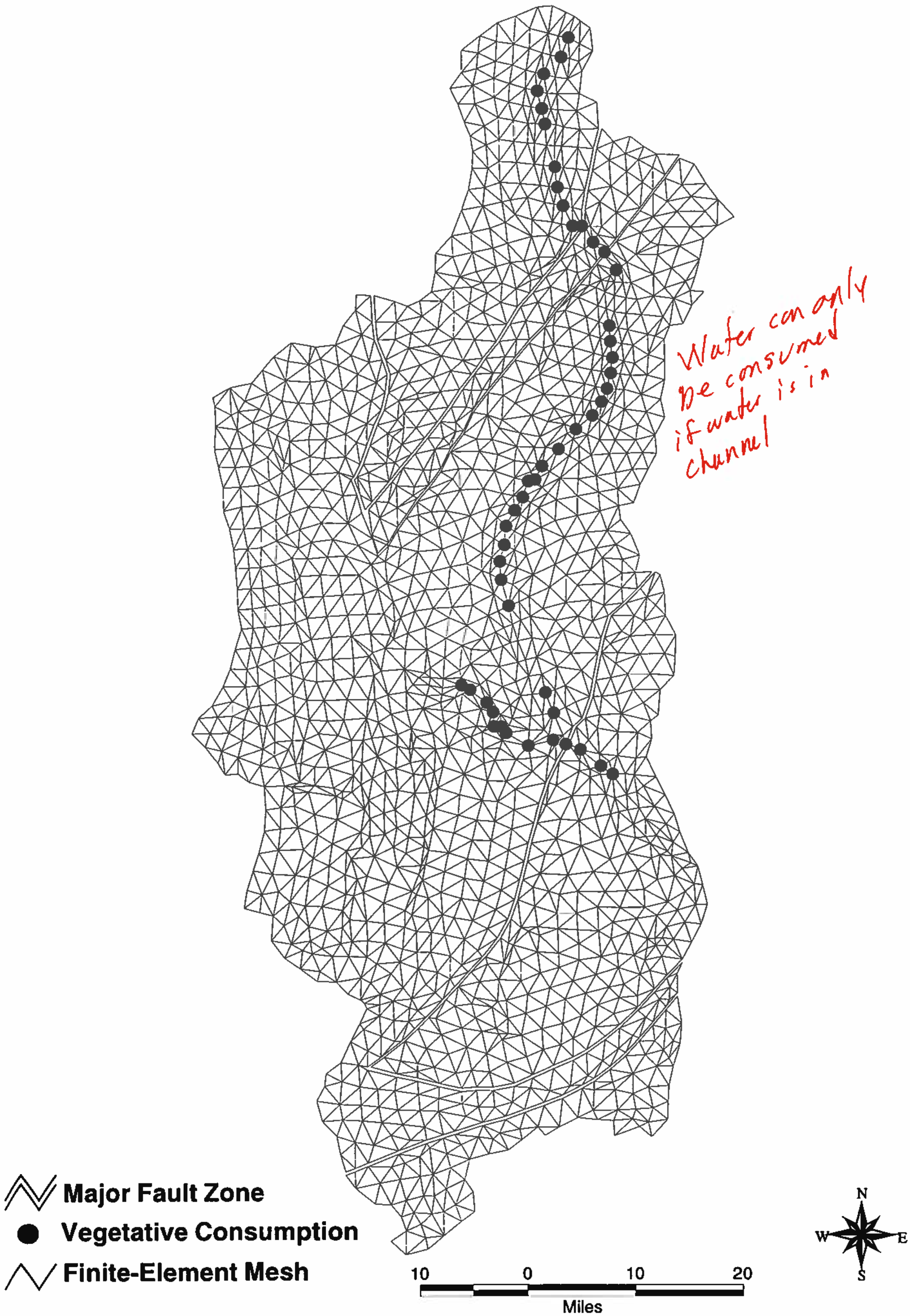

Figure 8-22. Location of vegetation consumptive use represented in model.

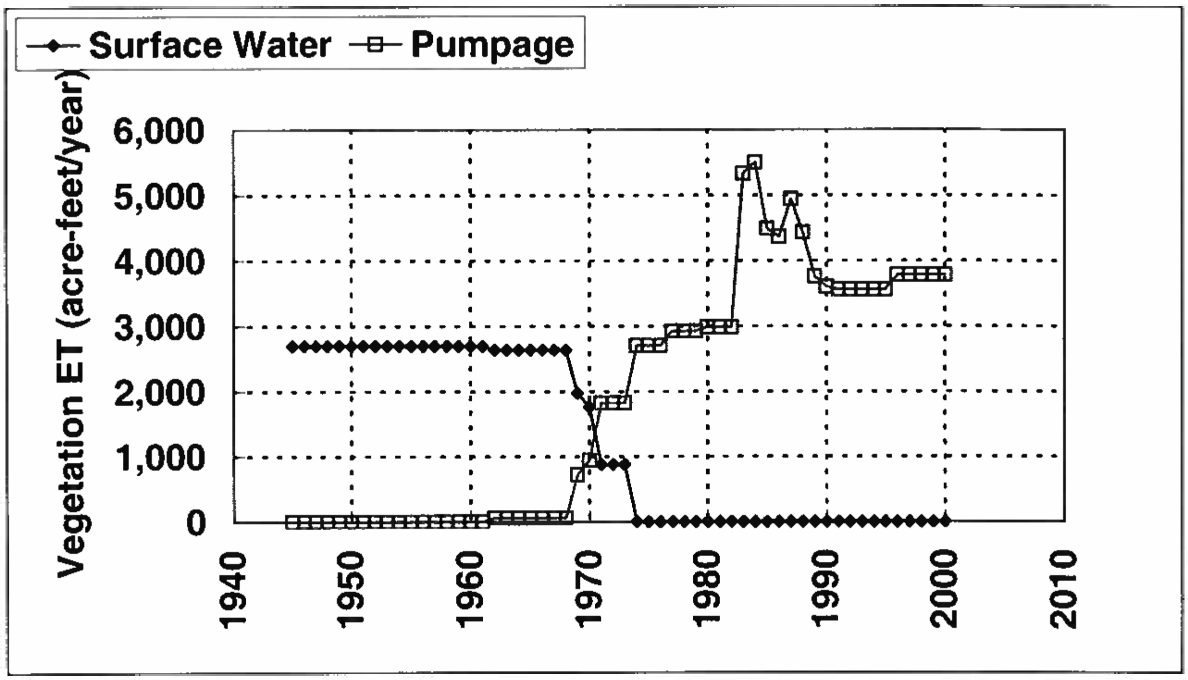

Figure 8-23a Lower Meadow Valley Wash Diversions and Pumpage below Rox.

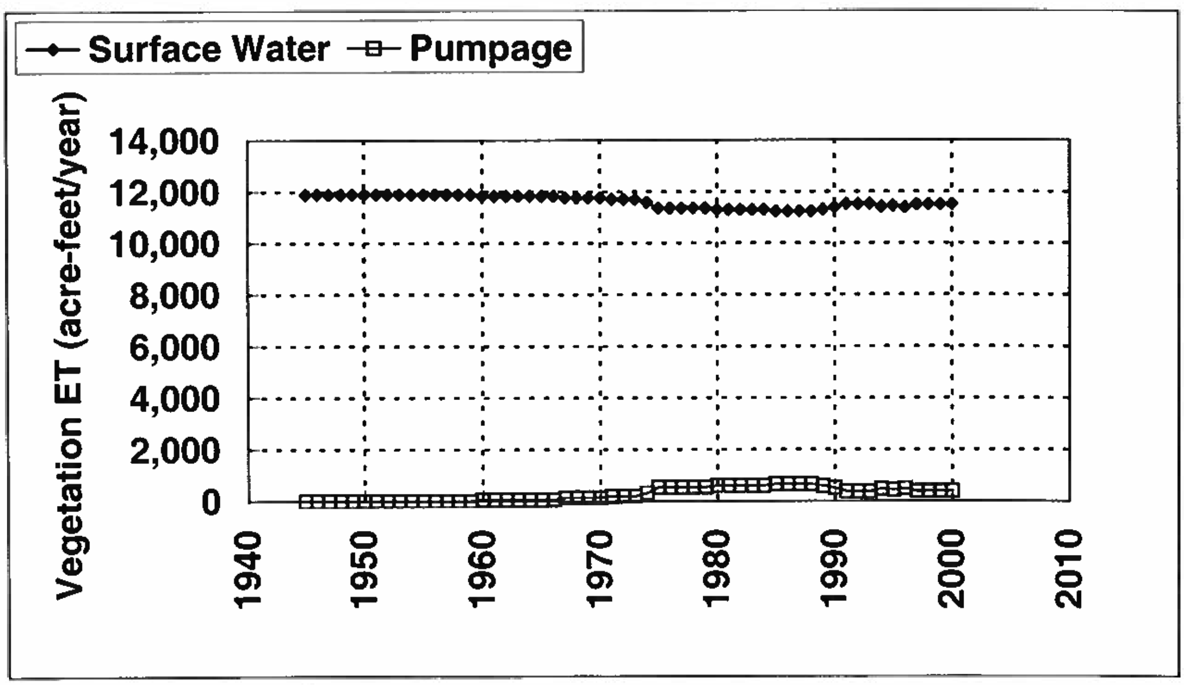

Figure 8-23b Muddy River Diversions and Pumpage Moapa to Glendale.

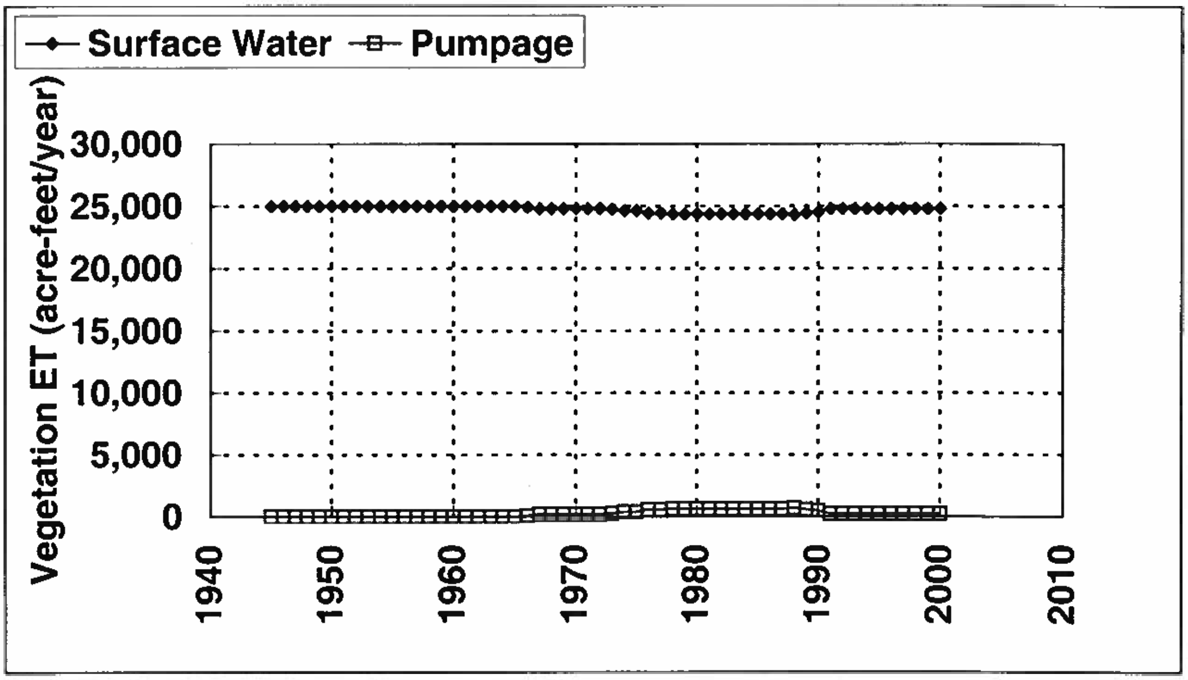

Figure 8-23c Muddy River Diversions and Pumpage Glendale to Overton.

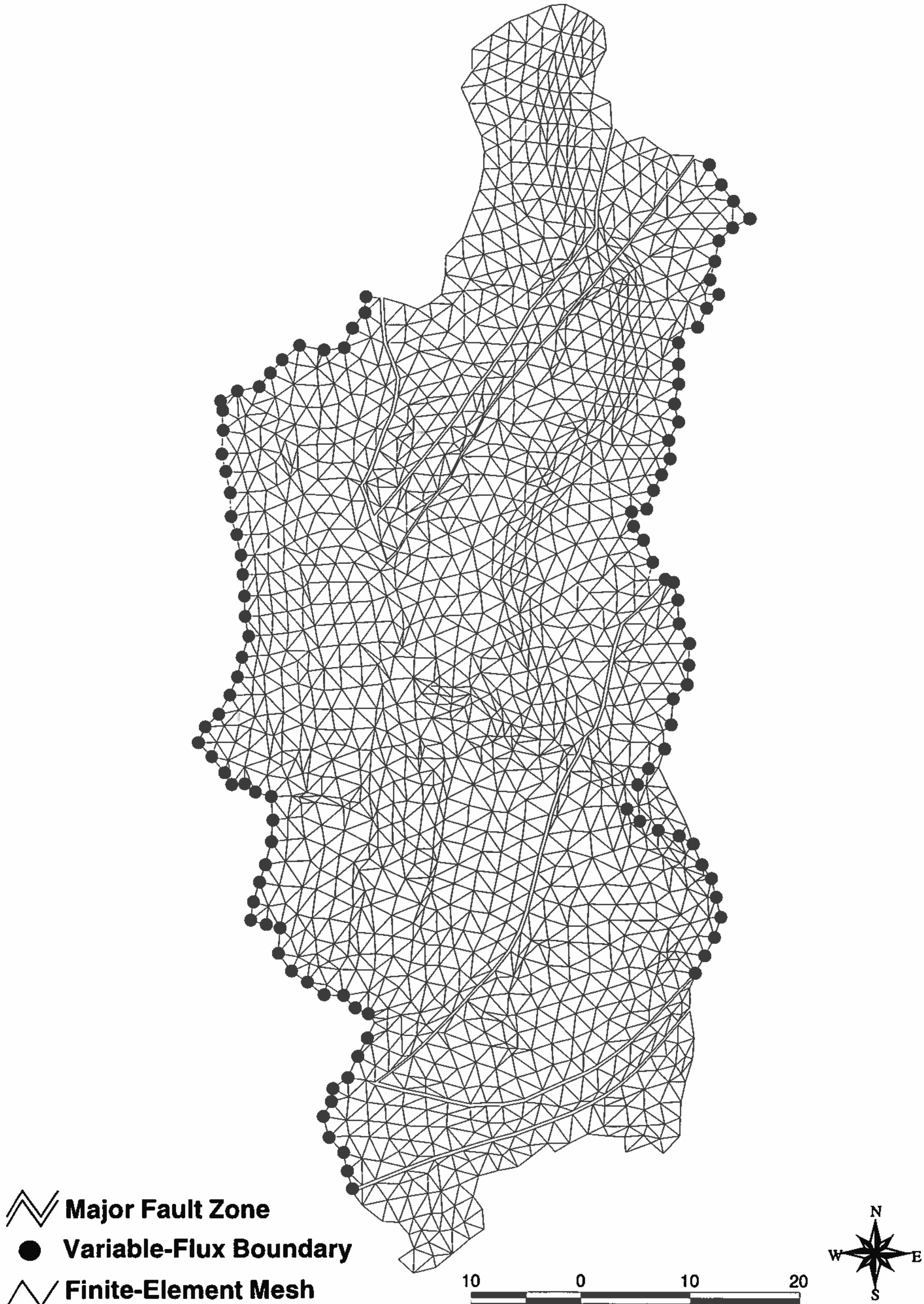

Figure 8-24. Location of variable-flux boundaries represented in model.

8.2.7 Identification of Model Parameters

8.2.7.1 Calibration Approach

Parameter values for the model were identified by calibrating the model to measured ground-water levels, spring flows, and streamflows. The model parameters include the permeability, specific storage, and specific yield for each hydrogeologic unit; the leakance for each spring or spring group; and the bed permeability for each stream channel. The calibration involved finding a set of parameter values such that the model best fit measured ground-water levels, spring flows, and streamflows. The model was used to simulate these quantities, and the simulated values were compared with the corresponding measured values in order to assess the model fit. Based on that comparison, parameter values were adjusted iteratively by a trial-and-error process to improve the model fit.

Both steady-state and transient-state simulations were used to calibrate the model. The calibration period was 1945-2000. Starting with a steady-state simulation for 1945, a transient-state simulation was made for 1946-2000. Correspondingly, the model was calibrated to the 1945 steady-state conditions and to the 1946-2000 transient-state conditions. The model was calibrated to streamflows, spring flows, and ground-water measurements representing 1945, including data collected later but nevertheless representative of 1945 conditions. Based on a steady-state simulation, these data were used to identify permeability for each hydrogeologic unit, permeability for the represented faults, and leakance for the carbonate springs. Additionally, the model was calibrated to streamflow, spring flow, and ground-water measurements during 1946-2000. Based on a transient-state simulation, these data were used to identify the specific storage and specific yield for each hydrogeologic unit.

Streamflow, spring flow, and ground-water data collected by the U. S. Geological Survey, Southern Nevada Water Authority and others were used in the model calibration. Streamflow data include those for the Caliente gage, Rox gage, Moapa gage, Glendale gage, and Overton gage. The location for these stream-gaging stations is shown on **Figure 8-5**, and annual streamflows are shown on **Figure 8-26** and **Figure 8-27** for the Moapa and Glendale gages. Spring flow data for Rogers Spring and Blue Point Spring are also included. Ground-water data include water-level measurements made by the U. S. Geological Survey and others in both valley-fill and carbonate wells. The well locations are shown on **Figure 8-25a** and **Figure 25b,** and represent wells in which repeated water-level measurements have been made over an extended period.

Ground-water levels were used to estimate hydraulic heads that were then compared to those simulated by the ground-water flow model during the calibration process. Hydraulic heads are a measure of the potential energy at a single point, and provide a measure of the driving energy that causes water to flow through permeable rocks. The difference between observed water levels and simulated hydraulic heads is a measure of how well the model simulates the ground-water flow system. Water-level data may also be used to estimate the direction of ground-water

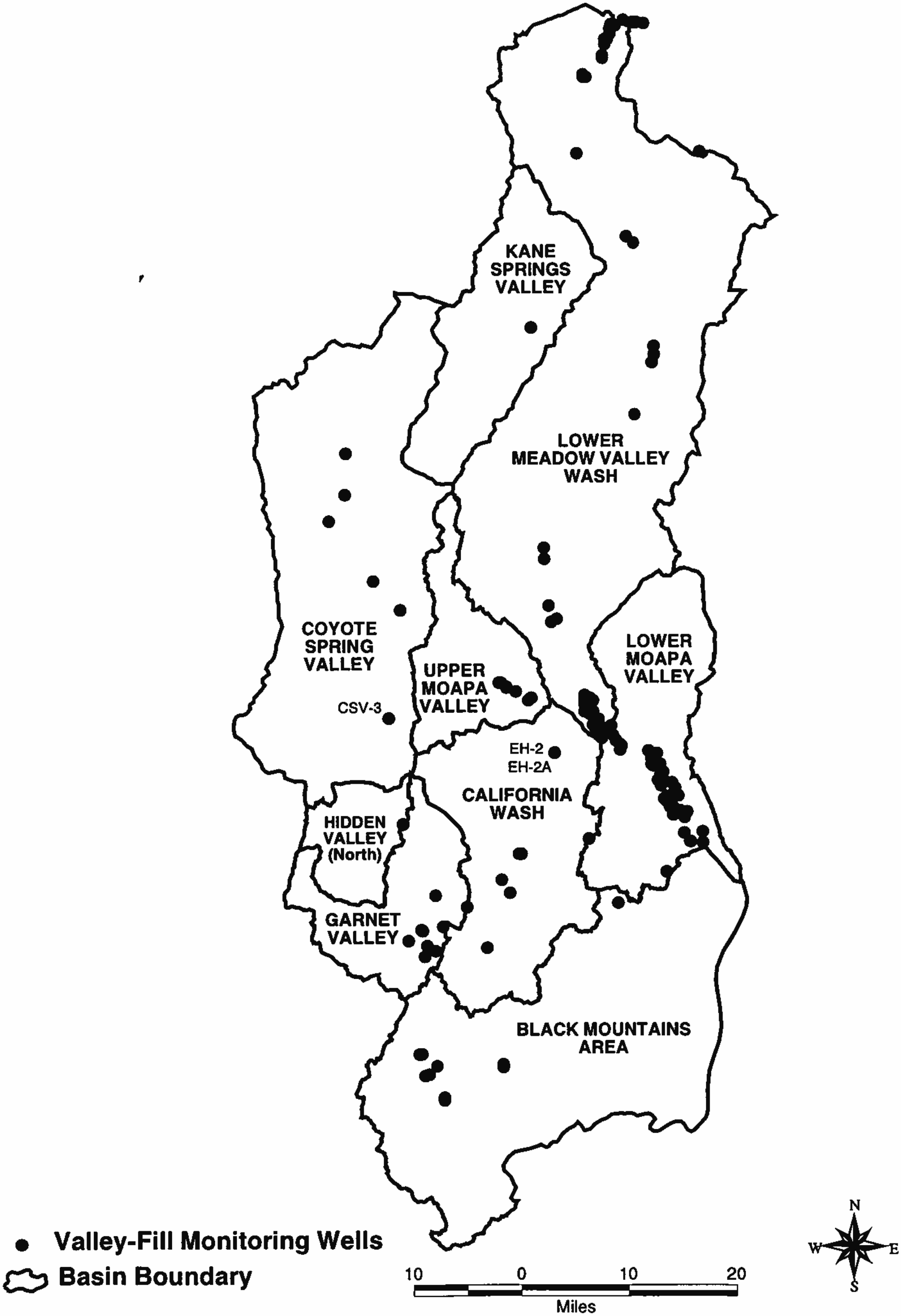

Figure 8-25a. Location of valley-fill monitoring wells used in model calibration.

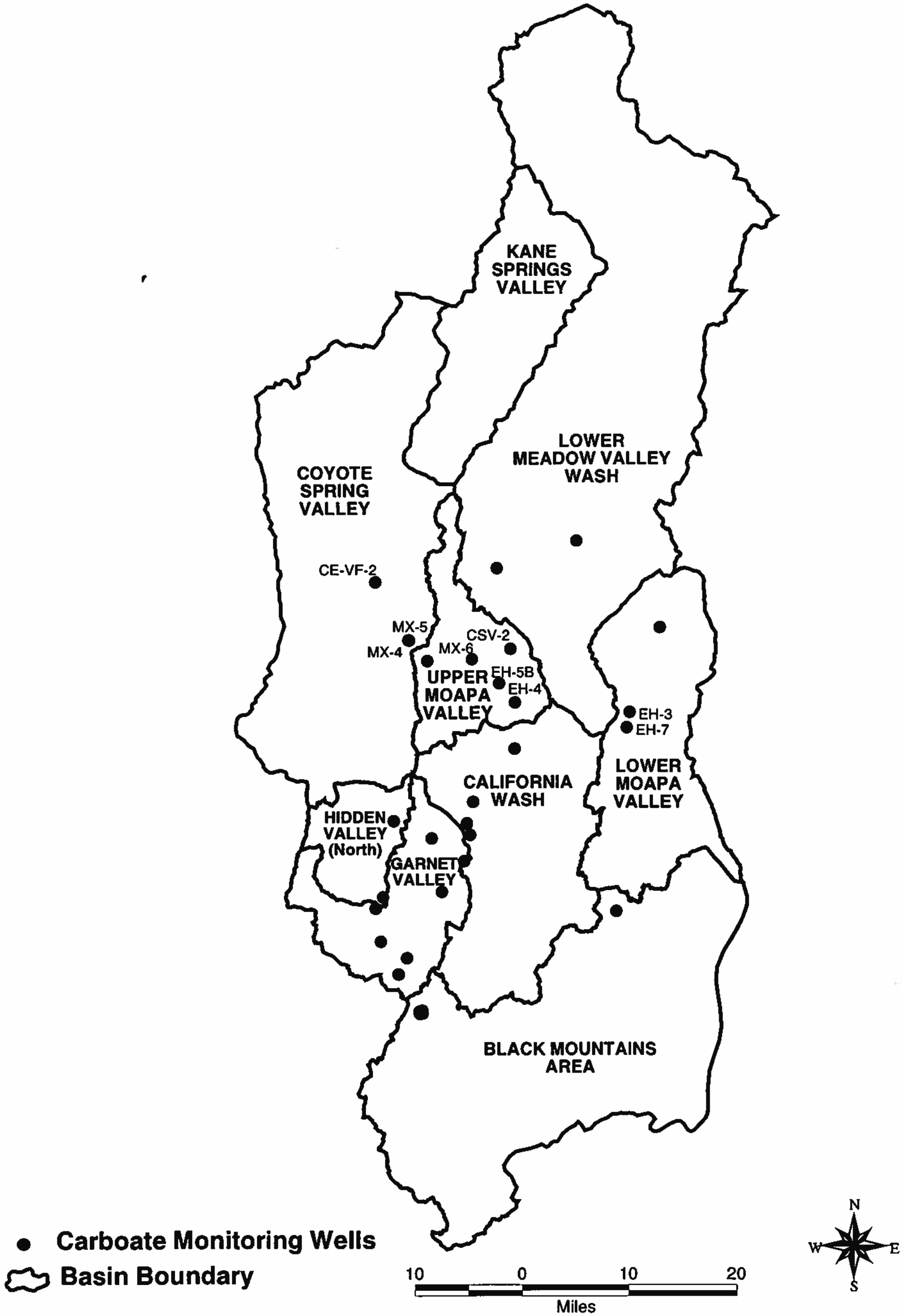

Figure 8-25b. Location of carbonate monitoring wells used in model calibration.

flow. For these purposes, water-level data was an integral part in developing the ground-water flow model. The greater the density of quality water-level data the greater certainty in the calibration process and subsequent model results.

Water levels are typically expressed temporally and spatially as elevations above mean sea level, requiring the following known parameters: location coordinates, measuring point elevation, depth-to-water, and date and time of measurement. Each of these parameters has some inherent uncertainty. Measurement error and procedural deficiencies lead to uncertainty in depth-to-water measurements. Expressing water levels as elevations introduces additional uncertainty related to the accuracy of the methods used to determine the measuring point elevation.

Well data containing these parameters were compiled from numerous sources including data collected by SNWA and data obtained from the USGS Ground-water Site Inventory database (GWSI), NDWR Well Log Database, and various reports and maps. Data compilation focused on well data for known carbonate wells and wells known to have a significant record of depth-to-water measurements (e.g. greater than 5-years of record). As **Figure C-1** in Appendix C illustrates, nearly all of these wells are located in Coyote Spring Valley and the Muddy River Springs Area. Many of the wells have limited historical records since they were completed in the early to mid-1980s as part of USGS hydrologic investigations, the U.S. Airforce MX-Missile program, and NPC ground-water-monitoring program. Appendix C provides individual hydrographs for these wells. Site information and depth-to-water data compiled for wells within the model boundary are also included in Appendix C **(Table C-1** and **Table C-2).**

Water-level data used to construct the hydrographs for wells ABBOTT, BEHMER, EH-2, EH-2A, EH-3, EH-4, EH-5B, EH-7, LDS-CENTRAL, LDS-WEST, LEWIS-NORTH, and LEWIS-SOUTH were compiled from NPC monitoring reports. Water-level data used to construct the hydrographs for wells CE-VF-1, CE-VF-2, CSV-1, CSV-2, CSV-3, MX-4, MX-5, and SHV-1 were compiled from SNWA records and the USGS GWSI database. Water-level data for these wells is considered good although methods by which the depth-to-water measurements were made and the accuracy of the measuring-point elevation are generally unknown.

Other well data compiled from Johnson et al. (2001, Appendix C) includes water-level data for additional carbonate monitoring wells, however many of the wells were completed in recent years and do not have a significant long-term record. Johnson et al. reported discrete carbonate water-level elevations for wells ECP-1, ECP-2, ECP-3, TH-1, TH-2, M-1, M-2, and M-3 located on the Moapa River Indian Reservation in California Wash. Also reported, were discrete water-level elevations for wells owned by Nevada Cogeneration Associates, Georgia Pacific Corporation, and U.S. Chemical Lime Company in the Black Mountains Area and Garnet Valley. These data are also provided in Appendix C in Table C-1 and C-2.

The remaining well data provided in Appendix C were compiled from individual well log records listed in the NDWR Well Log database. Few of these data were used for calibration purposes due to the high uncertainty of the methods used to determine depth-to-water and measuring point elevations. These data were used with great caution and only as a last resort to provide water-level control in areas where no other data were available.

Figure C-2 depicts the location of primary wells with significant water-level records. As stated previously, many of these wells were completed recent years in areas where ground-water development is occurring. However, due to the sparseness of quality water-level data within the model boundary, some were used during the calibration process.

8.2.7.2 Calibration Results

The parameter values produced from the model calibration are listed in **Table 8-4**. Permeability, specific storage, and specific yield values are listed separately in the table for each subarea within the modeled area, except that values are listed for northern and southern parts of the Upper Moapa Valley subarea. That subarea was subdivided to represent a region of higher permeability that occurs within a geographic band overlying the Glendale Thrust. Within this band, higher permeability is indicated by nearly flat hydraulic gradients, which presumably correspond to secondary faulting and fracturing that is associated with the Glendale Thrust.

Based on the listed parameter values, the streamflows and spring flows simulated with the calibrated model are summarized on **Figure 8-26** through **Figure 8-30**. **Figure 8-26** and **Figure 8-27** show hydrographs of computed and measured streamflow for the Moapa and Glendale gages. The simulated streamflow at the Overton gage is shown on **Figure 8-28**. There is no long-term historical record for the Overton gage. **Figure 8-29** and **Figure 8-30** show a hydrograph of computed springflow for the Muddy Springs and Rogers and Blue Point Springs. The ground-water levels simulated with the calibrated model are summarized on **Figure 8-31** through **Figure 8-33m**. **Figure 8-31** and **Figure 8-32** show scatter diagrams of measured and computed streamflow respectively for valley-fill and carbonate wells. **Figures 8-33a** through **Figure 8-33m** show hydrographs of measured and computed ground-water levels for selected valley-fill and carbonate wells.

Simulated ground-water levels for the model area are shown on **Figure 8-34** through **Figure 8-37**. **Figure 8-34** shows contours of ground-water elevation at the top of the carbonate aquifer for 1945, and **Figure 8-35** shows contours of ground-water elevation at the ground-water table. Likewise, **Figure 8-36** and **Figure 8-37** show those contours for 2000.

Table 8-4. Hydraulic properties assigned to hydrogeologic units and faults.

Material Name	Structural Block	Material	Kx ft/d	Ky ft/d	Kz ft/d	Ss 1/ft	Sy
Valley-Fill Deposits	Lake Mead Subarea	1	1.00	1.00	$1.80x10^{-3}$	$1.00x10^{-6}$	0.05
Valley-Fill Deposits	Black Mountains Subarea	2	1.00	1.00	$1.80x10^{-3}$	$1.00x10^{-6}$	0.05
Valley-Fill Deposits	Lower Moapa Subarea	3	1.00	1.00	$1.80x10^{-3}$	$1.00x10^{-6}$	0.05
Valley-Fill Deposits	Upper Moapa Subarea	4	1.00	1.00	$1.80x10^{-3}$	$1.00x10^{-6}$	0.05
Valley-Fill Deposits	Meadow Valley Mountains Subarea	5	1.00	1.00	$1.80x10^{-2}$	$1.00x10^{-6}$	0.05
Valley-Fill Deposits	Kane Springs Subarea	6	1.00	1.00	$1.80x10^{-2}$	$1.00x10^{-6}$	0.05
Volcanic Rocks	Lake Mead Subarea	7	$1.50x10^{-1}$	$1.50x10^{-1}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Volcanic Rocks	Black Mountains Subarea	8	$1.50x10^{-1}$	$1.50x10^{-1}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Volcanic Rocks	Lower Moapa Subarea	9	$1.50x10^{-1}$	$1.50x10^{-1}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Volcanic Rocks	Upper Moapa Subarea	10	$1.50x10^{-1}$	$1.50x10^{-1}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Volcanic Rocks	Meadow Valley Mountains Subarea	11	$1.50x10^{-1}$	$1.50x10^{-1}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Volcanic Rocks	Kane Springs Subarea	12	$1.50x10^{-1}$	$1.50x10^{-1}$	$2.70x10^{-1}$	$1.00x10^{-6}$	0.01
Intrusive Rocks	Lake Mead Subarea	13	$1.50x10^{-2}$	$1.50x10^{-2}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Intrusive Rocks	Black Mountains Subarea	14	$1.50x10^{-2}$	$1.50x10^{-2}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Intrusive Rocks	Lower Moapa Subarea	15	$1.50x10^{-2}$	$1.50x10^{-2}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Intrusive Rocks	Upper Moapa Subarea	16	$1.50x10^{-2}$	$1.50x10^{-2}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Intrusive Rocks	Meadow Valley Mountains Subarea	17	$1.50x10^{-2}$	$1.50x10^{-2}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Intrusive Rocks	Kane Springs Subarea	18	$1.50x10^{-2}$	$1.50x10^{-2}$	$2.70x10^{-2}$	$1.00x10^{-6}$	0.01
Clastic Rocks	Lake Mead Subarea	19	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Clastic Rocks	Black Mountains Subarea	20	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Clastic Rocks	Lower Moapa Subarea	21	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Clastic Rocks	Upper Moapa Subarea	22	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-3}$	$1.00x10^{-6}$	0.01
Clastic Rocks	Meadow Valley Mountains Subarea	23	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Clastic Rocks	Kane Springs Subarea	24	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Lake Mead Subarea	25	2.00	2.00	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Black Mountains Subarea	26	2.00	2.00	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Lower Moapa Subarea	27	2.00	2.00	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Upper Moapa Subarea (South)	28	$2.00x10^{+1}$	$2.00x10^{+1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Upper Moapa Subarea (North)	39	$3.50x10^{-1}$	$3.50x10^{-1}$	$9.00x10^{-2}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Meadow Valley Mountains Subarea	29	$3.50x10^{-1}$	$3.50x10^{-1}$	$9.00x10^{-2}$	$1.00x10^{-6}$	0.01
Carbonate Rocks	Kane Springs Subarea	30	$3.50x10^{-1}$	$3.50x10^{-1}$	$9.00x10^{-2}$	$1.00x10^{-6}$	0.01
Overthrust Clastic Rocks	Lower Moapa Subarea	31	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-2}$	$1.00x10^{-6}$	0.01
Overthrust Carbonate Rocks	Lower Moapa Subarea	32	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-1}$	$1.00x10^{-6}$	0.01
South Black Mountains Fault		33	$1.00x10^{-2}$	$1.00x10^{-2}$	$1.80x10^{-2}$	$1.00x10^{-6}$	0
North Black Mountains Fault		34	$1.00x10^{-2}$	$1.00x10^{-2}$	$1.80x10^{-2}$	$1.00x10^{-6}$	0
Glendale Thrust		35	$3.50x10^{-2}$	$3.50x10^{-2}$	$3.50x10^{-2}$	$1.00x10^{-6}$	0
Meadow Valley Mountains Fault		36	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-2}$	$1.00x10^{-6}$	0
Kane Springs Fault		37	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-2}$	$1.00x10^{-6}$	0
Coyote Spring Fault		38	$2.00x10^{-1}$	$2.00x10^{-1}$	$3.60x10^{-2}$	$1.00x10^{-6}$	0

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Table 8-4. Hydraulic properties assigned to hydrogeologic units and faults.

Material Name	Structural Block	Material	Kx ft/d	Ky ft/d	Kz ft/d	Ss 1/ft	Sy
Valley-Fill Deposits	Lake Mead Subarea	1	1.00	1.00	1.80×10^{-3}	1.00×10^{-6}	0.05
Valley-Fill Deposits	Black Mountains Subarea	2	1.00	1.00	1.80×10^{-3}	1.00×10^{-6}	0.05
Valley-Fill Deposits	Lower Moapa Subarea	3	1.00	1.00	1.80×10^{-3}	1.00×10^{-6}	0.05
Valley-Fill Deposits	Upper Moapa Subarea	4	1.00	1.00	1.80×10^{-3}	1.00×10^{-6}	0.05
Valley-Fill Deposits	Meadow Valley Mountains Subarea	5	1.00	1.00	1.80×10^{-2}	1.00×10^{-6}	0.05
Valley-Fill Deposits	Kane Springs Subarea	6	1.00	1.00	1.80×10^{-2}	1.00×10^{-6}	0.05
Volcanic Rocks	Lake Mead Subarea	7	1.50×10^{-1}	1.50×10^{-1}	2.70×10^{-2}	1.00×10^{-6}	0.01
Volcanic Rocks	Black Mountains Subarea	8	1.50×10^{-1}	1.50×10^{-1}	2.70×10^{-2}	1.00×10^{-6}	0.01
Volcanic Rocks	Lower Moapa Subarea	9	1.50×10^{-1}	1.50×10^{-1}	2.70×10^{-2}	1.00×10^{-6}	0.01
Volcanic Rocks	Upper Moapa Subarea	10	1.50×10^{-1}	1.50×10^{-1}	2.70×10^{-2}	1.00×10^{-6}	0.01
Volcanic Rocks	Meadow Valley Mountains Subarea	11	1.50×10^{-1}	1.50×10^{-1}	2.70×10^{-2}	1.00×10^{-6}	0.01
Volcanic Rocks	Kane Springs Subarea	12	1.50×10^{-1}	1.50×10^{-1}	2.70×10^{-1}	1.00×10^{-6}	0.01
Intrusive Rocks	Lake Mead Subarea	13	1.50×10^{-2}	1.50×10^{-2}	2.70×10^{-2}	1.00×10^{-6}	0.01
Intrusive Rocks	Black Mountains Subarea	14	1.50×10^{-2}	1.50×10^{-2}	2.70×10^{-2}	1.00×10^{-6}	0.01
Intrusive Rocks	Lower Moapa Subarea	15	1.50×10^{-2}	1.50×10^{-2}	2.70×10^{-2}	1.00×10^{-6}	0.01
Intrusive Rocks	Upper Moapa Subarea	16	1.50×10^{-2}	1.50×10^{-2}	2.70×10^{-2}	1.00×10^{-6}	0.01
Intrusive Rocks	Meadow Valley Mountains Subarea	17	1.50×10^{-2}	1.50×10^{-2}	2.70×10^{-2}	1.00×10^{-6}	0.01
Intrusive Rocks	Kane Springs Subarea	18	1.50×10^{-2}	1.50×10^{-2}	2.70×10^{-2}	1.00×10^{-6}	0.01
Clastic Rocks	Lake Mead Subarea	19	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
Clastic Rocks	Black Mountains Subarea	20	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
Clastic Rocks	Lower Moapa Subarea	21	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
Clastic Rocks	Upper Moapa Subarea	22	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-3}	1.00×10^{-6}	0.01
Clastic Rocks	Meadow Valley Mountains Subarea	23	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
Clastic Rocks	Kane Springs Subarea	24	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
Carbonate Rocks	Lake Mead Subarea	25	2.00	2.00	3.60×10^{-1}	1.00×10^{-6}	0.01
Carbonate Rocks	Black Mountains Subarea	26	2.00	2.00	3.60×10^{-1}	1.00×10^{-6}	0.01
Carbonate Rocks	Lower Moapa Subarea	27	2.00	2.00	3.60×10^{-1}	1.00×10^{-6}	0.01
Carbonate Rocks	Upper Moapa Subarea (South)	28	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
Carbonate Rocks	Upper Moapa Subarea (North)	39	3.50×10^{-1}	3.50×10^{-1}	9.00×10^{-2}	1.00×10^{-6}	0.01
Carbonate Rocks	Meadow Valley Mountains Subarea	29	3.50×10^{-1}	3.50×10^{-1}	9.00×10^{-2}	1.00×10^{-6}	0.01
Carbonate Rocks	Kane Springs Subarea	30	3.50×10^{-1}	3.50×10^{-1}	9.00×10^{-2}	1.00×10^{-6}	0.01
Overthrust Clastic Rocks	Lower Moapa Subarea	31	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-2}	1.00×10^{-6}	0.01
Overthrust Carbonate Rocks	Lower Moapa Subarea	32	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-1}	1.00×10^{-6}	0.01
South Black Mountains Fault		33	1.00×10^{-2}	1.00×10^{-2}	1.80×10^{-2}	1.00×10^{-6}	0
North Black Mountains Fault		34	1.00×10^{-2}	1.00×10^{-2}	1.80×10^{-2}	1.00×10^{-6}	0
Glendale Thrust		35	3.50×10^{-2}	3.50×10^{-2}	3.50×10^{-2}	1.00×10^{-6}	0
Meadow Valley Mountains Fault		36	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-2}	1.00×10^{-6}	0
Kane Springs Fault		37	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-2}	1.00×10^{-6}	0
Coyote Spring Fault		38	2.00×10^{-1}	2.00×10^{-1}	3.60×10^{-2}	1.00×10^{-6}	0

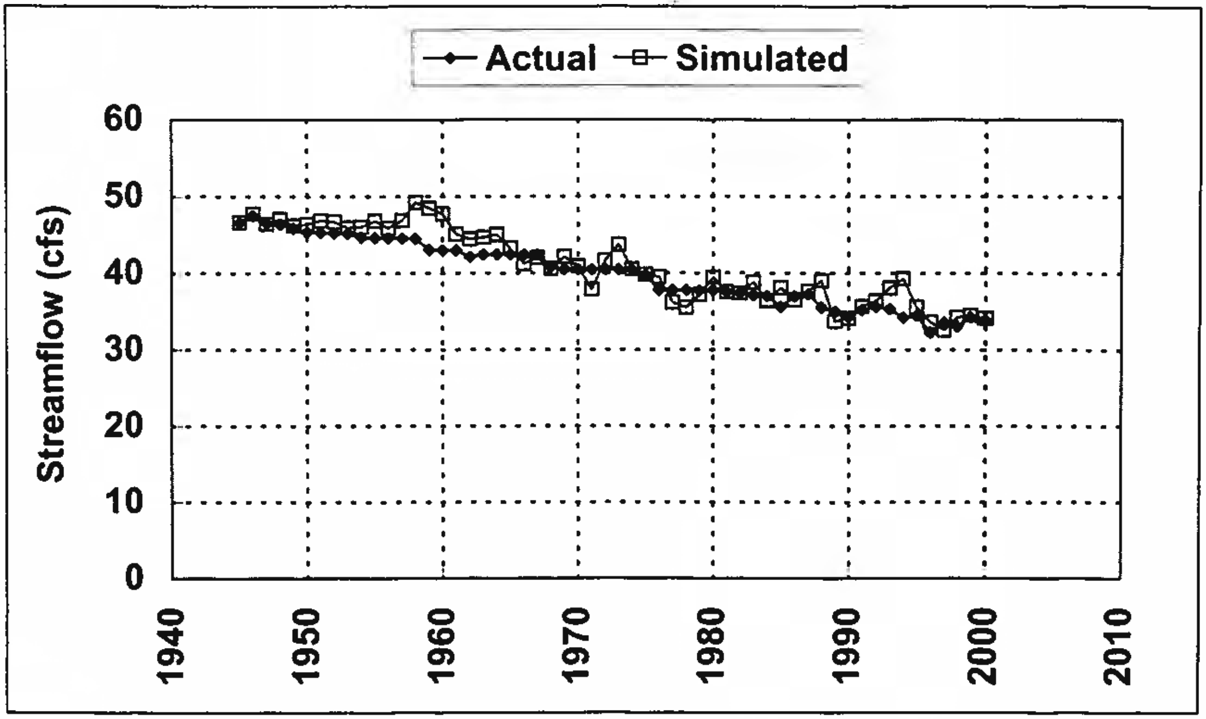

Figure 8-26 Muddy River Streamflow at Moapa Gage.

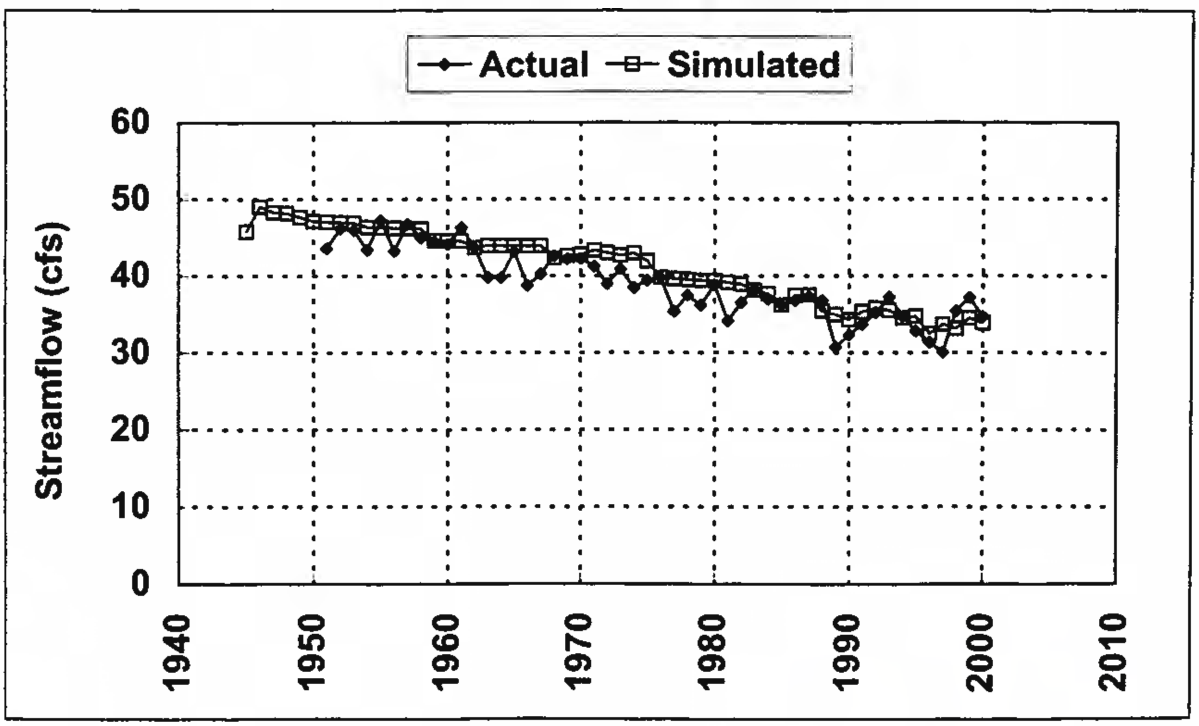

Figure 8-27 Muddy River Streamflow at Glendale Gage.

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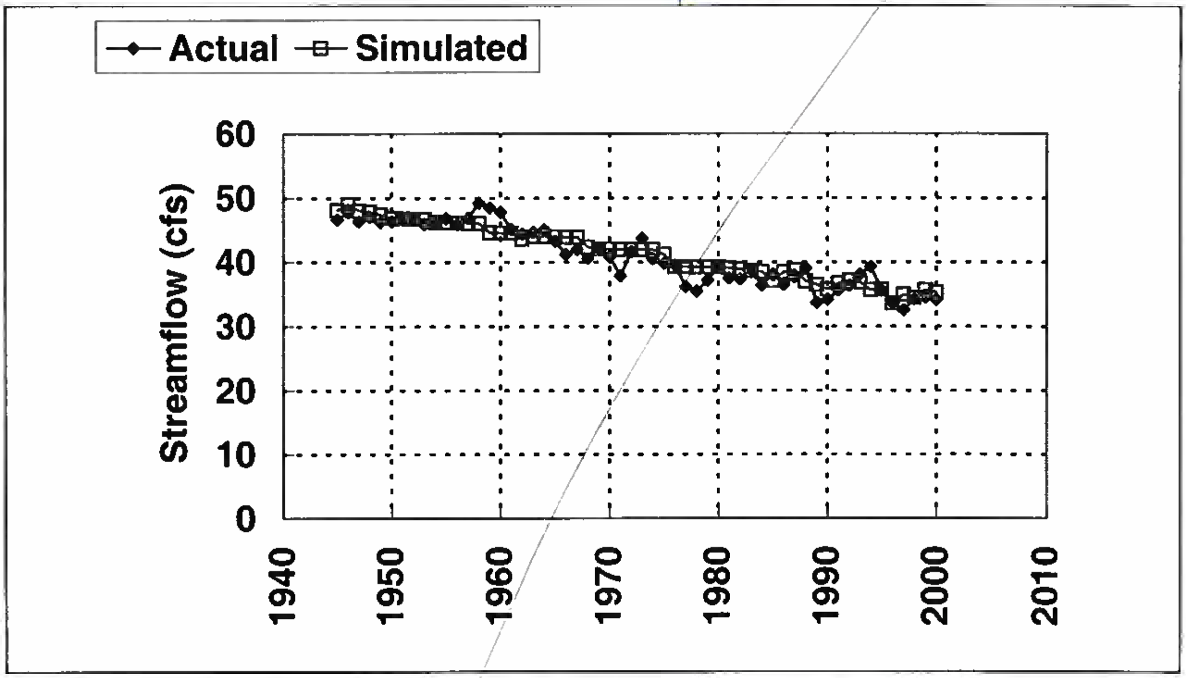

Figure 8-26 Muddy River Streamflow at Moapa Gage.

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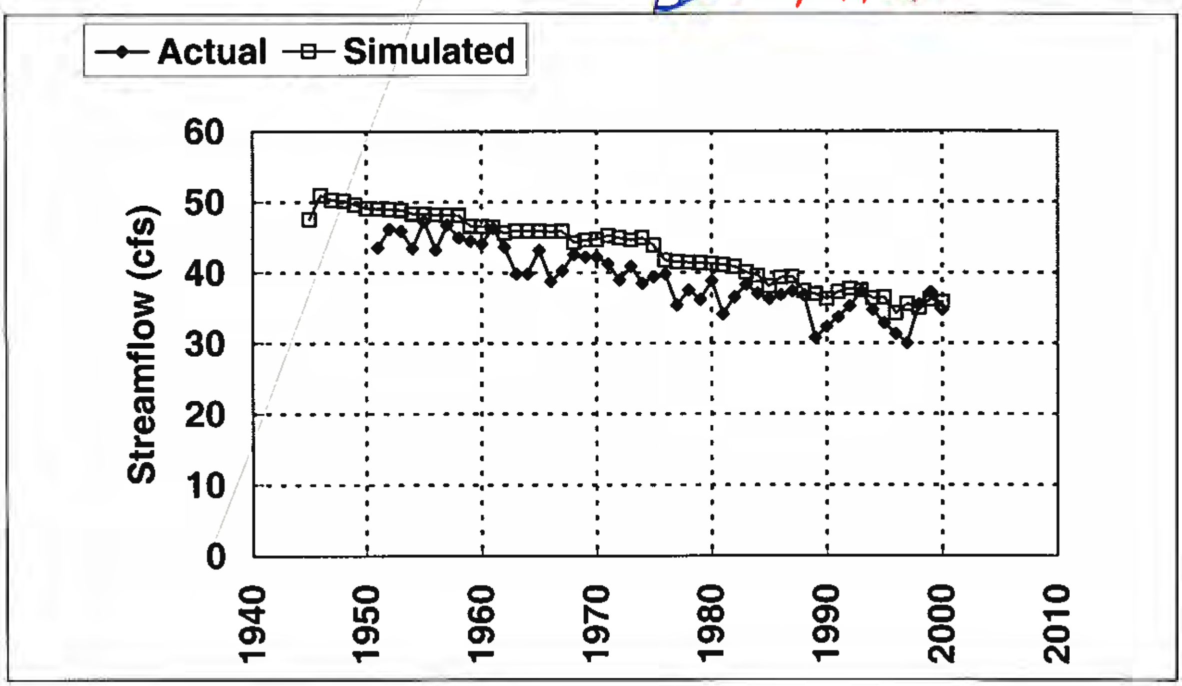

Figure 8-27 Muddy River Streamflow at Glendale Gage.

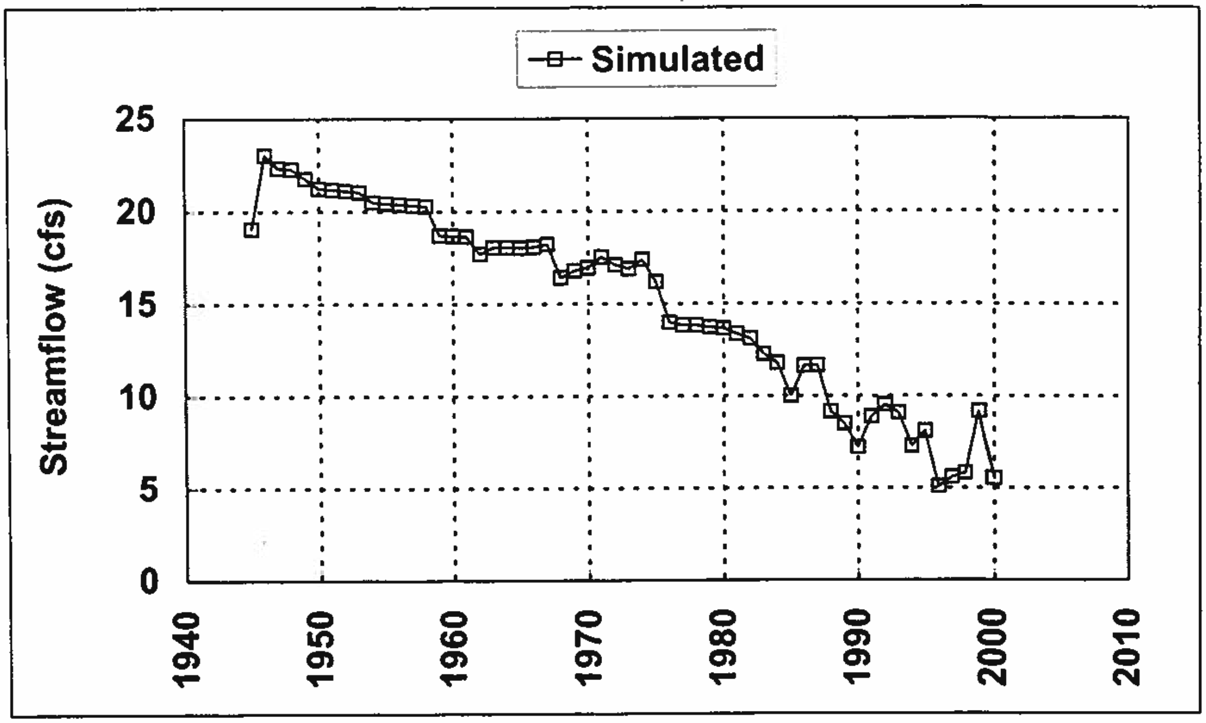

Figure 8-28 Muddy River Streamflow at Overton.

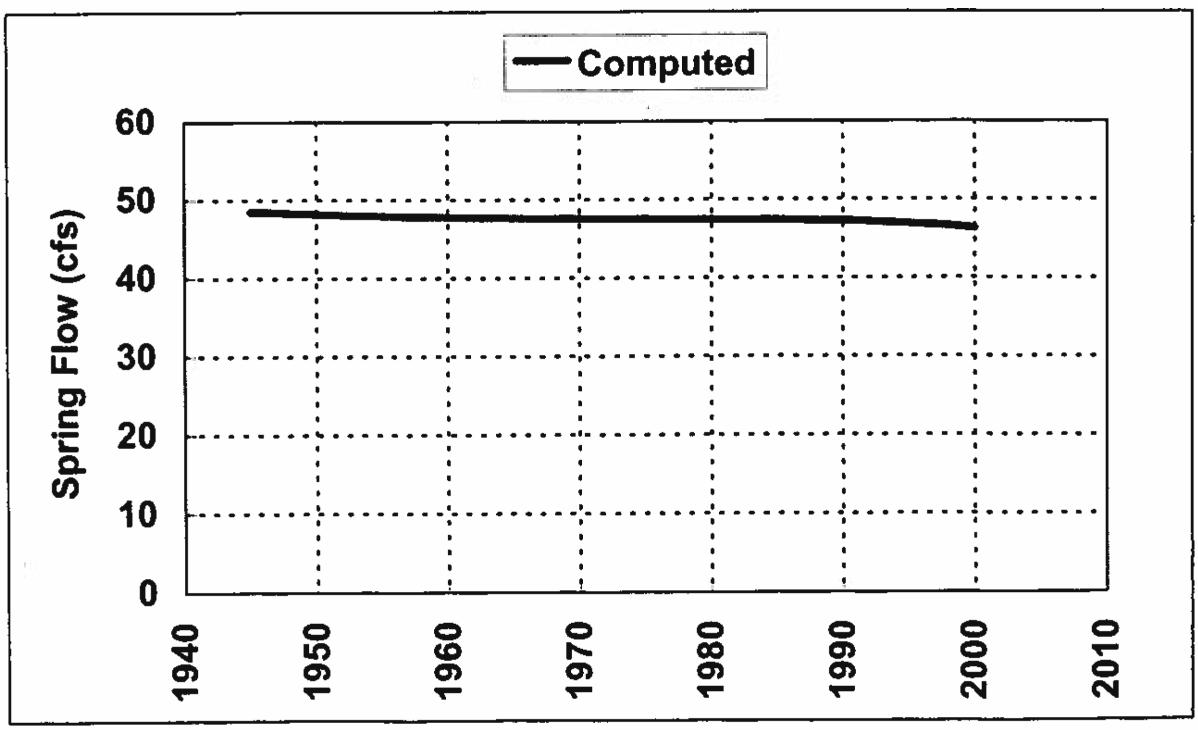

Figure 8-29 Muddy Springs Flow.

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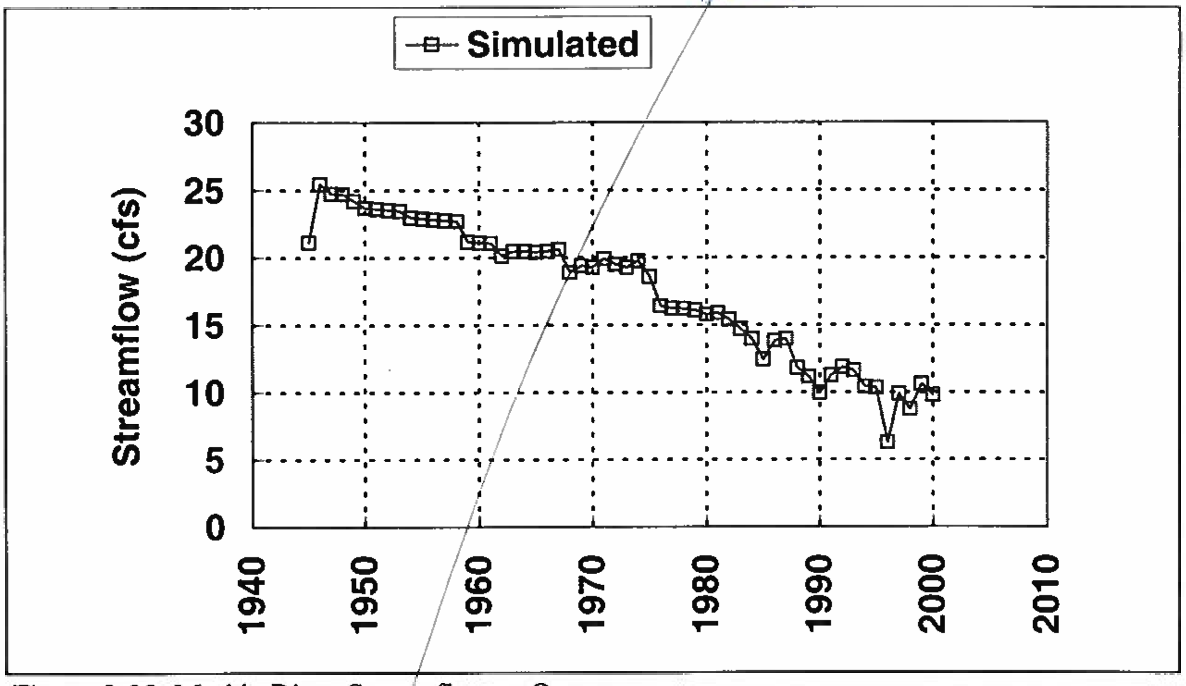

Figure 8-28 Muddy River Streamflow at Overton.

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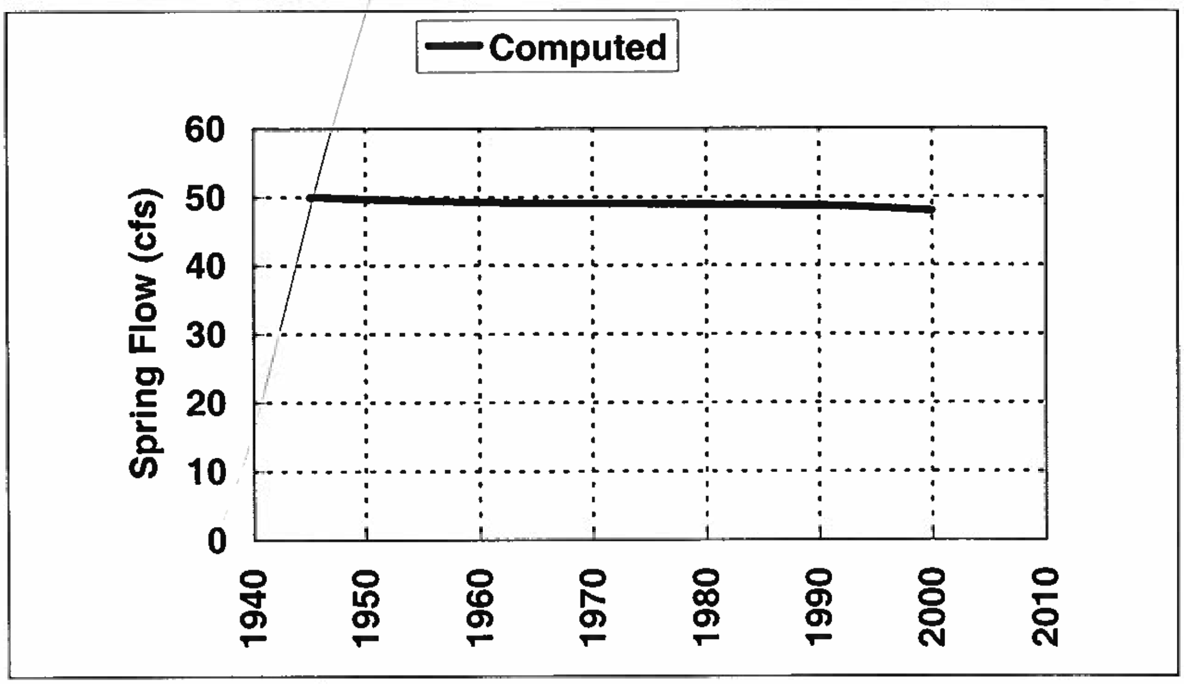

Figure 8-29 Muddy Springs Flow.

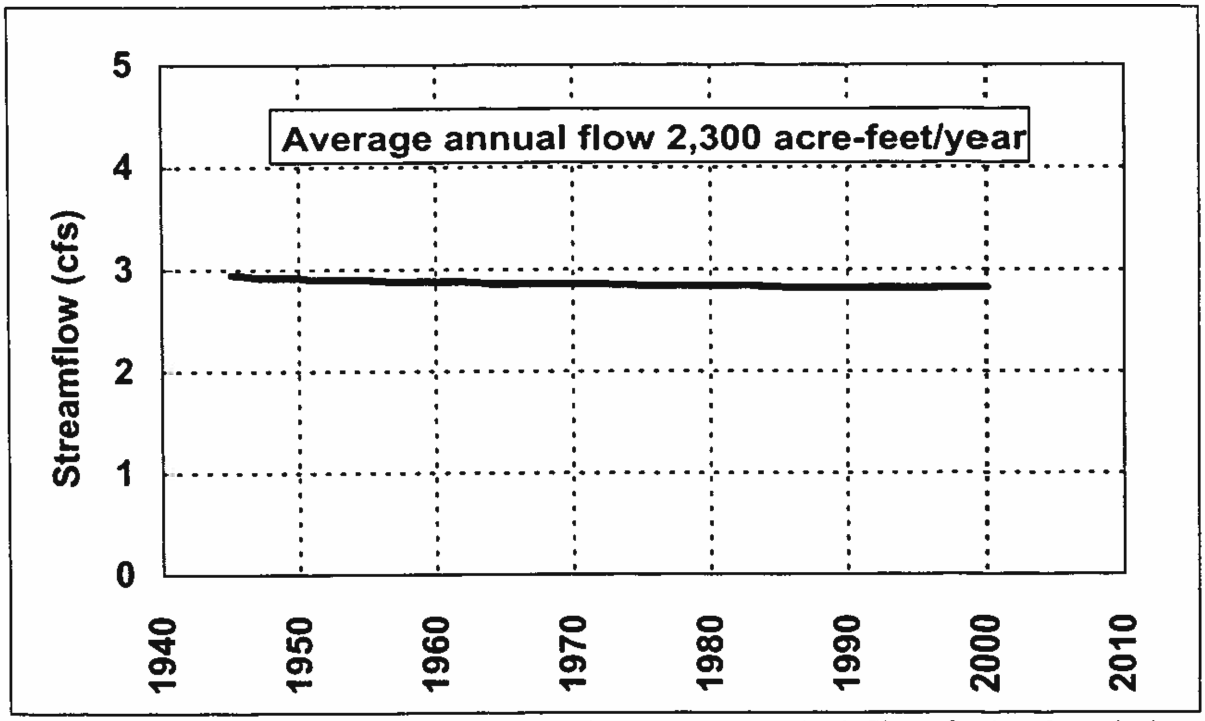

Figure 8-30 Rogers and Blue Point Springs Flow (represents North Shore Spring Complex).

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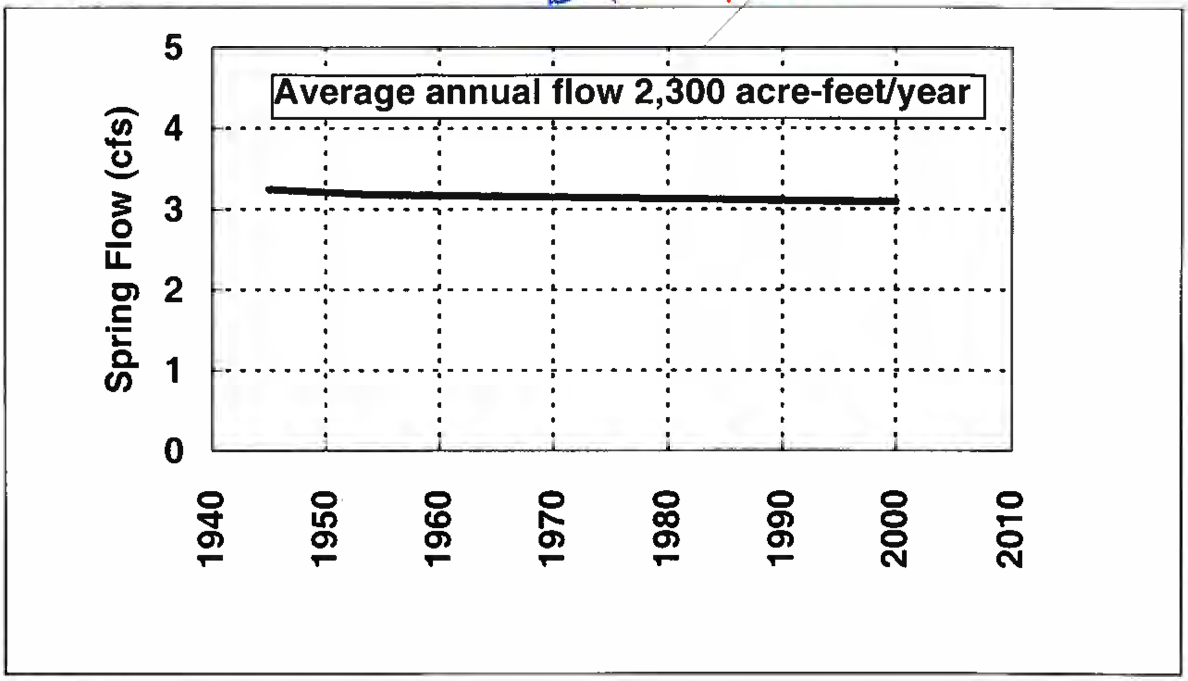


Figure 8-30 Rogers and Blue Point Springs Flow (represents North Shore Spring Complex).

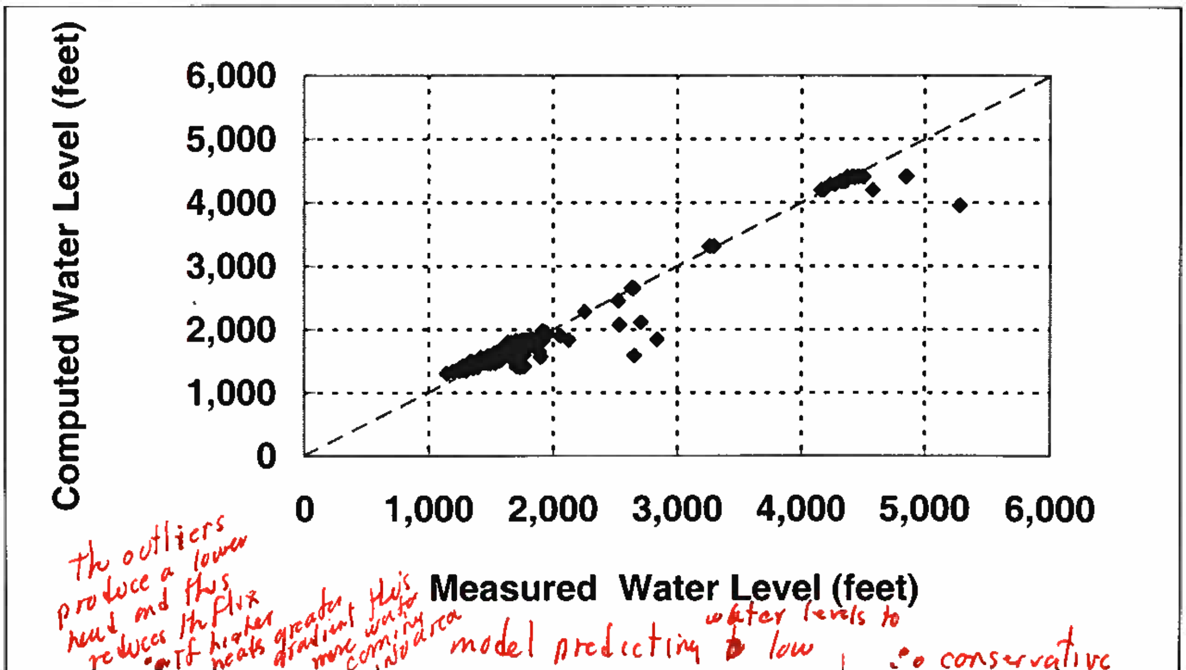


Figure 8-31 Valley-fill Wells Steady State.

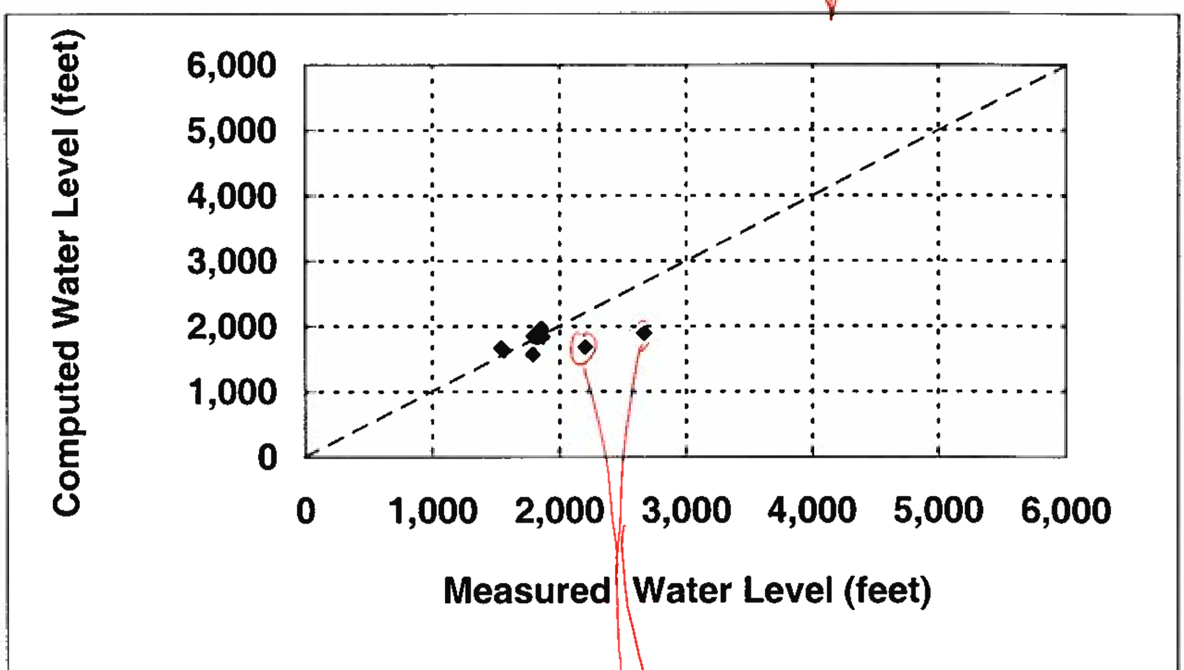


Figure 8-32 Carbonate Wells Steady State.

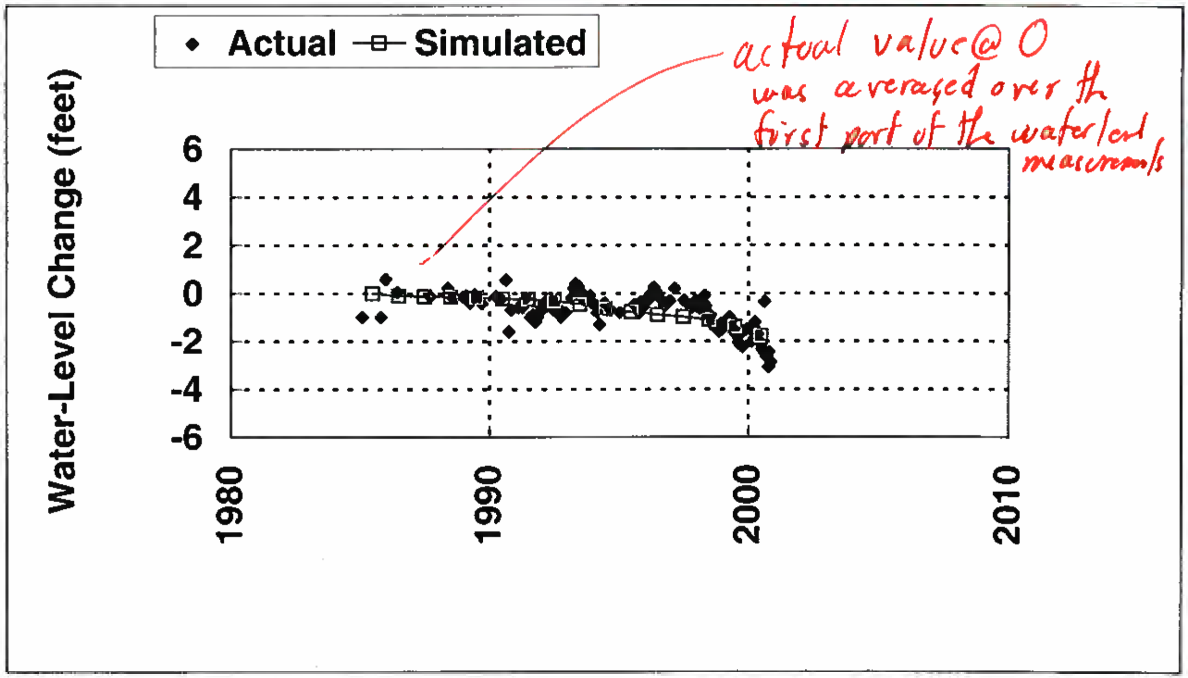


Figure 8-33a Well CSV-2 Actual and Simulated Ground-water Levels.

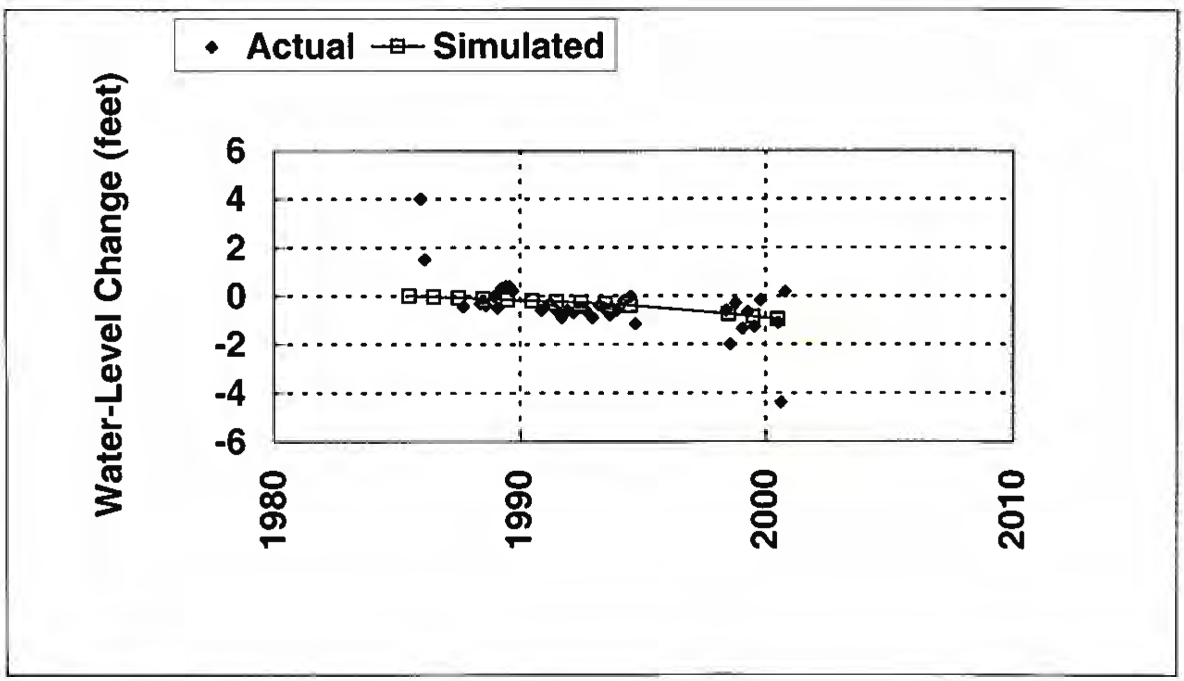


Figure 8-33b Well CSV-3 Actual and Simulated Ground-water Levels.

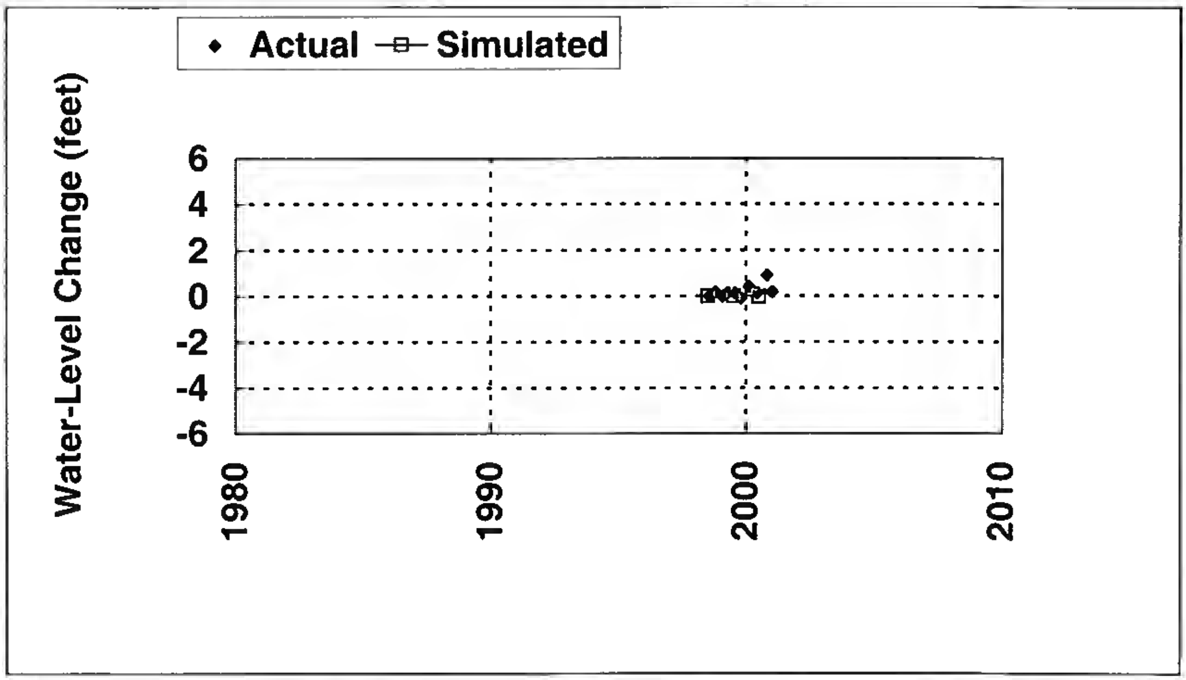


Figure 8-33c Well DF-1 Actual and Simulated Ground-water Levels.

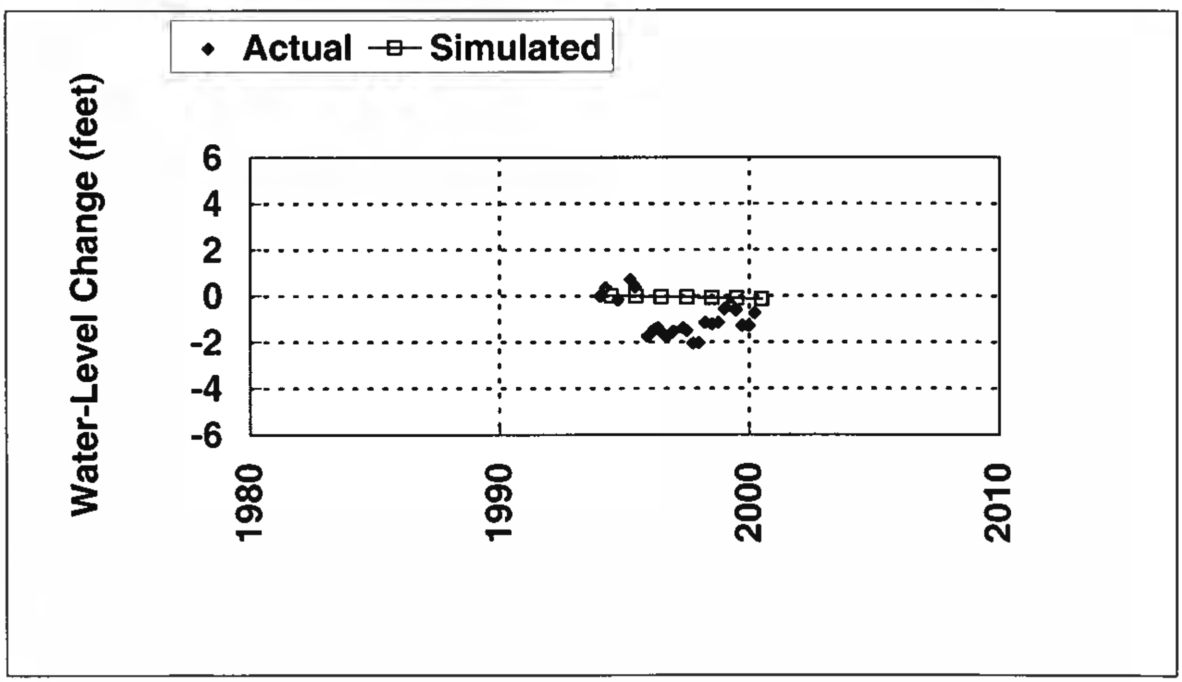


Figure 8-33d Well EH-2 Actual and Simulated Ground-water Levels.

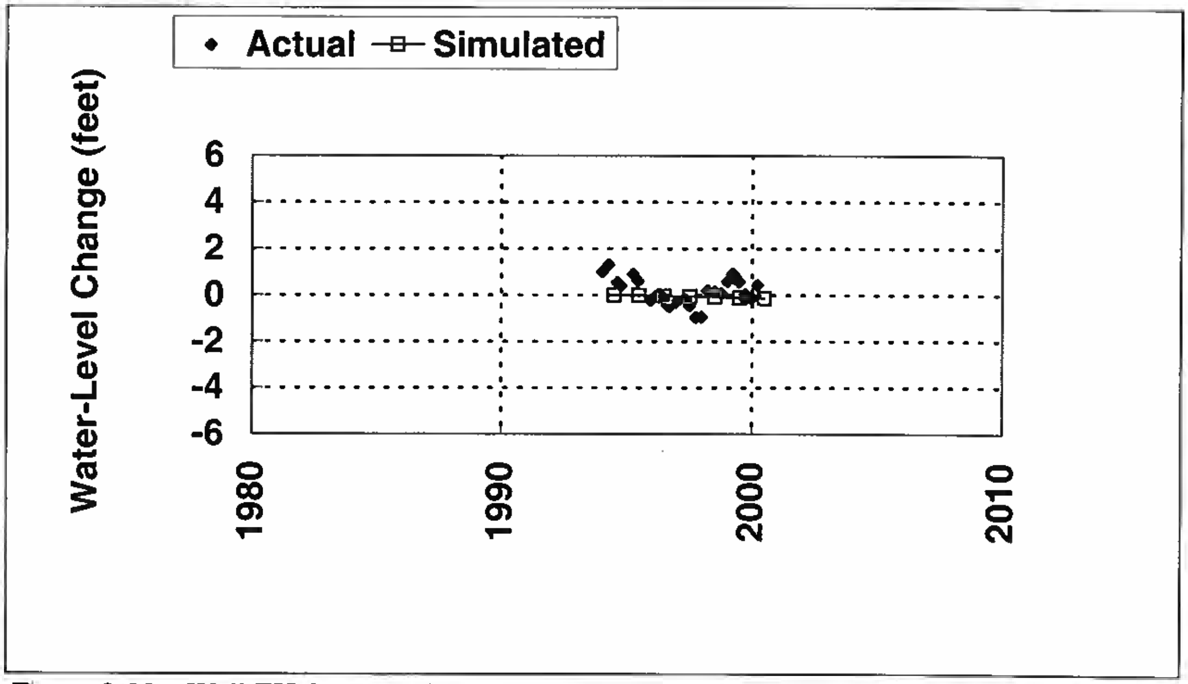


Figure 8-33e Well EH-2A Actual and Simulated Ground-water Levels.

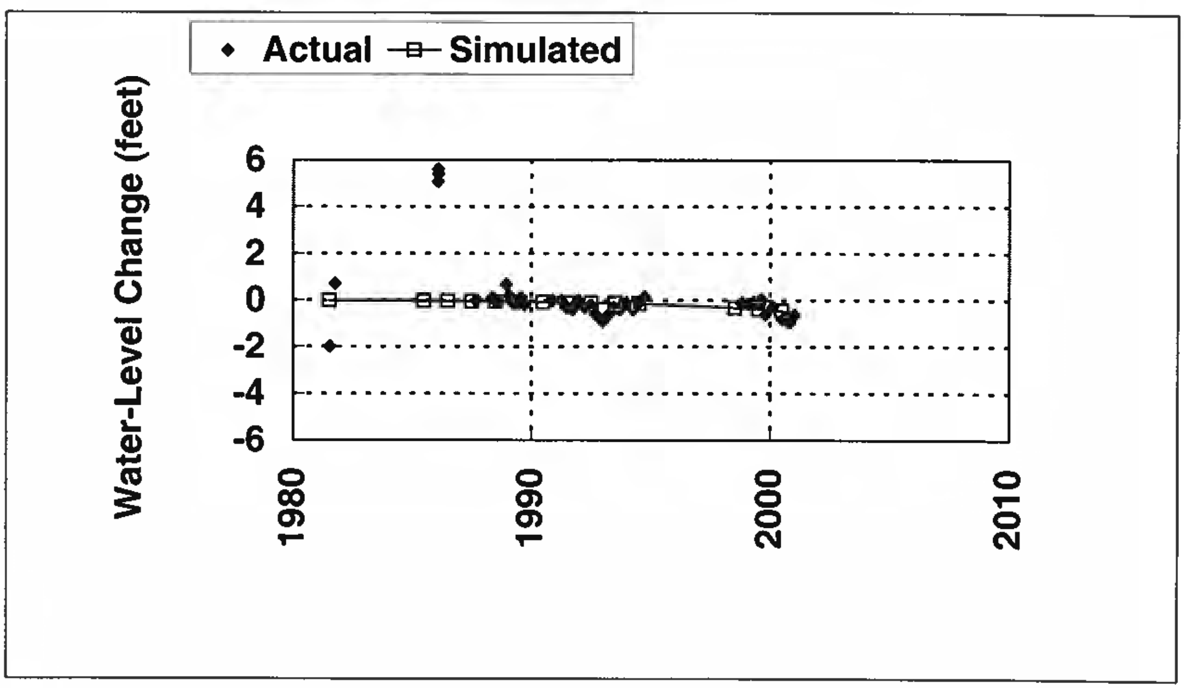


Figure 8-33f Well CE-VF-2 Actual and Simulated Ground-water Levels.

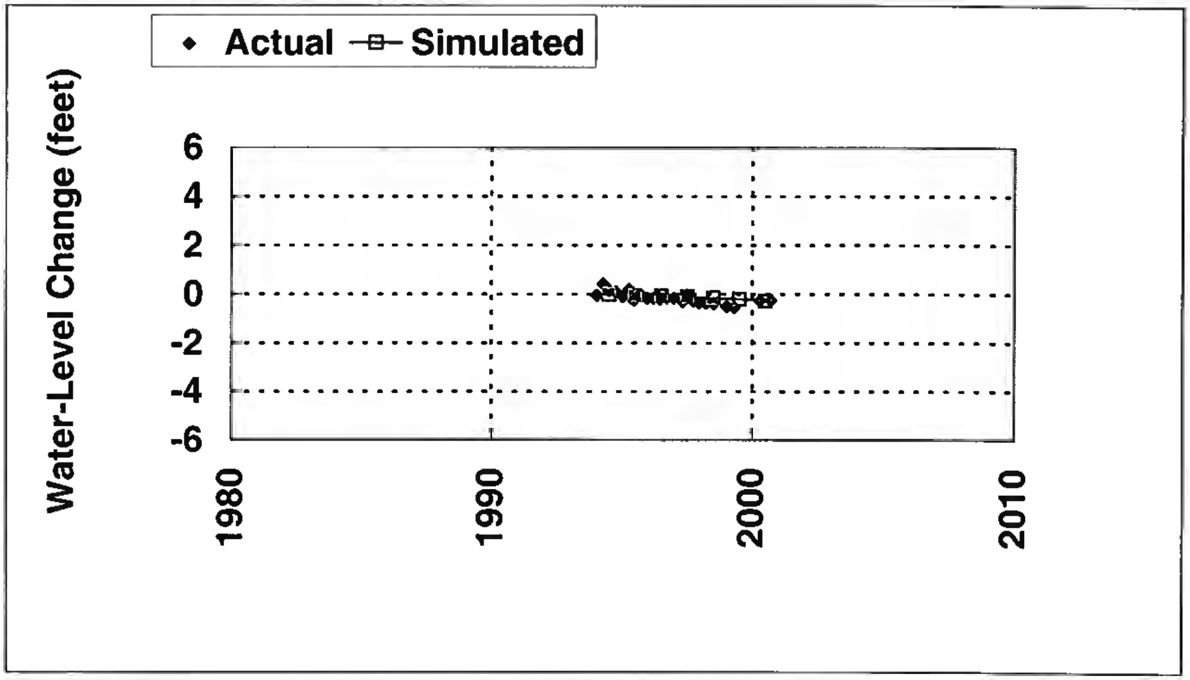


Figure 8-33g Well EH-3 Actual and Simulated Ground-water Levels.

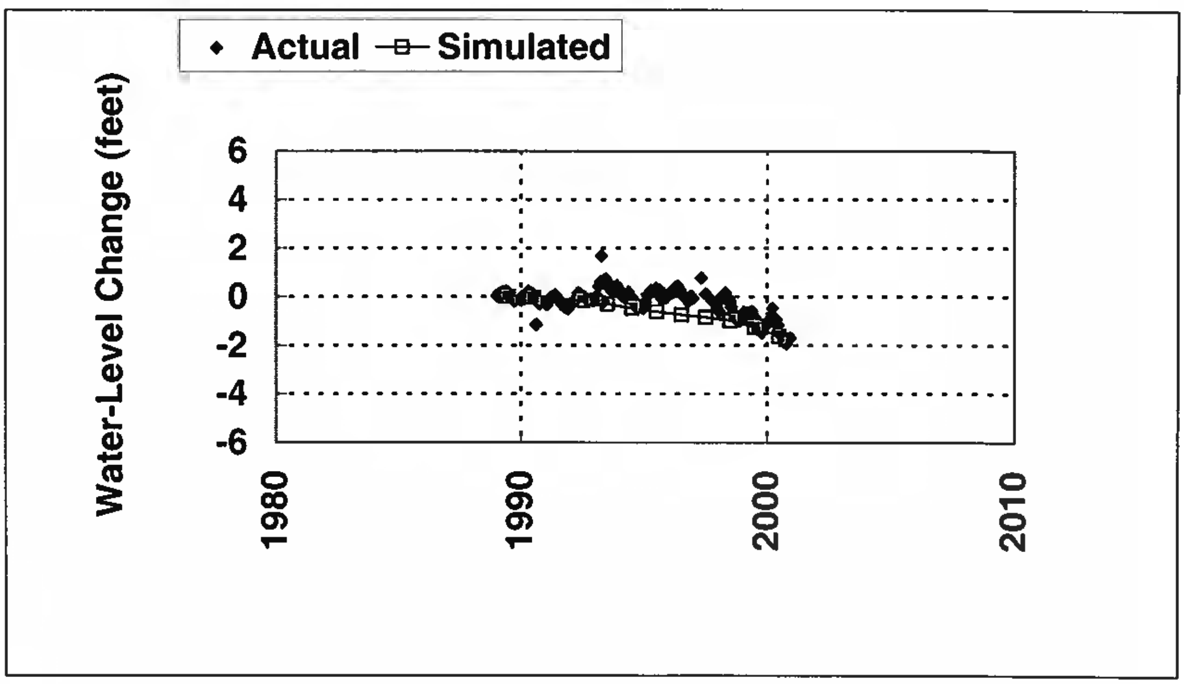


Figure 8-33h Well EH-4 Actual and Simulated Ground-water Levels.

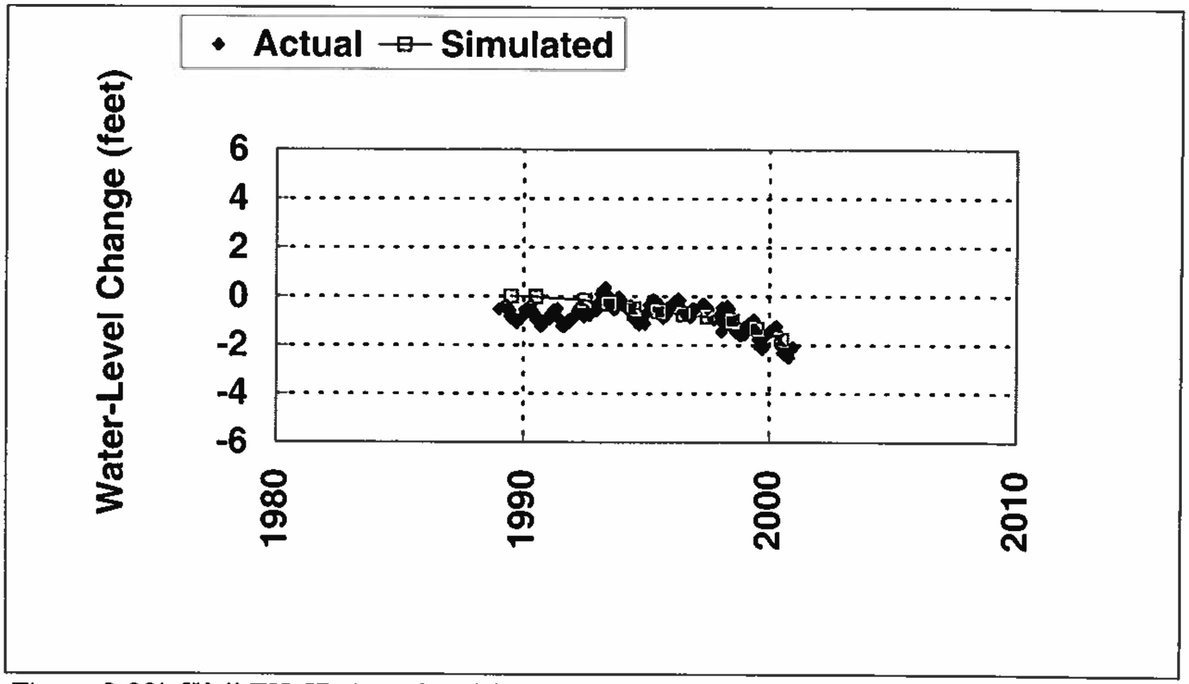


Figure 8-33i Well EH-5B Actual and Simulated Ground-water Levels.

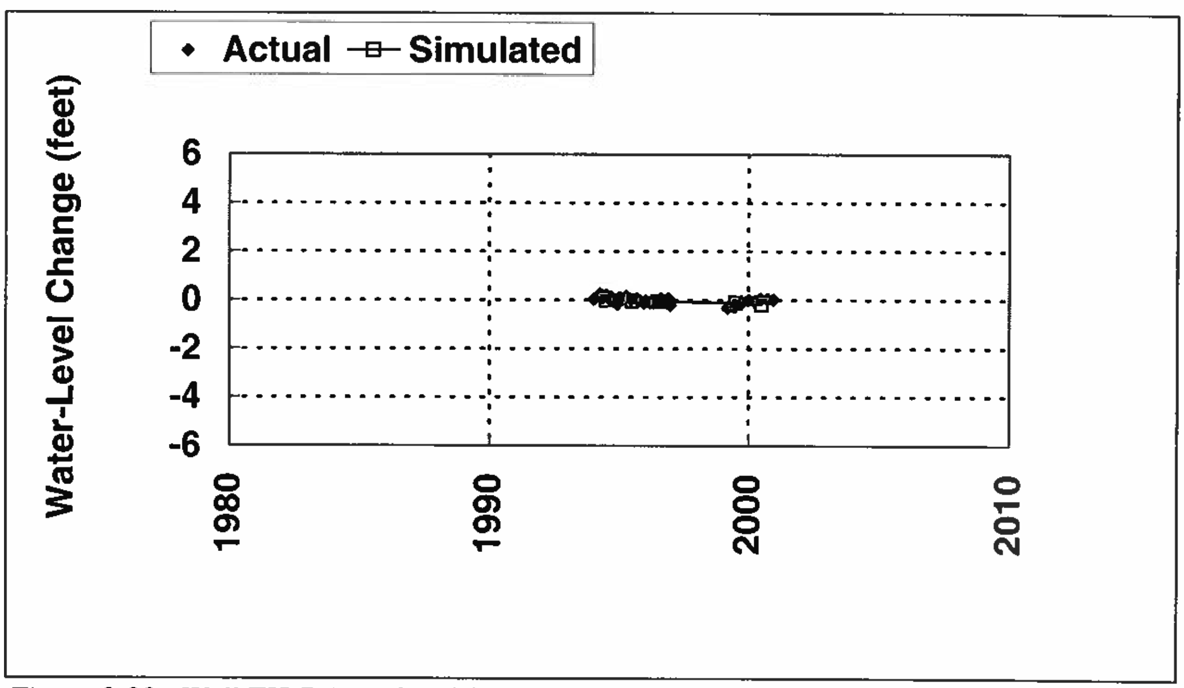


Figure 8-33j Well EH-7 Actual and Simulated Ground-water Levels.

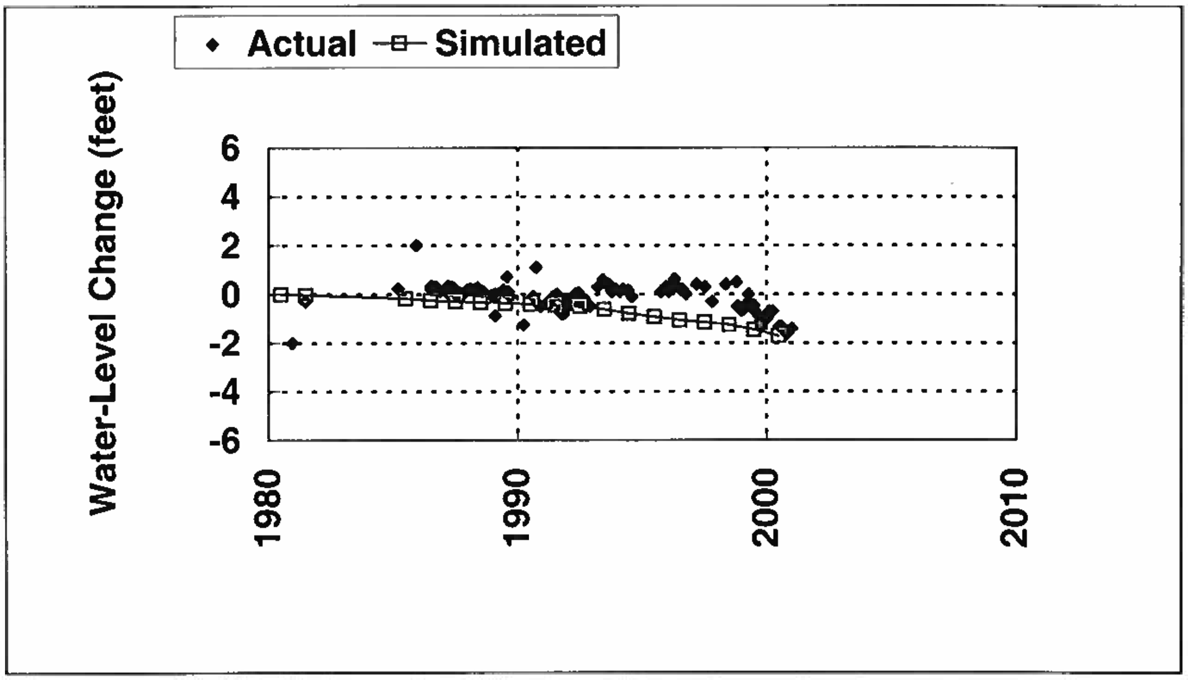


Figure 8-33k Well MX-4 Actual and Simulated Ground-water Levels.

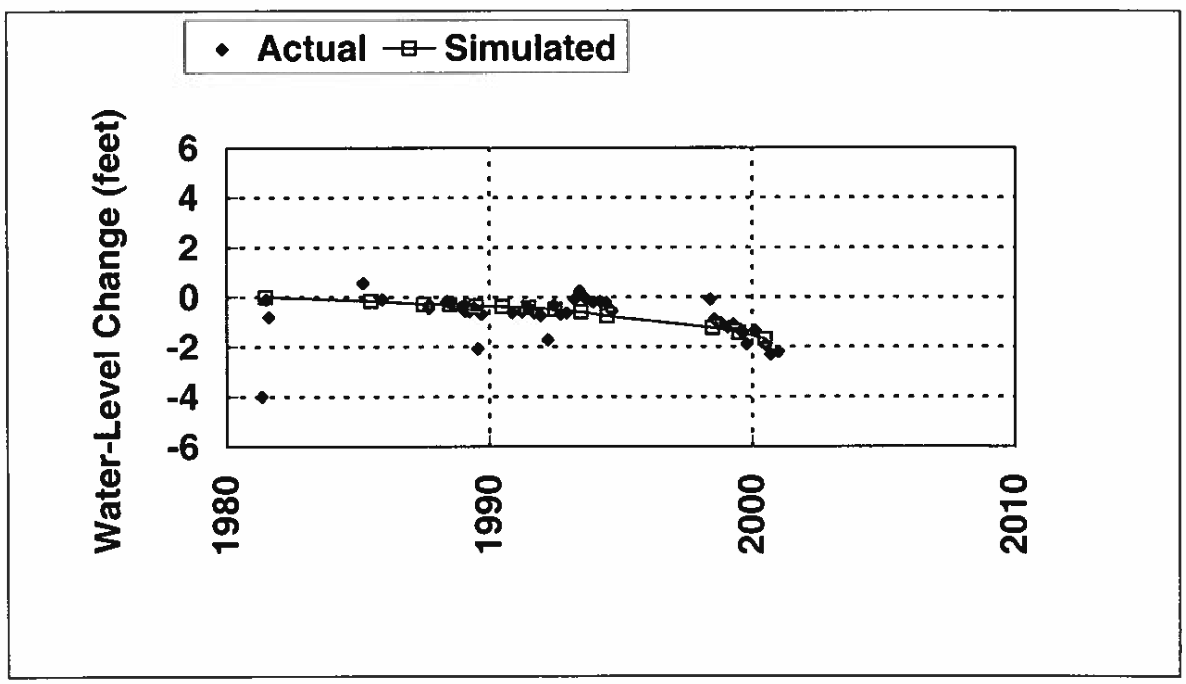


Figure 8-33l Well MX-5 Actual and Simulated Ground-water Levels.

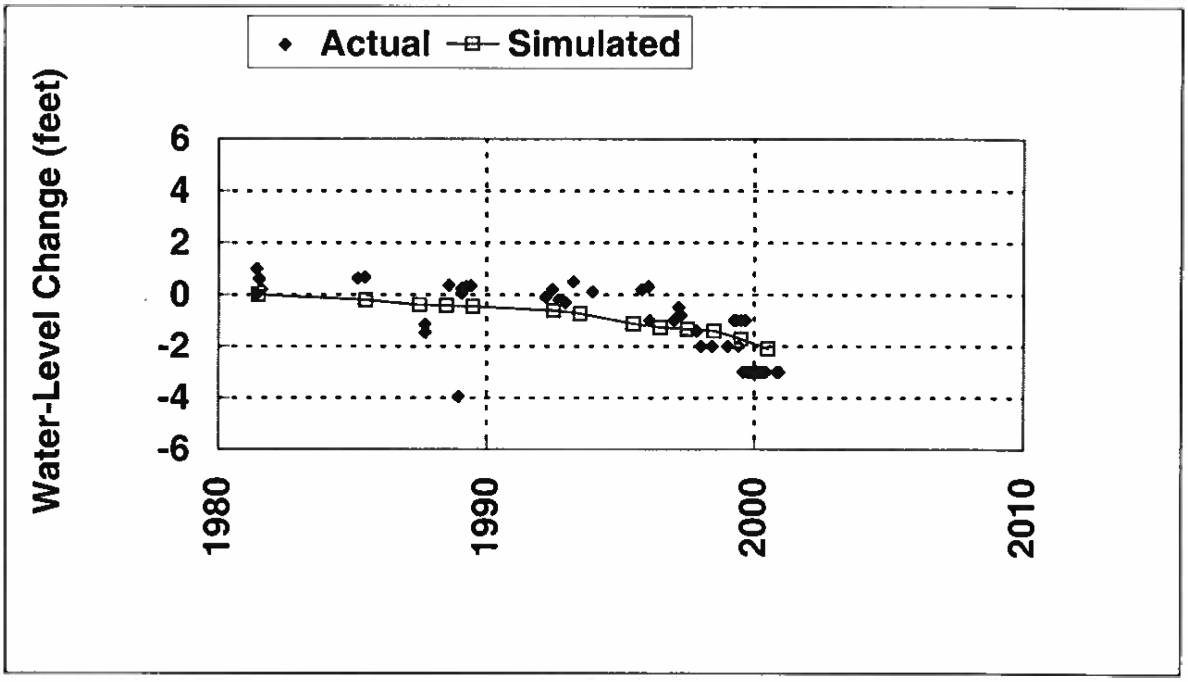


Figure 8-33m Well MX-6 Actual and Simulated Ground-water Levels.

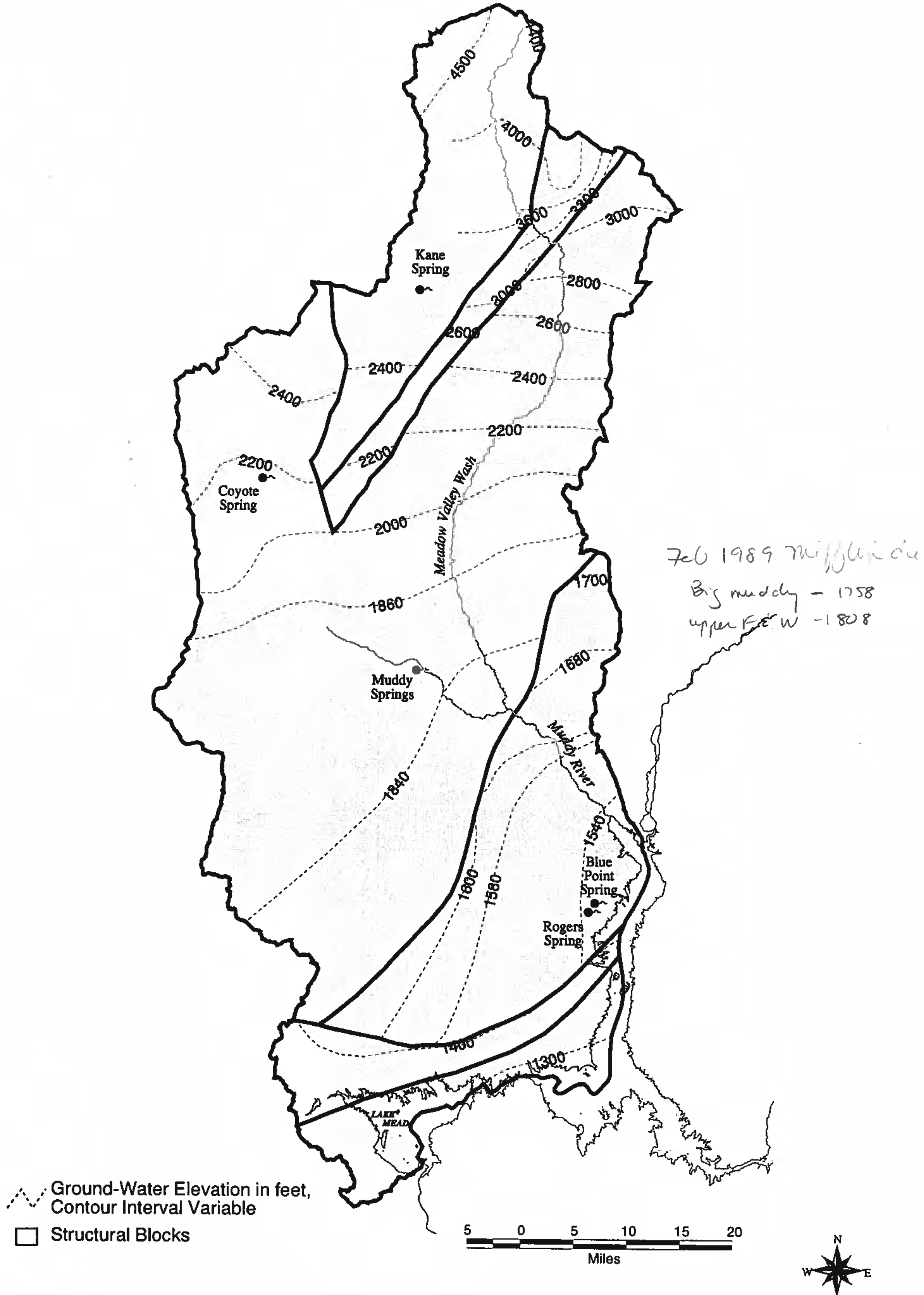


Figure 8-34. Simulated ground-water elevation at top of carbonate aquifer, 1945.

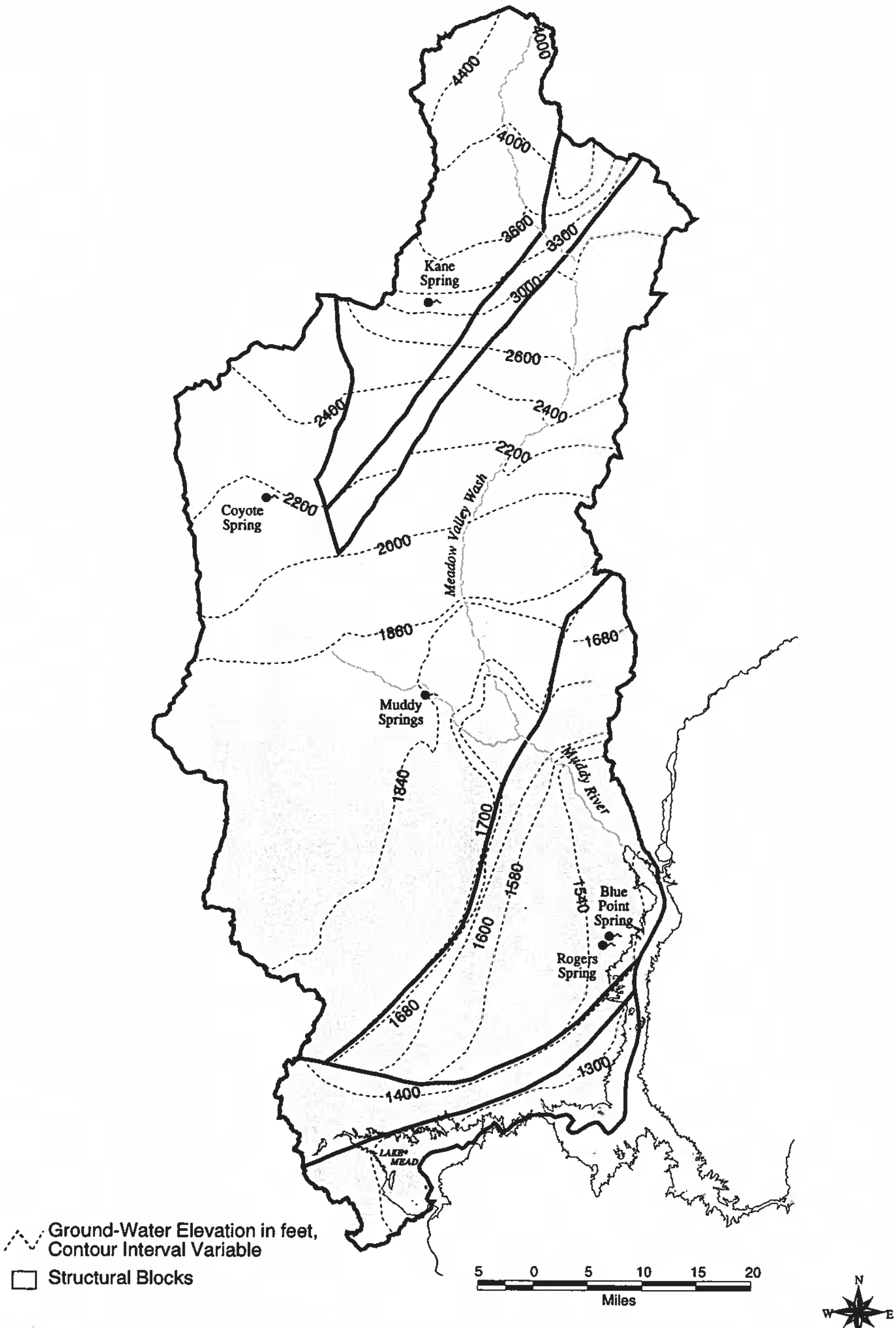
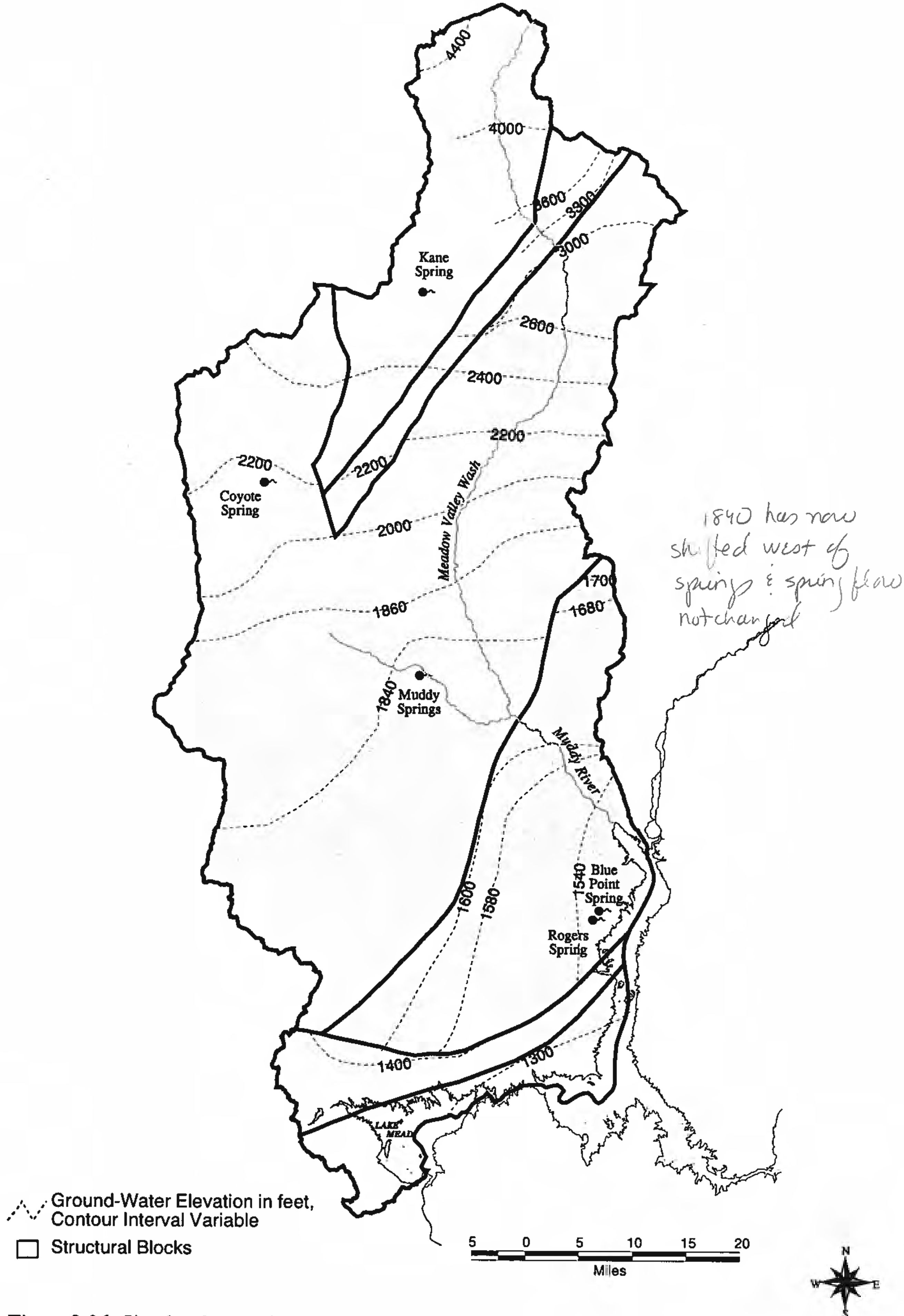


Figure 8-35. Simulated ground-water elevation of ground-water table, 1945.



1840 has now shifted west of springs & spring flow not changed

Figure 8-36. Simulated ground-water elevation at top of carbonate aquifer, 2000.

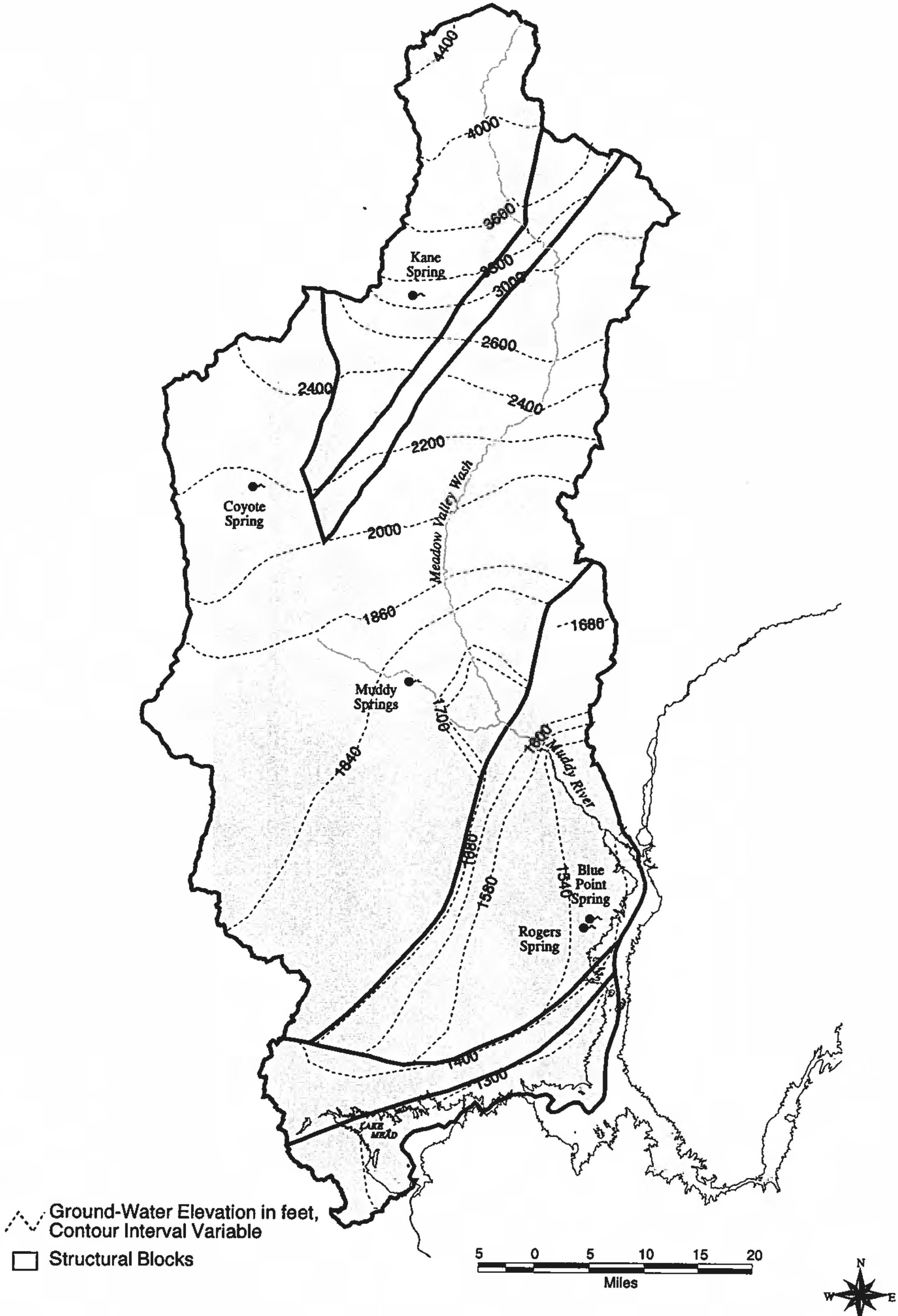


Figure 8-37. Simulated ground-water elevation of ground-water table, 2000.

8.2.7.3 Calibration Evaluation

The adequacy of the model can be evaluated only with respect to the intended use. The principal intended use of this model is to evaluate the impact of increased regional pumping on spring flows. For that purpose, the model adequately represents the ground-water system. The reliability of the evaluation in this regard depends on the difference between two model simulations. That difference tends to contain less uncertainty than its components, because some uncertainties in the components are canceled by the subtraction process (i.e., by each other). The components adequately represent the ground-water system, and the difference correspondingly better represents the ground-water system.

The model adequately reproduces the measured streamflows. **Figure 8-26** and **Figure 8-27** show the measured annual non-flood streamflows for the Moapa and Glendale gages. These are the annual streamflows that result from filtering daily values to remove streamflows resulting from runoff events. The filtered streamflows are those resulting from spring flows, ground-water inflows, and irrigation returns. The simulated non-flood streamflows adequately match the corresponding measured streamflows with respect to both magnitude and temporal trend. For the Moapa gage, the 1945-measured streamflow is 34,000 afy, and streamflow tends to decrease 200 afy per year. Correspondingly, the 1945 computed streamflow is 35,000 afy, and the streamflow tends to decrease 200 afy per year. As described in Section 5.2 the decline in streamflow at the Moapa gage correlates to alluvial ground-water pumpage, and spring flow data suggest spring flow has remained constant. For the Glendale gage, the 1945-measured streamflow is 34,000 afy, and streamflow tends to decrease 200 afy per year. Correspondingly, the 1945 computed streamflow is 35,000 afy, and the streamflow tends to decrease 200 afy per year.

The model adequately reproduces measured spring flows. **Figure 8-29** shows the simulated Muddy Springs discharge. As shown on the figure, the simulated spring flow changes little during 1945-2000. A corresponding measured discharge is not shown because the total Muddy Springs discharge is not measured. Muddy River streamflow is measured below the springs, but the streamflow at that site is impacted by upstream diversions, pumping, and consumption. However, selected spring discharges have been measured since 1986, and the measured spring flows display no long-term trend as discussed in Section 5.2.

Figure 8-30 shows the simulated Rogers Spring and Blue Point Spring discharge. As shown on the figure, the simulated spring flow does not change during 1945-2000. The Rogers Spring discharge has been measured since 1985, and the Blue Point Spring discharge has been measured since 1997. These records indicate that the spring flows are not displaying long-term changes.

The model adequately reproduces measured ground-water levels. **Figure 8-31** and **Figure 8-32** show the simulated ground-water levels correspond to the measured levels. On this scatter diagram, the deviation of simulated ground-water levels from the measured level is represented by the vertical deviation from diagonal line shown on **Figure 8-31** and **Figure 8-32**. If the simulated ground-water level is higher than the measured level, the scatter point representing the values will be positioned above the diagonal line by the difference between the values. Likewise, if the simulated ground-water level is lower than the measured level, the scatter point representing the values will be positioned below the diagonal line by the difference between the values. Most of the simulated ground-water levels are positioned near the diagonal relative to the total range of values, which means in statistical terms that the model explains a large part of the total variance in the measured ground-water levels.

The deviations that do occur between a simulated ground-water level and the corresponding measured level result from at least three factors. They result first because the model does not represent phenomena that impact the measured ground-water level. As a first example, computed ground-water levels are extracted from the model based on the mesh node that is nearest the well with respect to both geographic location and depth. Except by chance, a mesh node will not coincide with the three-dimensional center of a well screen, and even with a perfect model, the simulated ground-water-level will deviate from the measured level. As a second example, simulated ground-water levels represent average conditions over large three-dimensional scales. The horizontal averaging is on scales of 20,000 ft or more, and the vertical averaging is on scales of 2,000 ft or more. However, the ground-water level measured in a well represents averaging over much smaller scales. Depending on the complexity of the local hydrogeologic setting, the horizontal averaging is on scales of 2,000 ft or less, and the vertical averaging is on scales of 200 ft or less. Accordingly, the model represents not every measured ground-water level, but the average of the measured ground-water levels over model scales. As a third example, the available ground-water data are noisy. While measurements of ground-water depth are likely reliable, the corresponding ground-water elevation is often unreliable because the measuring-point elevation is uncertain. Owing to that uncertainty, the simulated ground-water-level will deviate from the measured level.

In addition to being noisy, the ground-water data are so geographically sparse that ground-water levels are unknown over large parts of the model area. Ground-water data for alluvial wells are limited mostly to wells located along Meadow Valley Wash and the Muddy River. Additionally, data are available for a few locations within the modeled area. Ground-water data are available for carbonate wells at scattered locations within the modeled area. However, for large parts of the modeled area, ground-water data are absent not only for carbonate wells but also for alluvial wells. Additionally, a few monitoring wells identified as carbonate wells **(Figure 8-38)** actually may be alluvial wells.

Even though ground-water data for the modeled area are few, the model is an adequate tool for interpolating and extrapolating the available ground-water data. The model can be used spatially or temporally to interpolate between measurement points, and it can be used to extrapolate to locations and times for which data are not available. While some other approach might be used to interpret the available ground-water data, the interpolations and extrapolations based on the model have the advantage that they are based on explicit hydrogeologic and hydrologic characterizations of the ground-water system that are coupled with the mathematical laws of ground-water flow. As a result, the model simulations of ground-water levels are more constrained and correspondingly more reliable than less quantitative approaches to describing the ground-water levels. The simulated ground-water levels are constrained by not only the measured ground-water levels but also the measured streamflows and spring flows.

8.3 UTILIZATION OF THE GROUND-WATER MODEL

The calibrated ground-water model was used to simulate the effects of future pumping within the modeled area. The model was used to simulate the resulting streamflows, spring flows, and ground-water levels from existing permitted rights and LVVWD applications.

8.3.1 Description of Simulations

The simulations describe future pumping for the 61-year period 2001-2061. The simulations are similar in the assumption that the current pumping within the modeled area will continue. The simulations differ in the specification of additional pumping. The particular specifications for each simulation are as follows:

8.3.1.1 Simulation of Existing Permitted Rights

The existing-permits simulation involved the pumping of 17,660 afy of all existing water permits within the Coyote Spring Valley, Garnet Valley, Lower Meadow Valley Wash, Lower Moapa Valley, Upper Moapa Valley, and the Black Mountain Area to observe the pumping impacts on spring discharge and ground-water heads decades into the future. The total rights within the Coyote Spring Valley includes 7,500 afy of SNWA water rights for the MX-5 well, 2,500 afy of NPC rights, and 6,100 afy of CSI rights (includes 5,000 afy purchased from NPC). The Garnet Valley water rights include 2,200 afy for SNWA, and 178 afy for Dry Lake LLC. Within the Lower Meadow Valley Wash, 5,000 afy of water rights belonging to the MVWD for the PG&E power plant is included. Existing water rights in the Black Mountains area that were included in the pumping simulation are 1,392 afy for Dry Lake LLC and 1,870 afy for the Nevada Cogeneration. An additional 4,981 afy of MVWD rights for the Arrow Canyon and MX-6 wells were added in the pumping simulation.

The simulation assumes that the pumpage will be distributed to the wells shown on **Figure 8-38**. None of the wells were sited within the Moapa Paiute Indian Reservation. For the SNWA water rights, 7,500 afy was pumped out of MX-5 well and the rights of 2,200 afy within Garnet Valley were divided between two wells. We assumed that the MVWD water rights of 5,000 afy within the Lower Meadow Valley Wash is temporary and that pumping within the Lower Meadow Valley Wash will be reduced by 5,000 afy beginning in year 2031.

The representation of simulating existing permitted rights in the model is shown on **Figure 8-38**. **Figure 8-39** shows the geographic distribution of annual pumpage to regions within the modeled area.

8.3.1.2 Simulation of LVVWD Ground-Water Applications

The simulation of LVVWD applications involved the pumping from the previous simulation in addition to the 27,512 afy of LVVWD applications. The amount of 27,512 afy requested was

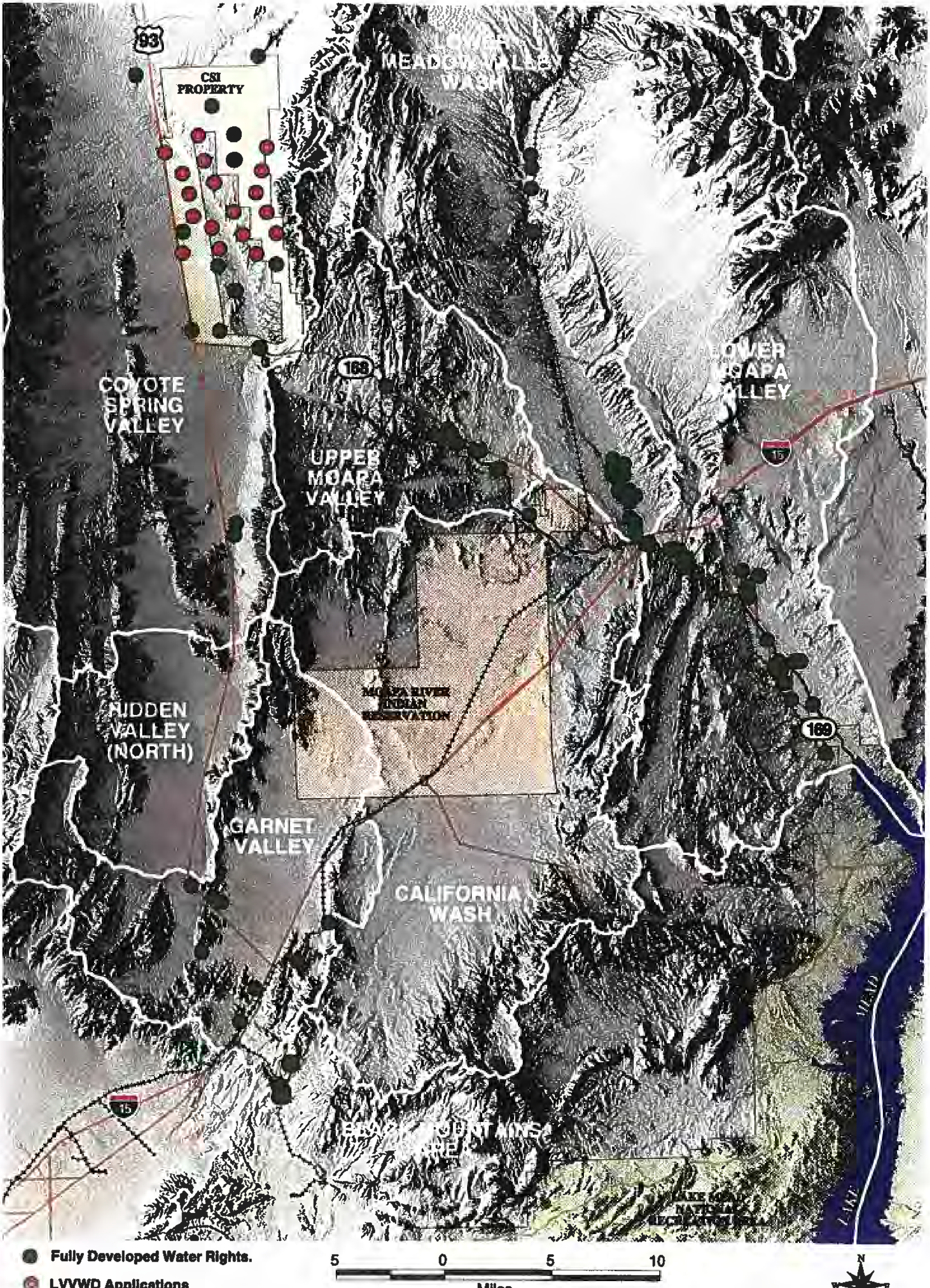


Figure 8-38. Locations of pumping wells with fully developed water rights and LVVWD Applications.

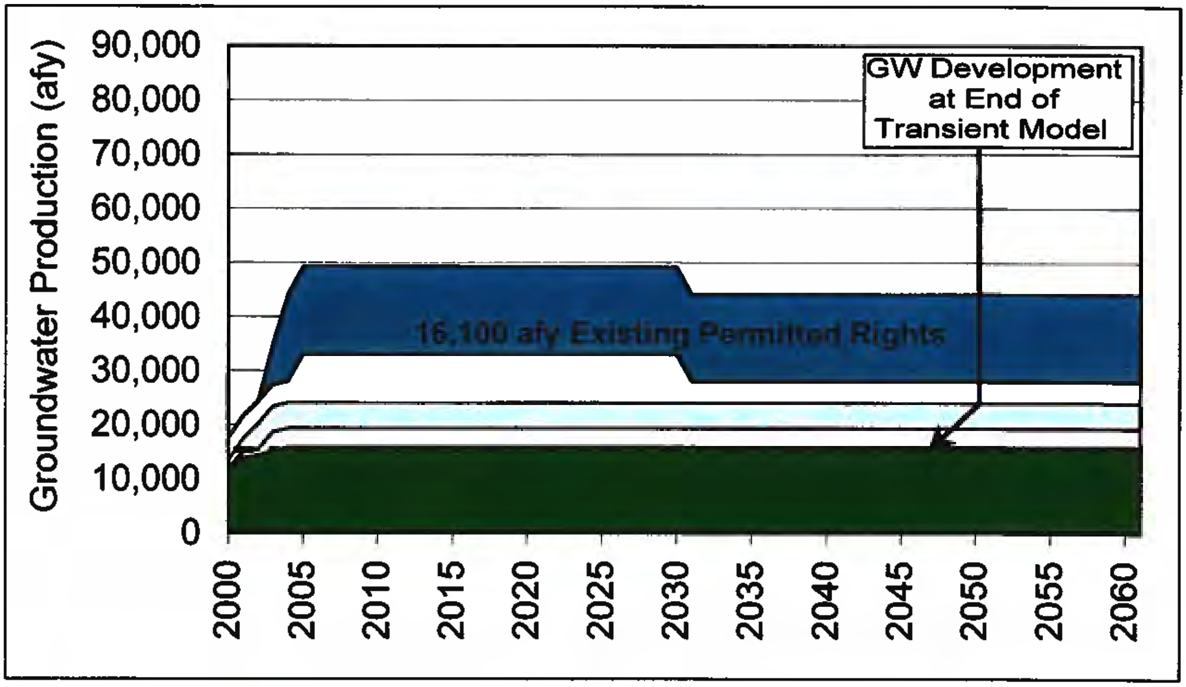


Figure 8-39 Distribution of Ground-water Pumping Existing Permitted Rights.

Legend: Coyote Springs; L. Meadow Valley Wash; Black Mountains; Garnet; Muddy Springs Area; Lower Moapa Valley

Note: Production from valley-fill and carbonate rocks.

pumped in three-year increments of 9,171 afy starting from the year 2017. In the first year (2017), the 9171 afy was divided among six wells sited within the Coyote Spring Valley. As in the previous simulation, all the wells were sited on CSI Property with majority of them within Lincoln County. None of them were sited within the Moapa Pauite Indian Reservation. Pumpage from six additional wells with a total duty of 9,171 afy was added in the second year (2018). The final increment of 9,171 afy was again divided among six wells in the third year. As in the first simulation, 7,500 afy was pumped out of MX-5 and 2,200 afy from two other SNWA wells in Garnet Valley. The simulation assumes that the pumpage will be distributed to the wells shown on **Figure 8-38**.

The representation of simulating LVVWD applications in the model is shown on **Figure 8-38**. **Figure 8-40** shows the geographic distribution of annual pumpage to regions within the modeled area.

8.3.2 <u>Simulation Results</u>

8.3.2.1 Existing Permitted Rights

Figure 8-41 through **Figure 8-49** and **Table 8-5** summarizes the simulation of existing permitted rights. **Figure 8-41** shows contours of computed ground-water elevation at the top of the carbonate aquifer for 2061. **Figure 8-42** shows contours of computed ground-water elevation at the ground-water table. **Figure 8-43** shows contours of computed change in ground-water elevation at the top of the carbonate aquifer for 2000-2061. **Figure 8-44** shows contours of computed change in ground-water elevation at the ground-water table. **Figure 8-45** through **Figure 8-47** shows hydrographs of computed streamflow, and **Figure 8-48** and **Figure 8-49** shows hydrographs of computed spring flows. **Table 8-5** lists the components of the ground-water budget for 2061.

As indicated on **Figure 8-45** through **Figure 8-49**, spring flows and streamflows in the simulation show a decline as a result of pumping existing permits. **Figure 8-43** and **Figure 8-44** also show a slight decline in simulated ground-water levels as a result of the specified future pumping. Within Coyote Springs Valley, the maximum water-level decline at the top of the carbonate is approximately 30 ft in 2061. At Muddy Springs, the water-level decline is <10 ft. At the western boundary of the modeled area, the water-level decline is approximately 2 ft in 2061. At the eastern boundary of the modeled area, the water-level decline is approximately 3 ft.

As indicated in **Table 8-5**, water-level declines at the model boundaries induce ground-water inflow to the modeled area. The boundary inflow during 2061 is 25,000 afy.

8.3.2.2 LVVWD Ground-Water Applications

Figure 8-50 through **Figure 8-58** and **Table 8-5** summarize the simulation for LVVWD applications. **Figure 8-50** shows contours of computed ground-water elevation at the top of the carbonate aquifer for 2061. **Figure 8-51** shows contours of computed ground-water elevation at the ground-water table. **Figure 8-52** shows contours of computed change in ground-water

Table 8-5. Water budgets for streams and hydrologic systems[1].

Budget Component	Historical Pumping / Diversions 1945	Historical Pumping / Diversions 2000	Existing Permits 2061	LVVWD Applications 2061
WATER BUDGETS FOR MEADOW VALLEY WASH AND MUDDY RIVER				
Inflows – Meadow Valley Wash				
• Streamflow at model boundary	10,000	10,000	10,000	10,000
• Ground-water inflows above Rox	11,000	9,000	9,000	8,000
• Ground-water inflows Rox to mouth	4,000	3,000	2,000	2,000
Total	**25,000**	**22,000**	**21,000**	**20,000**
Outflows – Meadow Valley Wash				
• ET above Rox[2]	21,000	20,000	19,000	18,000
• ET from Rox to mouth[2]	2,000	0	0	0
• Streamflow at mouth	2,000	2,000	2,000	2,000
Total	**25,000**	**22,000**	**21,000**	**20,000**
Inflows – Muddy River				
• Meadow Valley Wash streamflow at mouth	2,000	2,000	2,000	2,000
• Ground-water inflows above Moapa	38,000	31,000[3]	27,000[3]	26,000[3]
• Ground-water inflows Moapa to Glendale	6,000	6,000	4,000	4,000
• Ground-water inflows Glendale to Overton	7,000	7,000	6,000	6,000
Total	**53,000**	**46,000**	**39,000**	**38,000**
Outflows – Muddy River				
• ET above Moapa[2]	3,000	5,000	5,000	5,000
• ET Moapa to Glendale[2]	9,000	9,000	9,000	9,000
• ET Glendale to Overton[2]	25,000	25,000	20,000	19,000
• Streamflow at Overton	16,000	8,000	6,000	5,000
Total	**53,000**	**47,000**	**40,000**	**38,000**
HYDROLOGIC SYSTEM				
Inflows				
Ground-water underflow - Pahranagat Valley	28,000	28,000	28,000	28,000
Ground-water underflow - Delemar Valley	16,000	16,000	16,000	16,000
Ground-water underflow - Panaca Valley	17,000	17,000	17,000	17,000
Ground-water underflow - Clover Valley	9,000	9,000	9,000	9,000
Meadow Valley Wash streamflow at boundary	10,000	10,000	10,000	10,000
Boundary underflows	0	0	25,000	41,000
Precipitation recharge	37,000	37,000	37,000	37,000
Total	**117,000**	**117,000**	**142,000**	**158,000**
Outflows				
Ground-water pumpage	0	18,000	44,000	72,000
Surface-water outflow - Muddy River	16,000	8,000	6,000	5,000
Ground-water discharge to Colorado River	37,000	37,000	37,000	37,000
ET – Coyote Springs	1,000	1,000	1,000	1,000
ET – Kane Springs	1,000	1,000	1,000	1,000
ET – Rogers Springs	1,000	1,000	1,000	1,000
ET – Blue Point Springs	1,000	1,000	1,000	1,000
ET – Meadow Valley Wash above Rox	21,000	20,000	19,000	18,000
ET – Meadow Valley Wash below Rox	2,000	0	0	0
ET – Muddy River above Moapa	3,000	5,000	5,000	5,000
ET – Muddy River – Moapa to Glendale	9,000	9,000	9,000	9,000
ET – Muddy River – Glendale to Overton	25,000	25,000	20,000	19,000
Total	**117,000**	**126,000**	**144,000**	**169,000**
STORAGE CHANGE	**0**	**-9,000**	**-2,000**	**-11,000**

[1] See Figure 8-5 for definition of control volumes.
[2] ET includes consumption of diverted streamflow and riparian ground water.
[3] After-effects of diversions and ground-water pumping above Muddy River streamgaging station near Moapa.

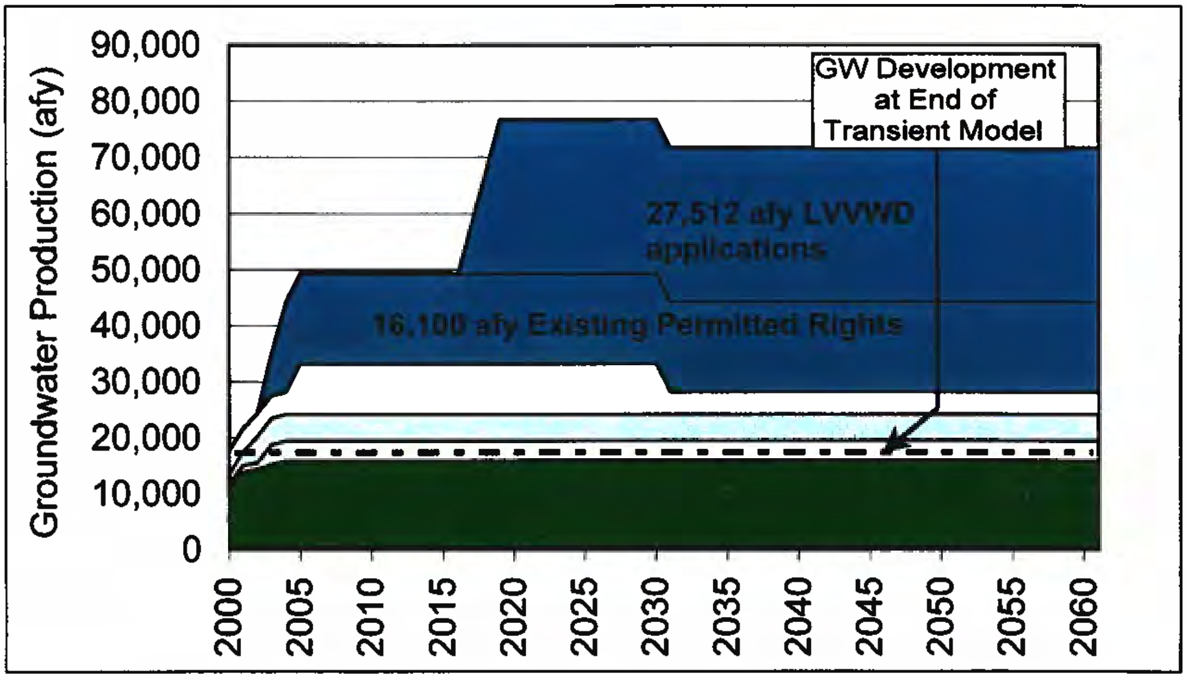
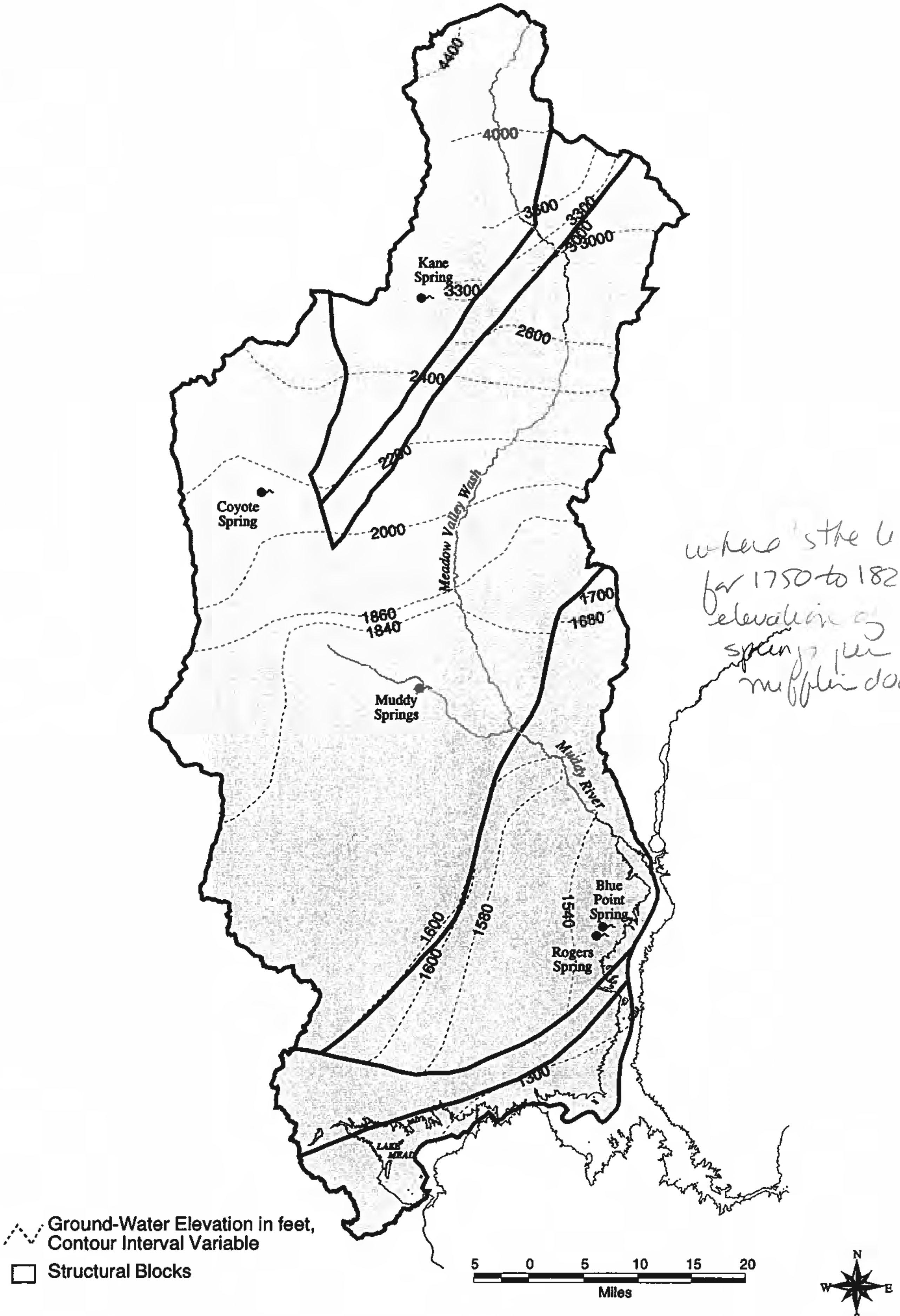


Figure 8-40 Distribution of Ground-water Pumping for LVVWD Applications.

Legend: Coyote Springs; L. Meadow Valley Wash; Black Mountains; Garnet; Muddy Springs Area; Lower Moapa Valley

Note: Production from valley-fill and carbonate rocks.



where's the line for 1750 to 1820' elevation of springs per mifflin doc.

Figure 8-41. Simulated ground-water elevation at top of carbonate aquifer for existing permitted rights, 2061.

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JA_11372

HYDROGEOLOGIC ASSESSMENT
UPPER MUDDY RIVER VALLEY, NEVADA

By:

M. D. Mifflin

C. L. Johnson

R. J. Johnson

next 3 pages not part of Ex. 54 - Mifflin's supplied after the hearing

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Las Vegas, Nevada 89120

MN890202a

For:

Nevada Power Company

Las Vegas, Nevada

February 1989

MN890202a

Appendix I Table 1 continued

	Spring orifice	DATE	ELEVATION *
Big Muddy Spg Pool	S8	6/23/87	1758.94
Big Muddy Spg	S8a	6/23/87	1751.85
Near Big Muddy Spg	S9	6/23/87	1769.81
Near LDS Pool spg	S12	6/23/87	1785.64
Near LDS Pool Spg	S13/14	6/23/87	1799.21
upper F+W pool spg	S20A	6/23/87	1808.17
upper F+W pool spg	S25	6/23/87	1809.01 (Playboy pool)
upper Warm Spgs Resort	S33	6/23/87	1766.21
Lower Warm Spgs Resort	S36	6/23/87	1753.38
Apcar/MVWD Spg Box	S47	6/23/87	1777.76
Warm Spgs Resort Area	S57	6/23/87	1765.50

* Static water elevation in feet above mean sea level.

** Driller's log water level.

*** DRI recorder measurement.

† Well blocked, water level below given measurement.

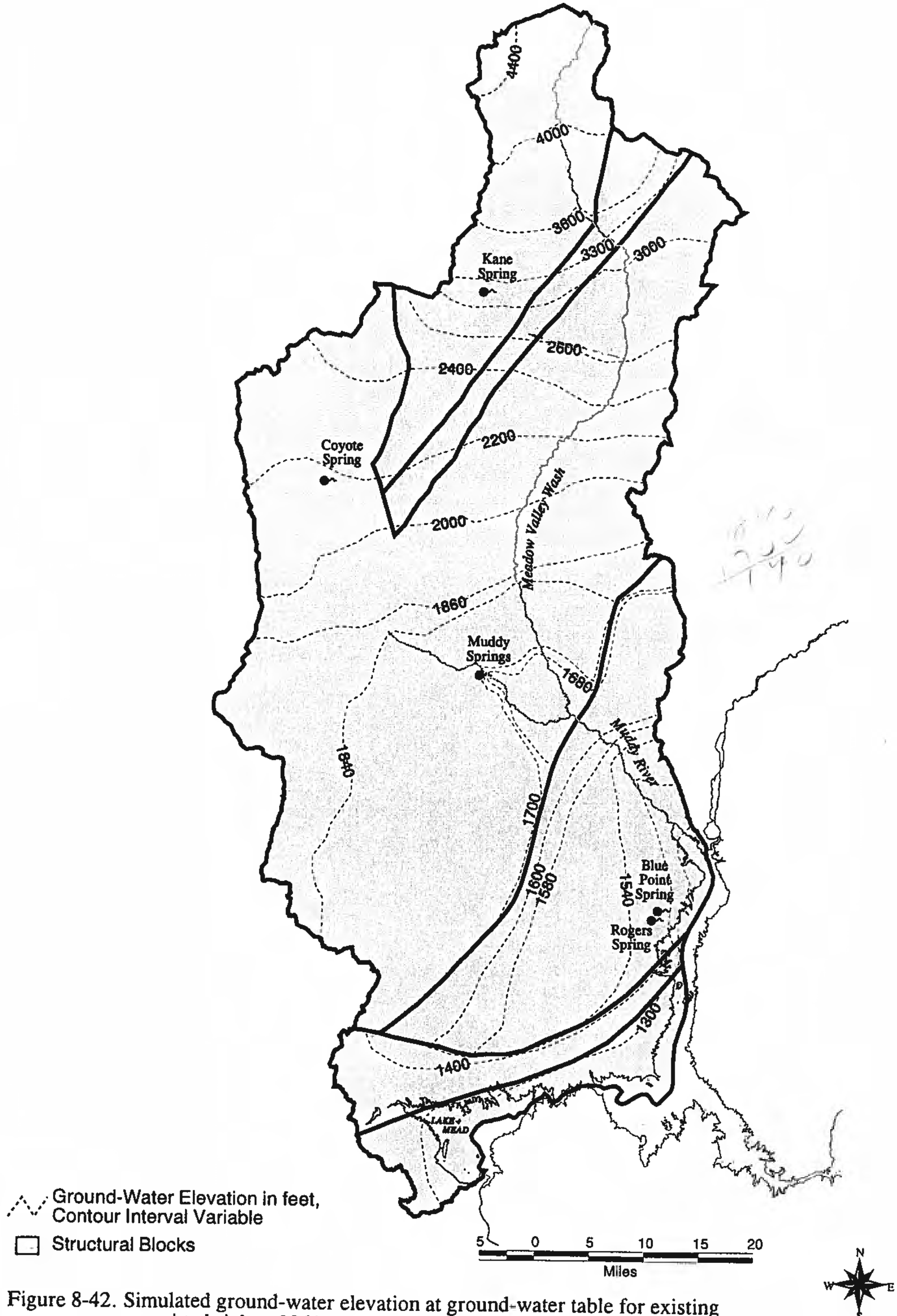

Figure 8-42. Simulated ground-water elevation at ground-water table for existing permitted rights, 2061.

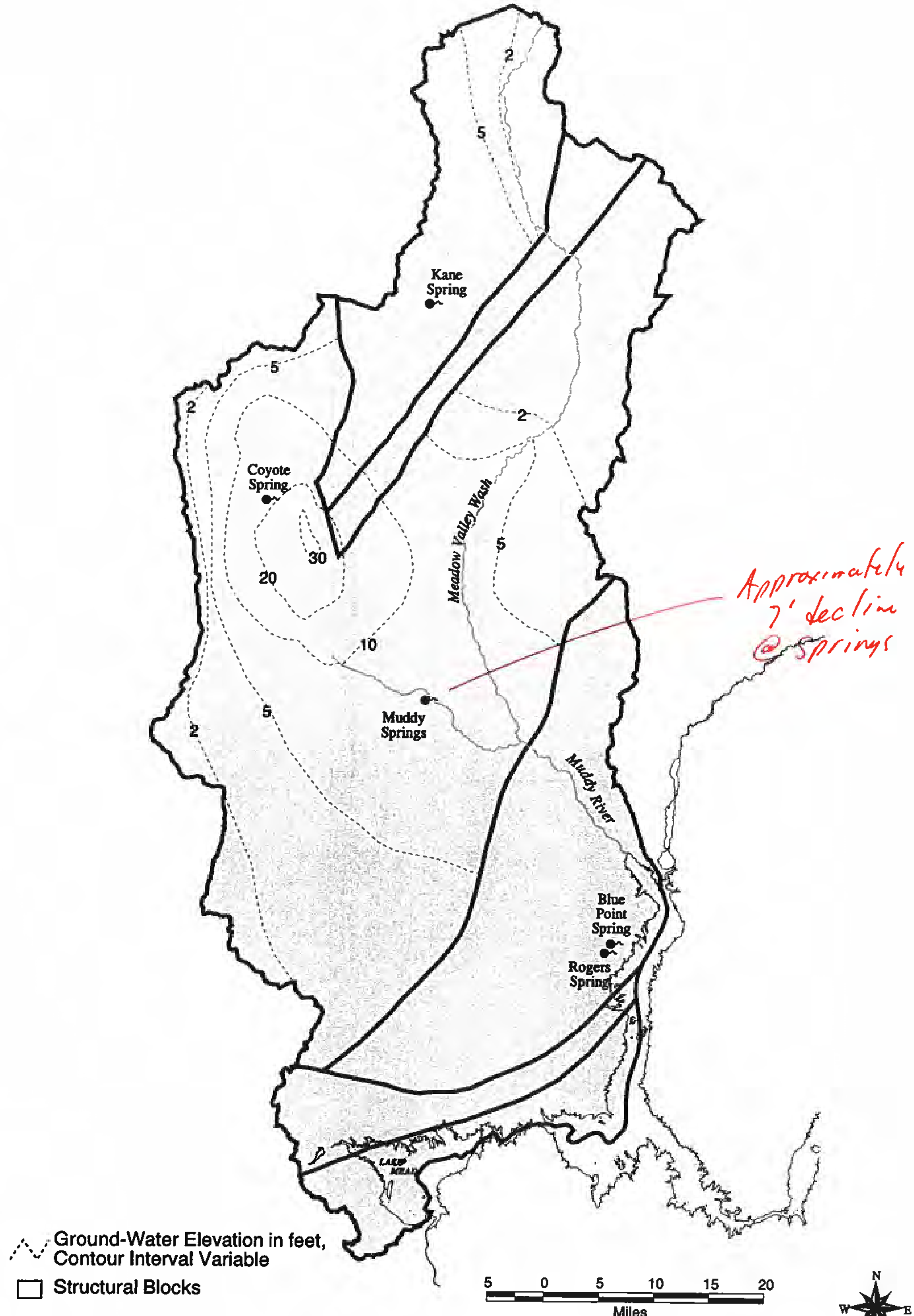

Figure 8-43. Simulated change in ground-water elevation at top of carbonate aquifer for existing permitted rights, 2000-2061.

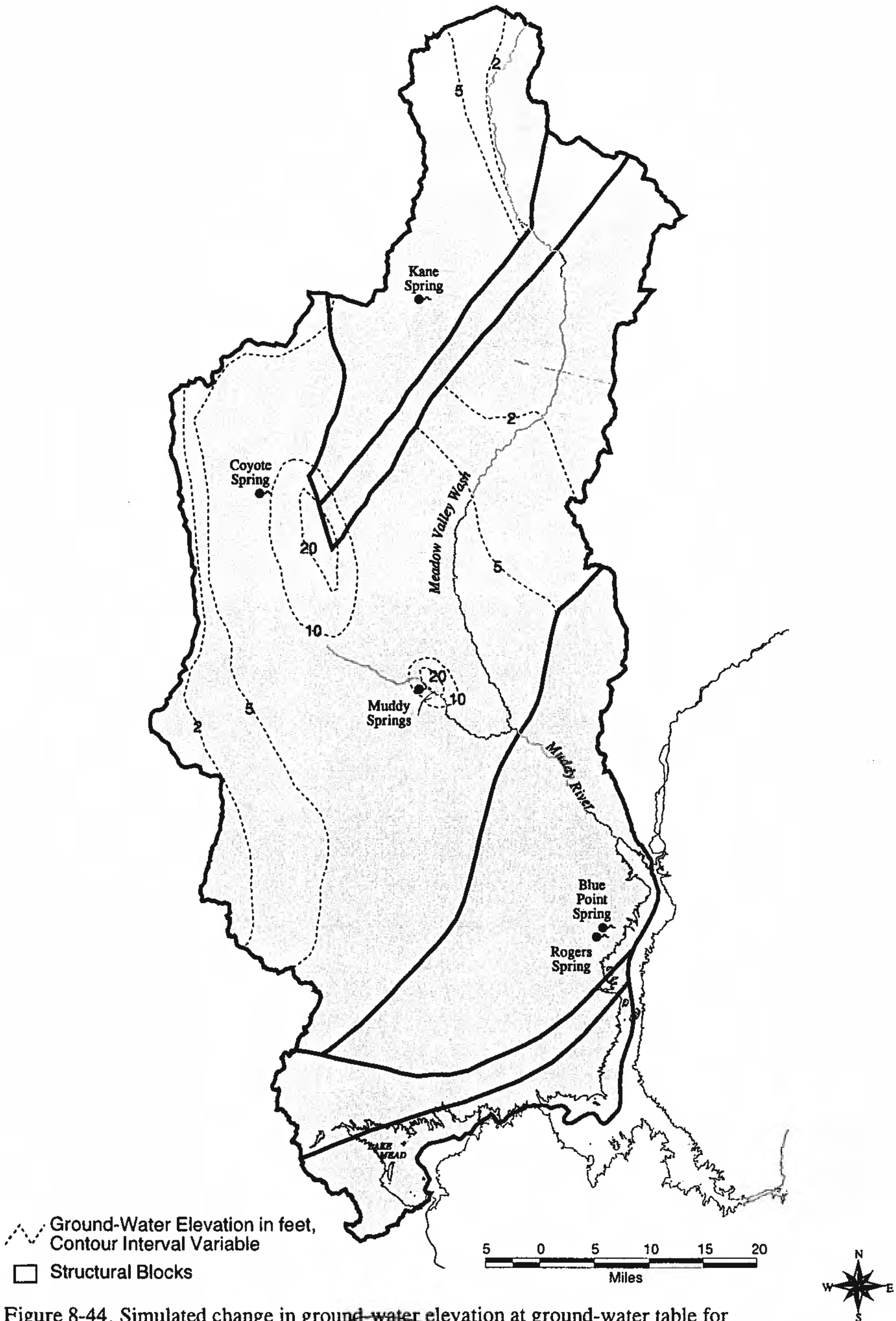

Figure 8-44. Simulated change in ground-water elevation at ground-water table for existing permitted rights, 2000-2061.

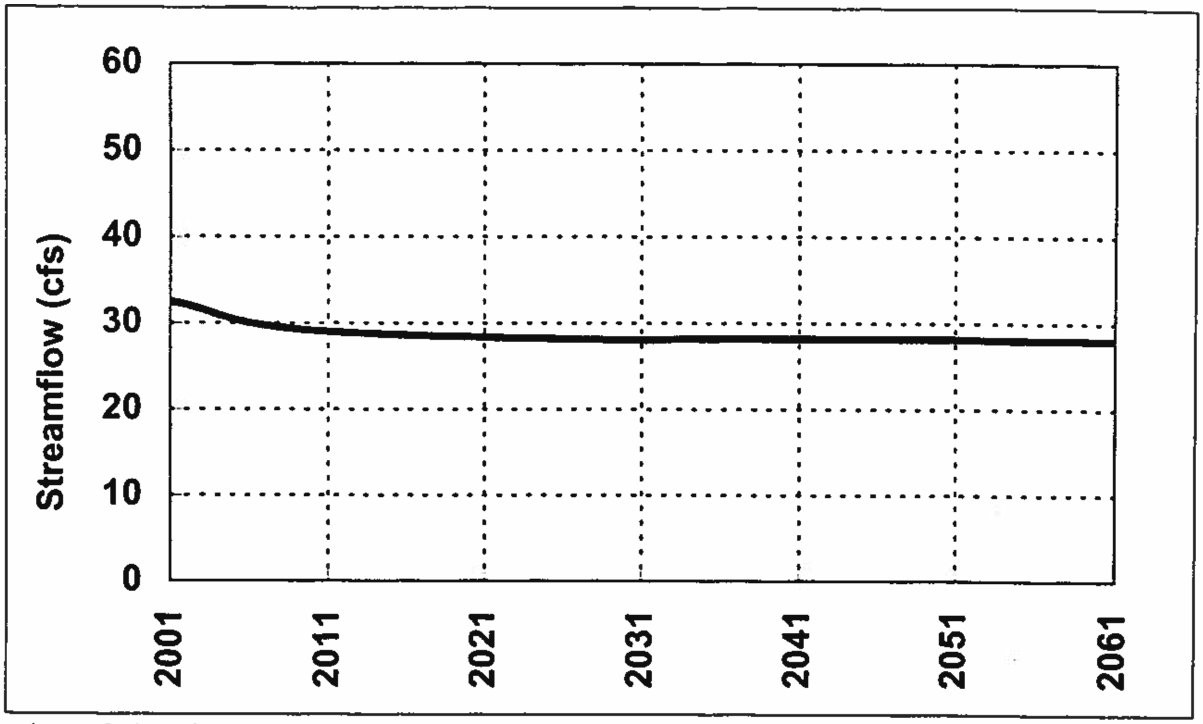

Figure 8-45 Simulated Muddy River Streamflow at Moapa Gage-Existing Permitted Rights.

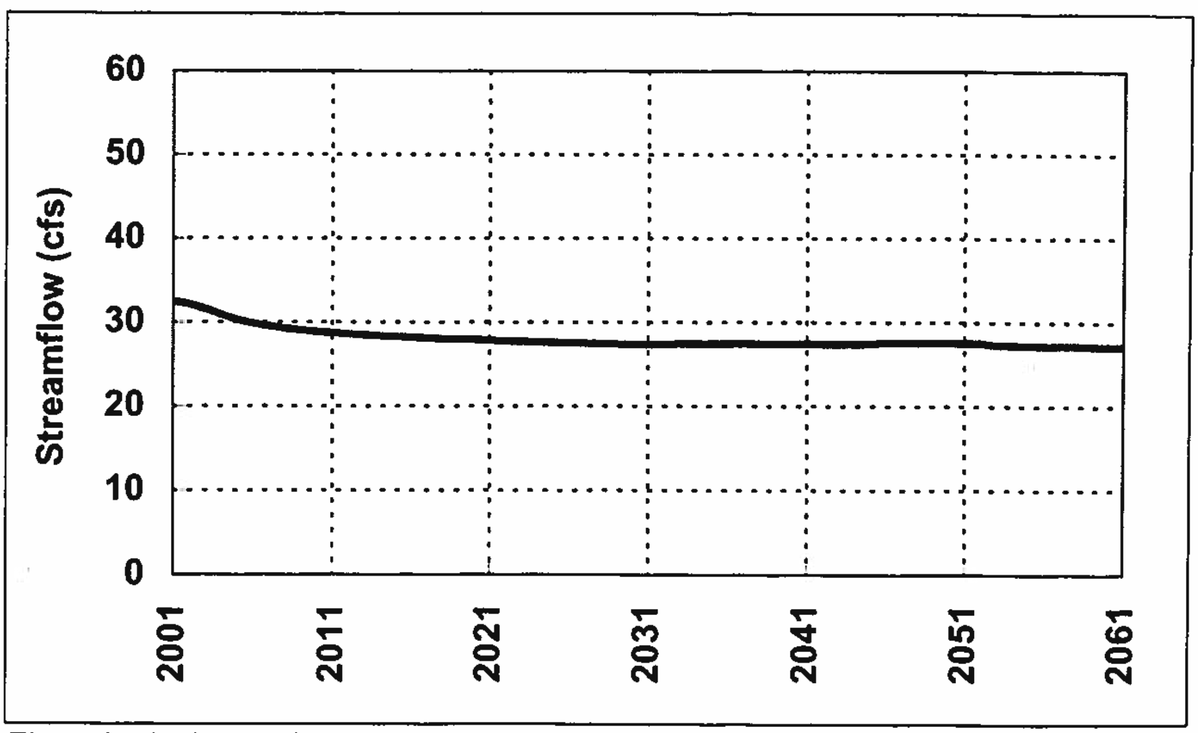

Figure 8-46 Simulated Muddy River Streamflow at Glendale Gage-Existing Permitted Rights

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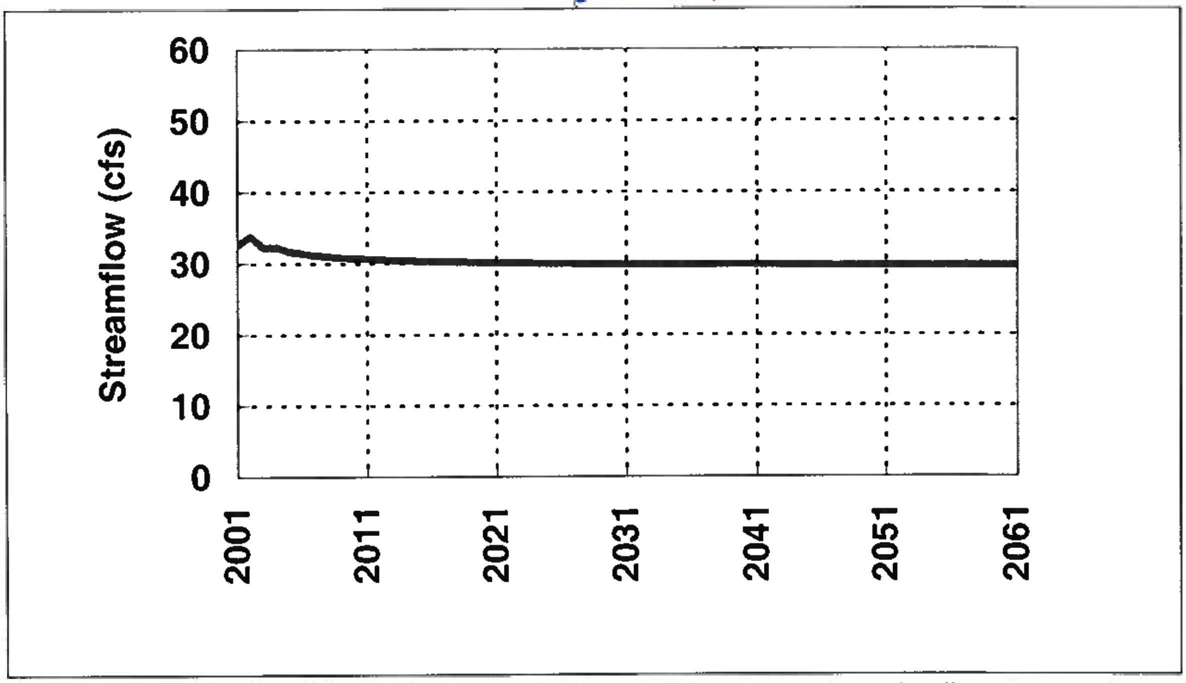

Figure 8-45 Simulated Muddy River Streamflow at Moapa Gage-Existing Permitted Rights.

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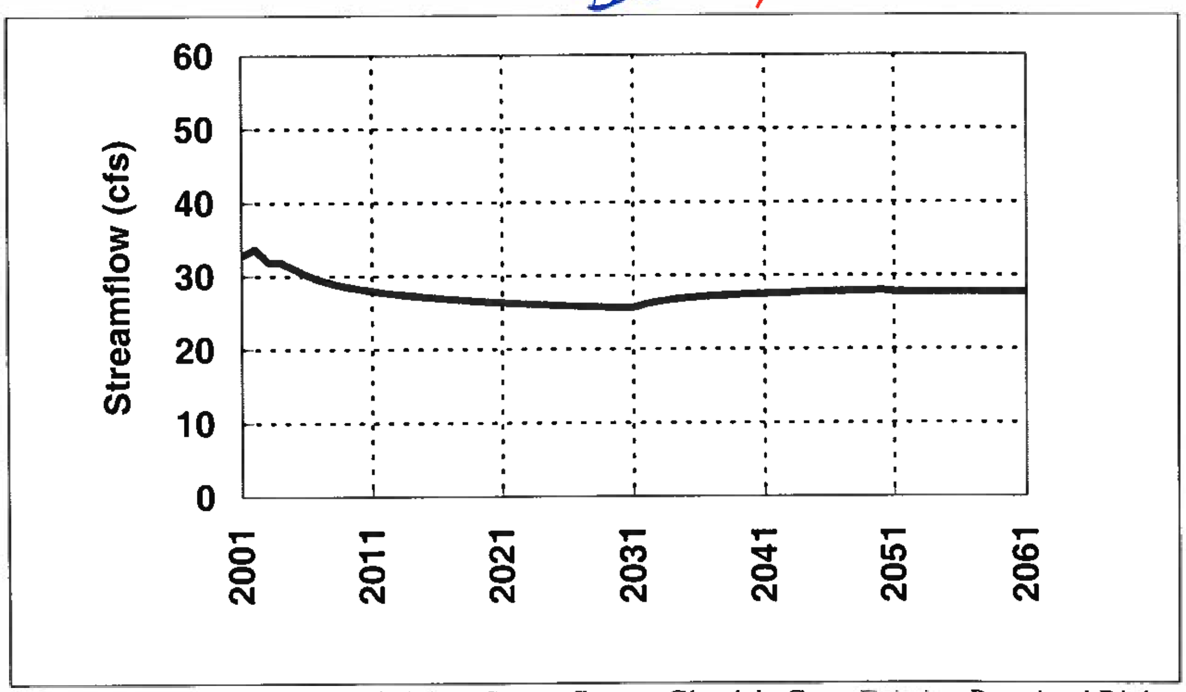

Figure 8-46 Simulated Muddy River Streamflow at Glendale Gage-Existing Permitted Rights.

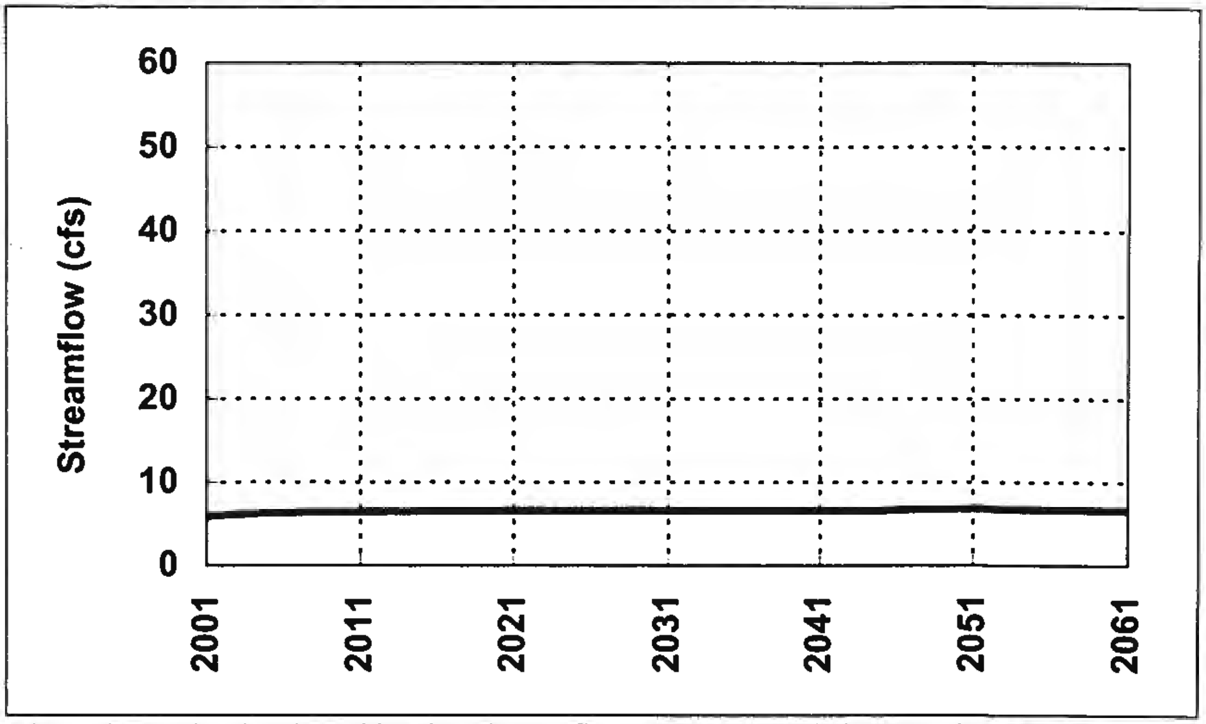

Figure 8-47 Simulated Muddy River Streamflow at Overton-Existing Permitted Rights.

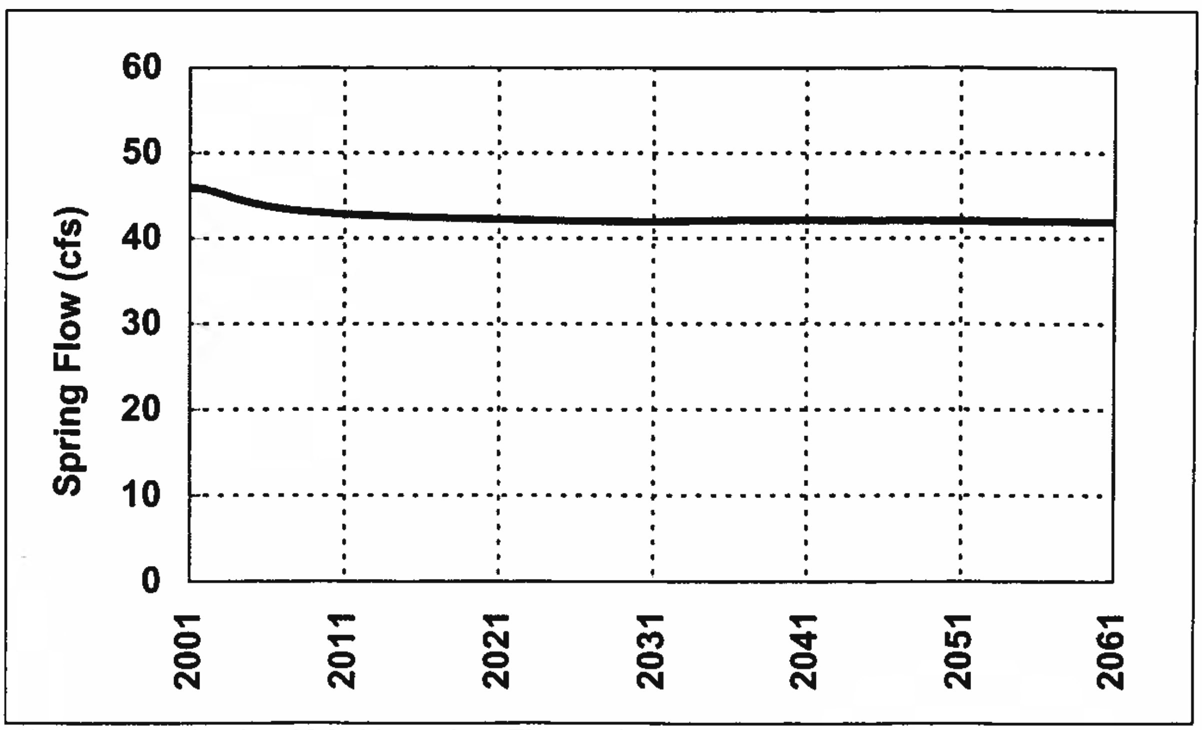

Figure 8-48 Simulated Muddy Springs Flow-Existing Permitted Rights.

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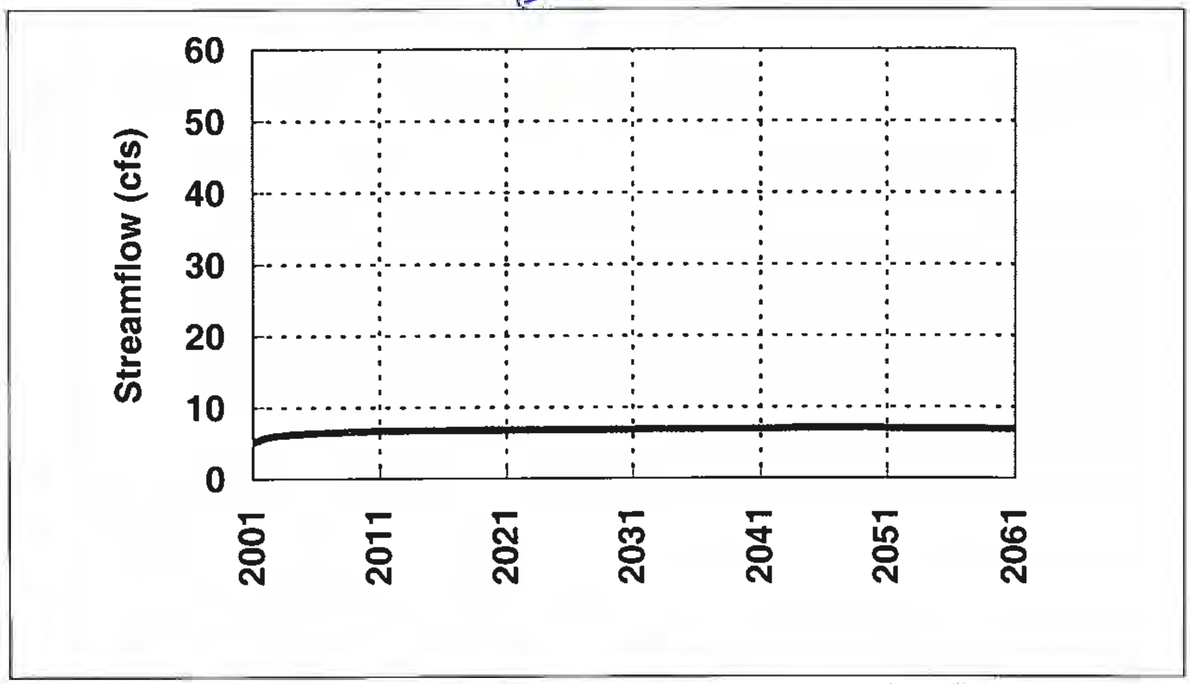

Figure 8-47 Simulated Muddy River Streamflow at Overton-Existing Permitted Rights.

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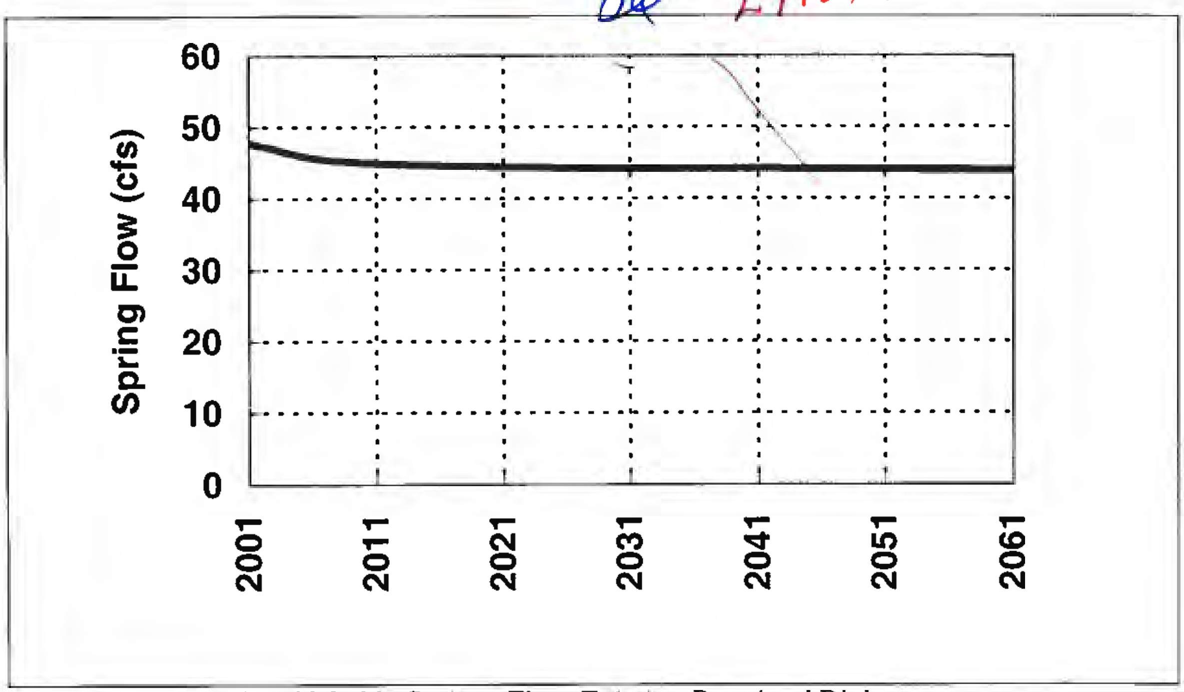

Figure 8-48 Simulated Muddy Springs Flow-Existing Permitted Rights.

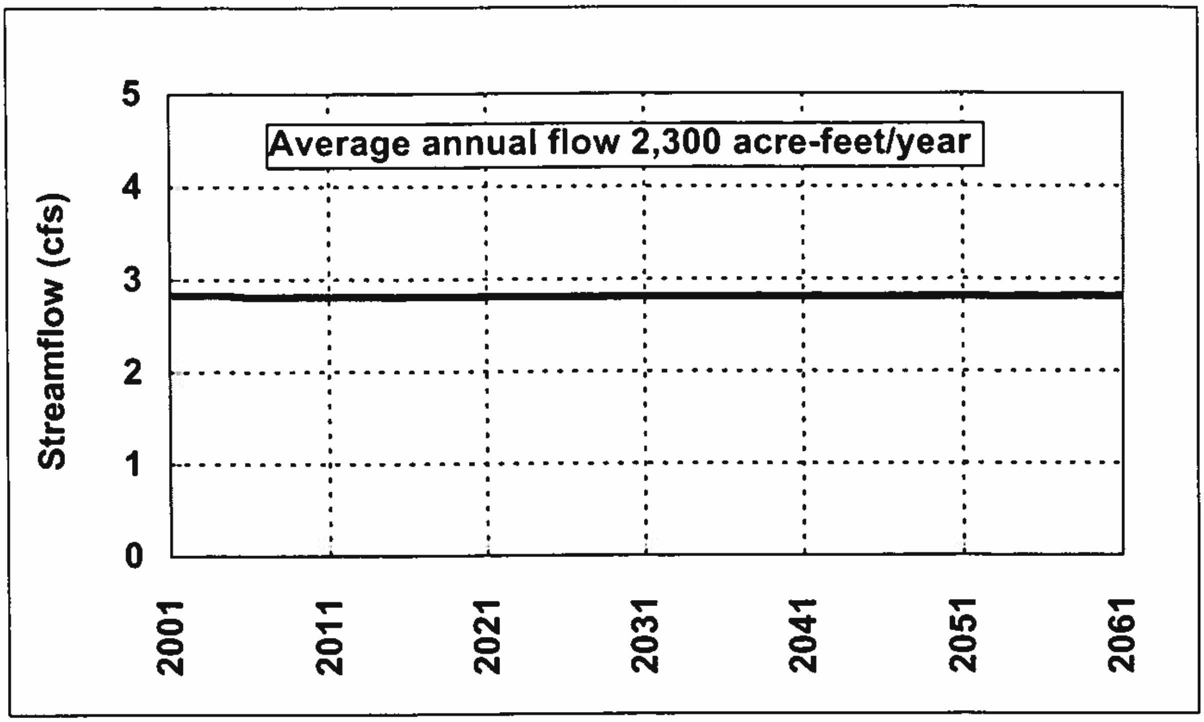

Figure 8-49 Simulated Rogers and Blue Point Springs Flow-Existing Permitted Rights (represents North Shore Spring Complex).

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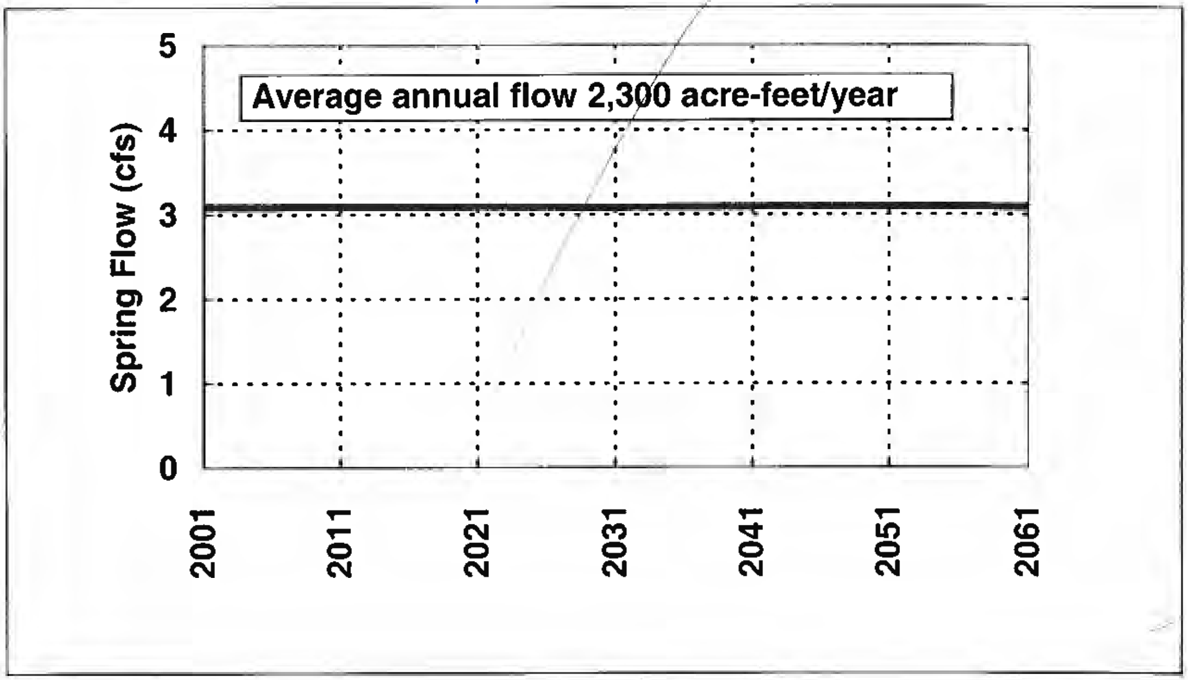

Figure 8-49 Simulated Rogers and Blue Point Springs Flow-Existing Permitted Rights. (represents North Shore Spring Complex).

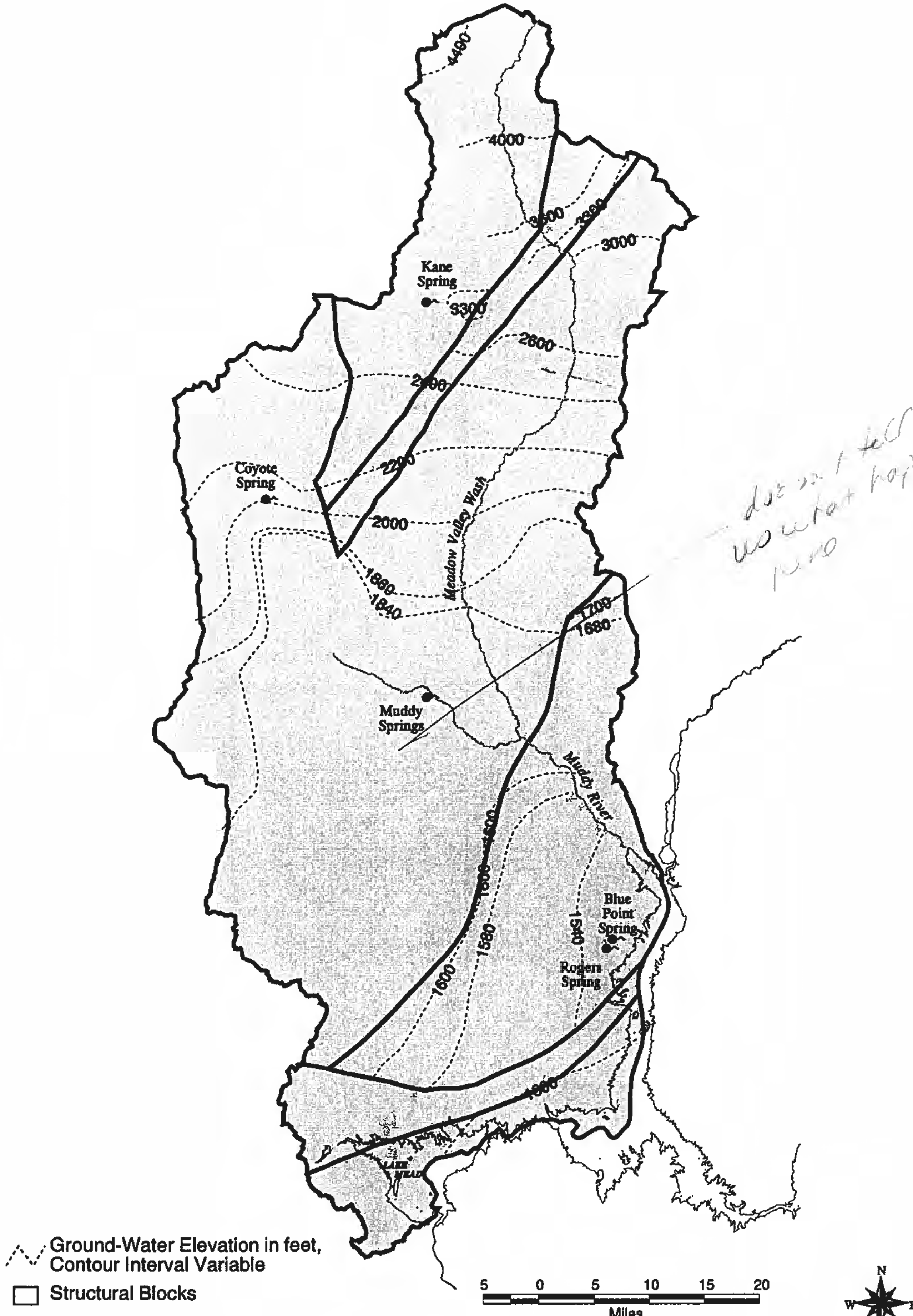

Figure 8-50. Simulated ground-water elevation at top of carbonate aquifer for LVVWD applications, 2061.

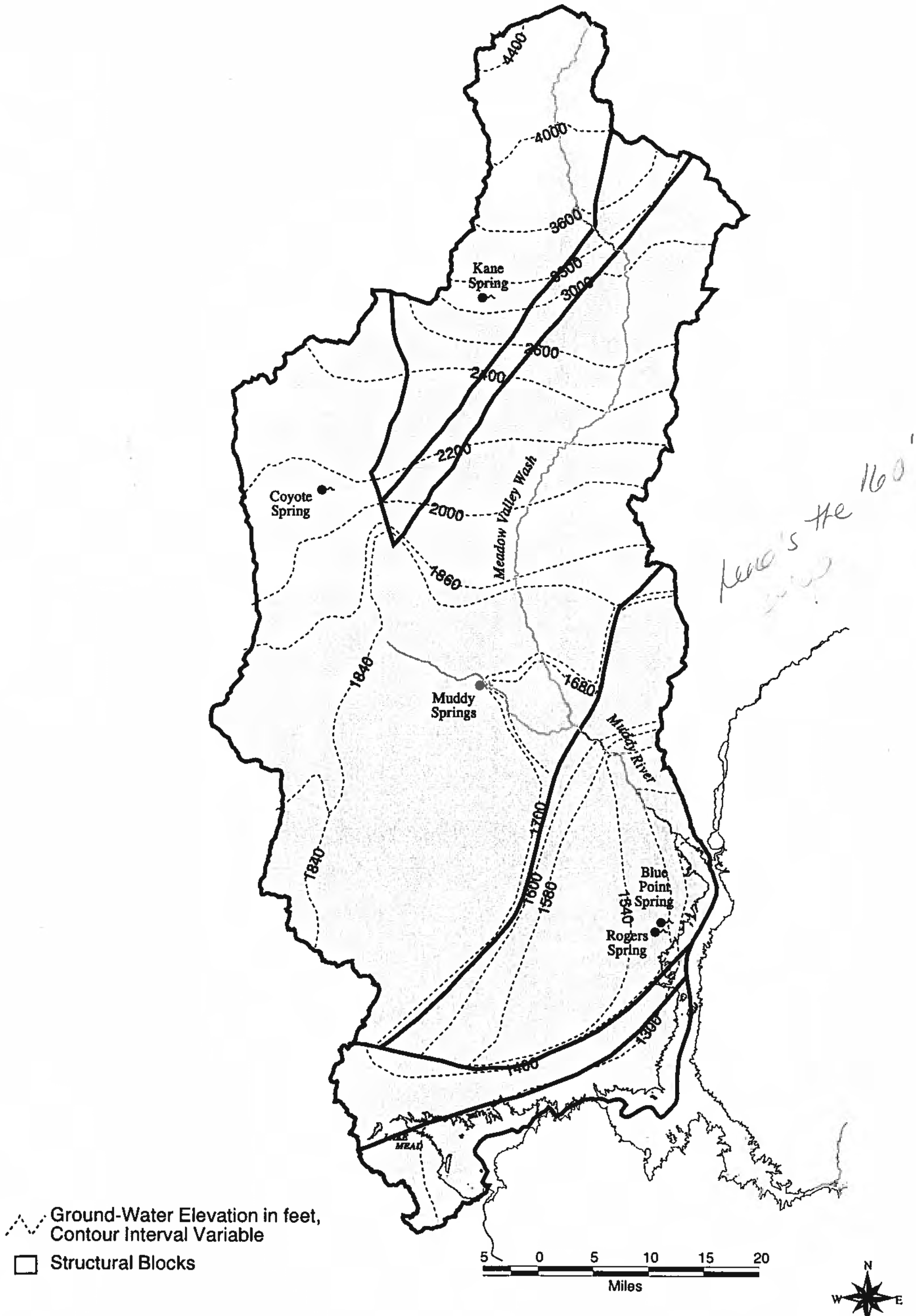

Figure 8-51. Simulated ground-water elevation for LVVWD applications, 2061.

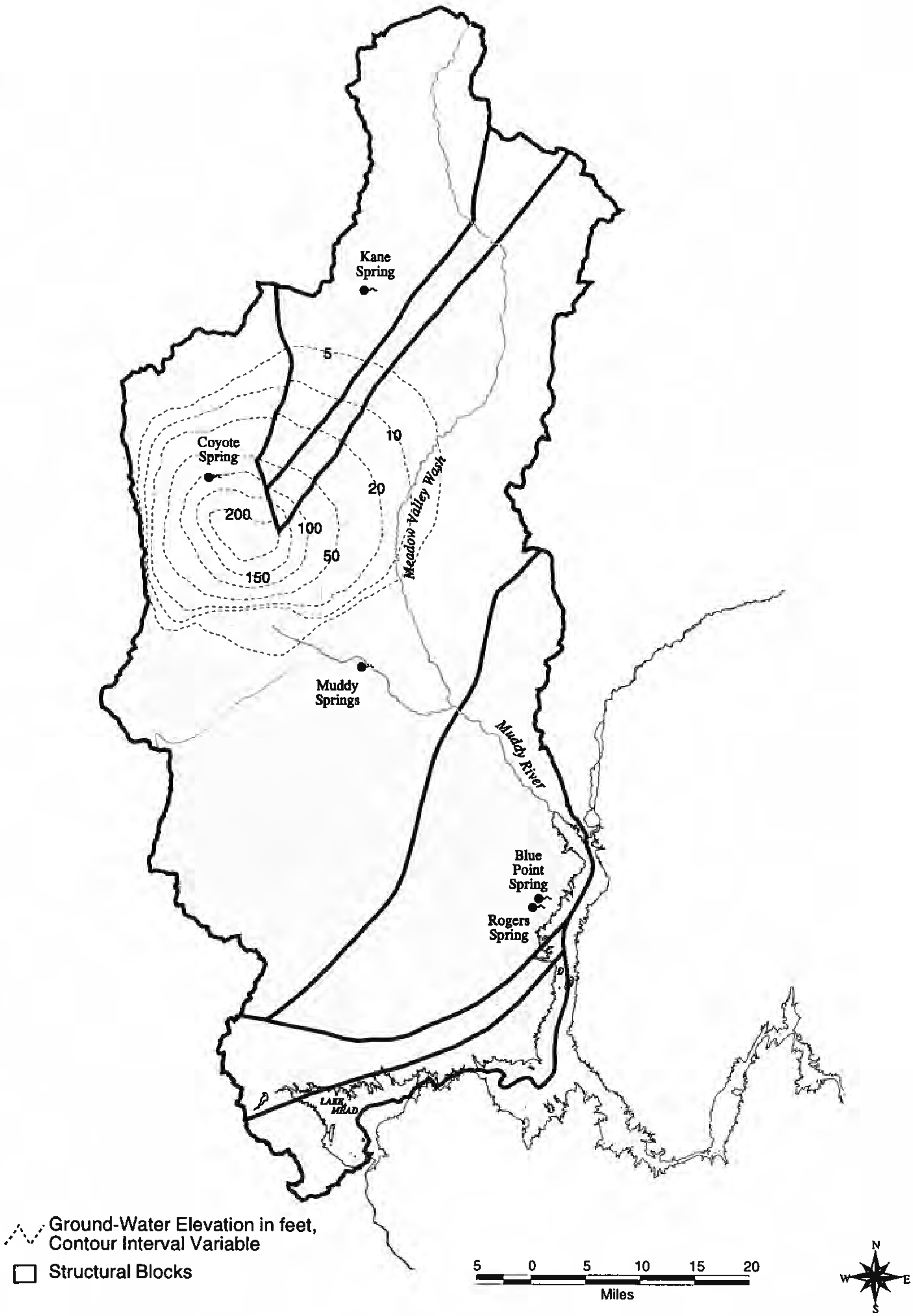

Figure 8-52. Simulated net change in ground-water elevation at top of carbonate aquifer in 2061 between existing permits and LVVWD applications.

elevation at the top of the carbonate aquifer in 2061 between existing permitted rights and LVVWD applications. **Figure 8-53** shows contours of computed change in ground-water elevation at the ground-water table in 2061 between existing permitted rights and LVVWD applications. **Figure 8-54** through **Figure 8-56** show hydrographs of computed streamflow, and **Figure 8-57** and **Figure 8-58** shows hydrographs of computed spring flows. **Table 8-5** lists the components of the ground-water budget for 2061.

As indicated on **Figure 8-54** through **Figure 8-58**, spring flows and streamflows in the simulation show a slight decline as a result of LVVWD applications compared to existing permitted rights. The Muddy Springs discharge shows a decrease from 44 to 41 cfs, but the Rogers Spring and Blue Point Springs discharges remain unchanged. Corresponding to the decrease at Muddy Springs, the Muddy River has a net decline in streamflow at the Moapa gage of approximately 2.5 cfs. The Muddy River streamflow near Glendale declines by approximately 3 cfs, and the decline of Muddy River streamflow at Overton is negligible (<0.1 cfs).

As indicated on **Figure 8-52** and **Figure 8-53**, ground-water levels in the simulation show a decline as a result of LVVWD applications compared to existing permitted rights. Within Coyote Spring Valley, the net water-level decline at the top of the carbonate aquifer is approximately 5 ft in 2061. At Muddy Springs, the net water-level decline at the top of the carbonate aquifer is approximately 2 ft. At the western boundary of the modeled area, the net water-level decline is 1 ft in 2061. At the eastern boundary of the modeled area, the net water-level decline is 2 ft.

As indicated in **Table 8-5**, water-level declines at the model boundaries induce ground-water inflow to the modeled area. The boundary inflow in year 2061 is approximately 41,000 afy.

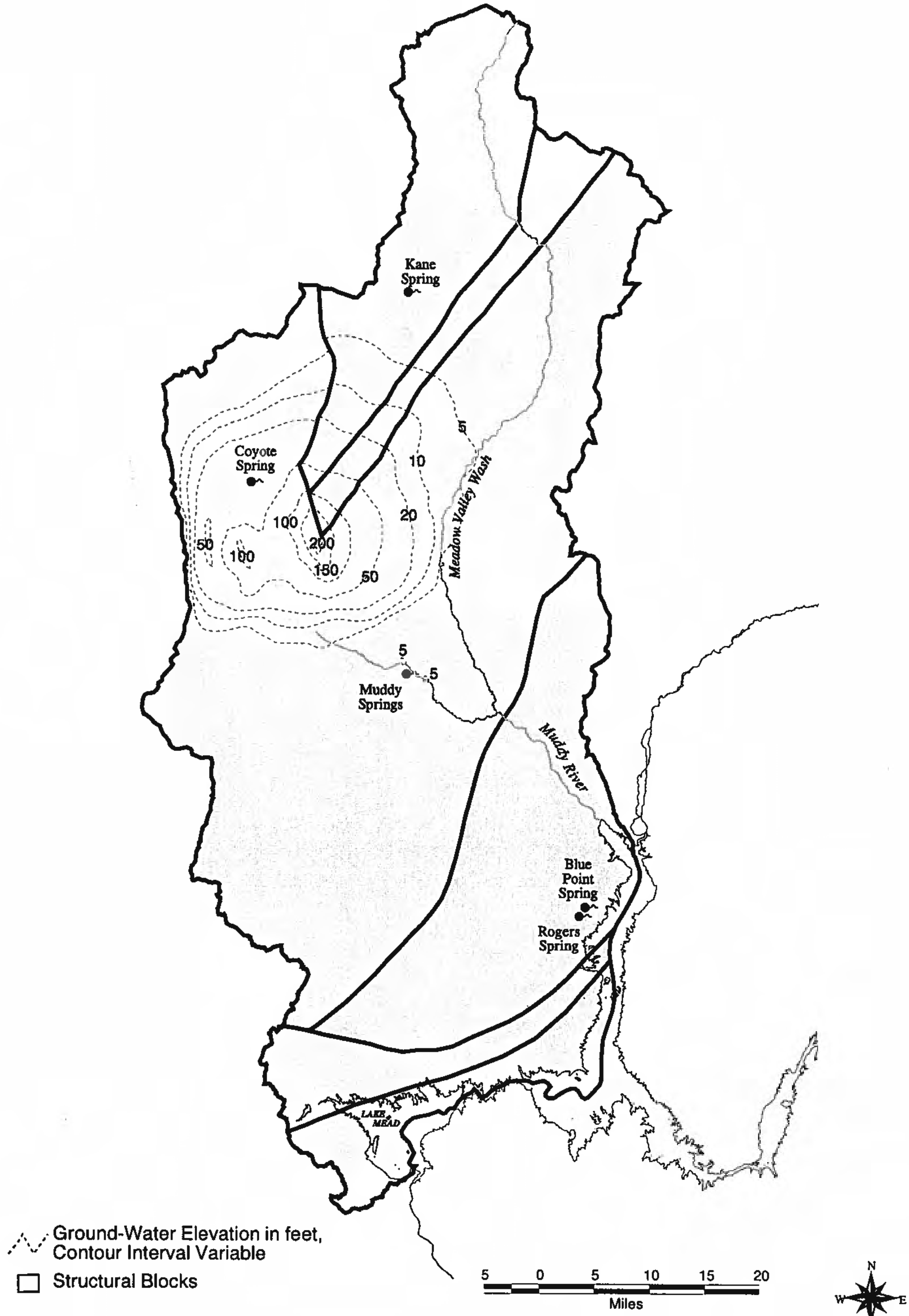

Figure 8-53. Simulated net change in ground-water elevation at ground-water table in 2061 between existing permits and LVVWD applications.

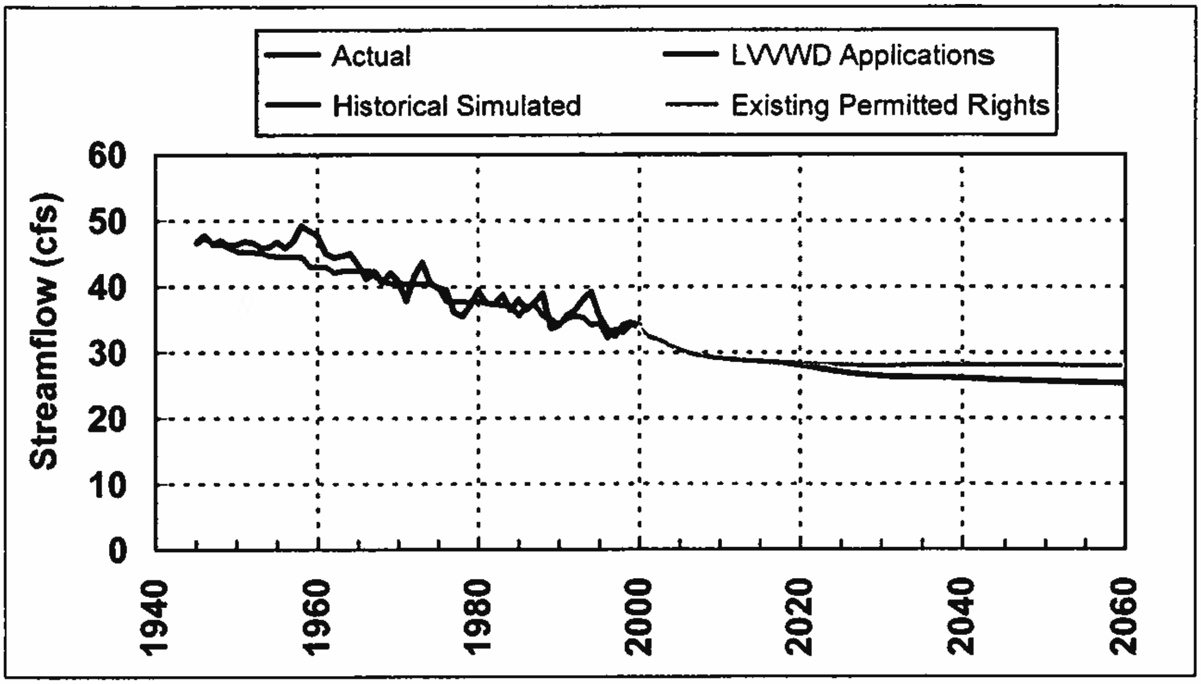

Figure 8-54. Muddy River Streamflow at Moapa Gage - Actual, Historical Simulated, Existing Permitted Rights, and LVVWD Applications in Coyote Spring Valley.

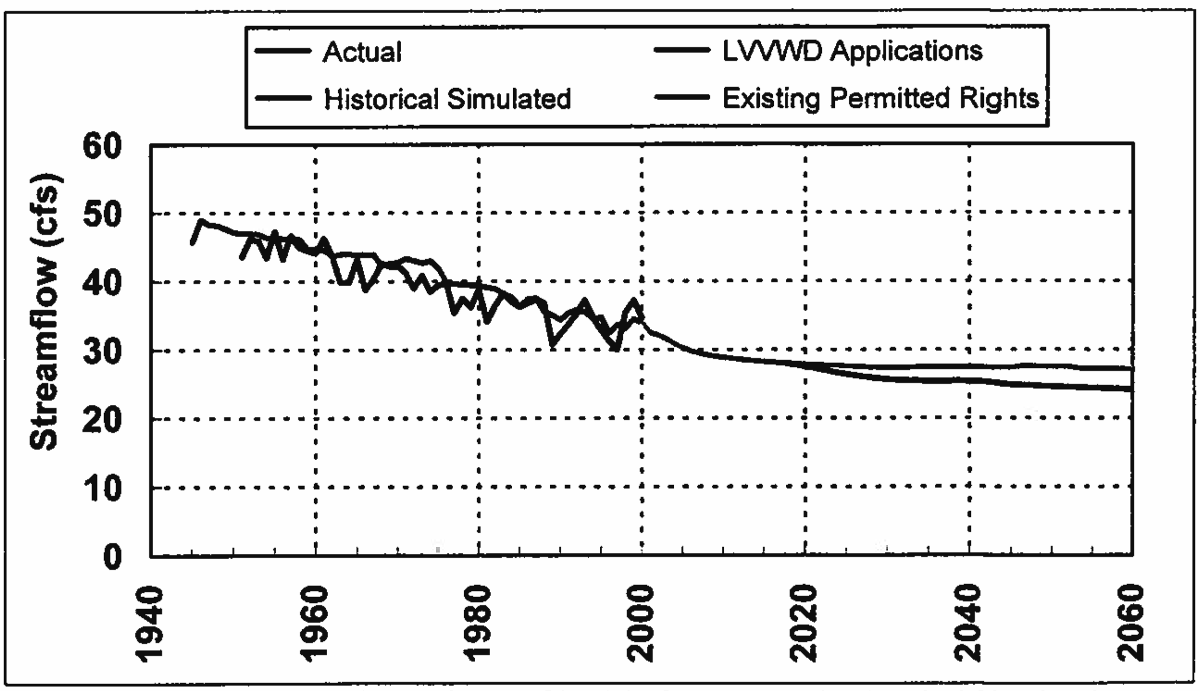

Figure 8-55. Muddy River Streamflow at Glendale Gage - Actual, Historical Simulated, Existing Permitted Rights, and LVVWD Applications in Coyote Spring Valley.

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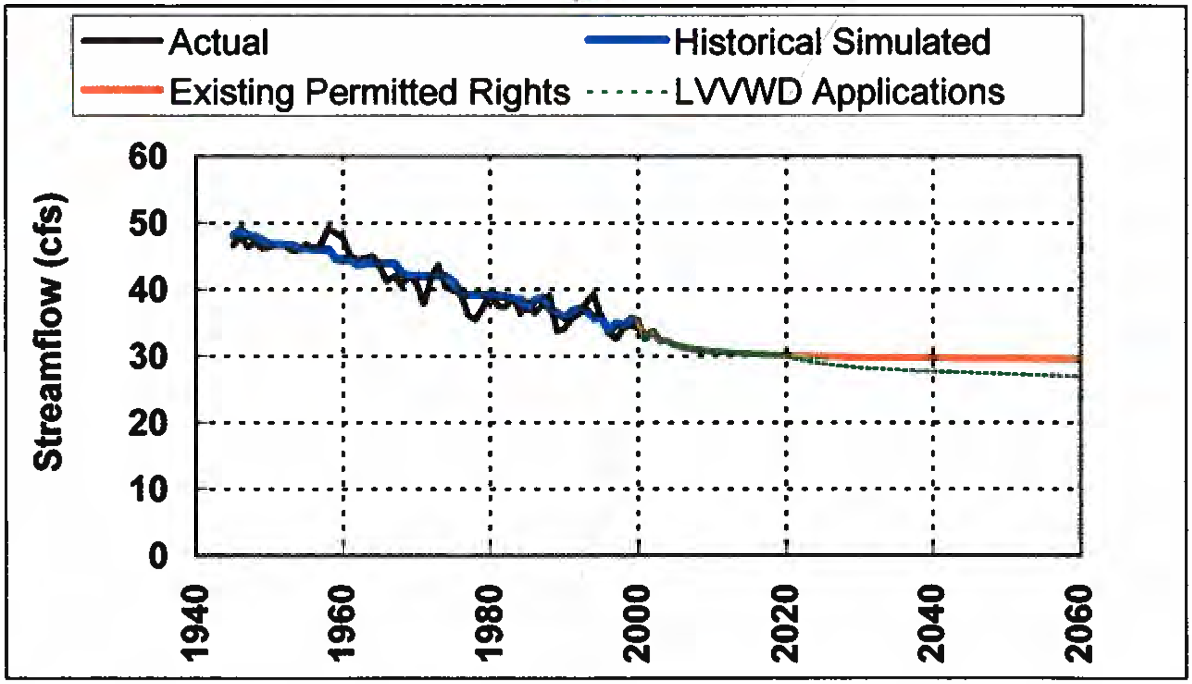

Figure 8-54 Muddy River Streamflow at Moapa Gage-Actual, Historical Simulated, Existing Permitted Rights, and LVVWD Applications.

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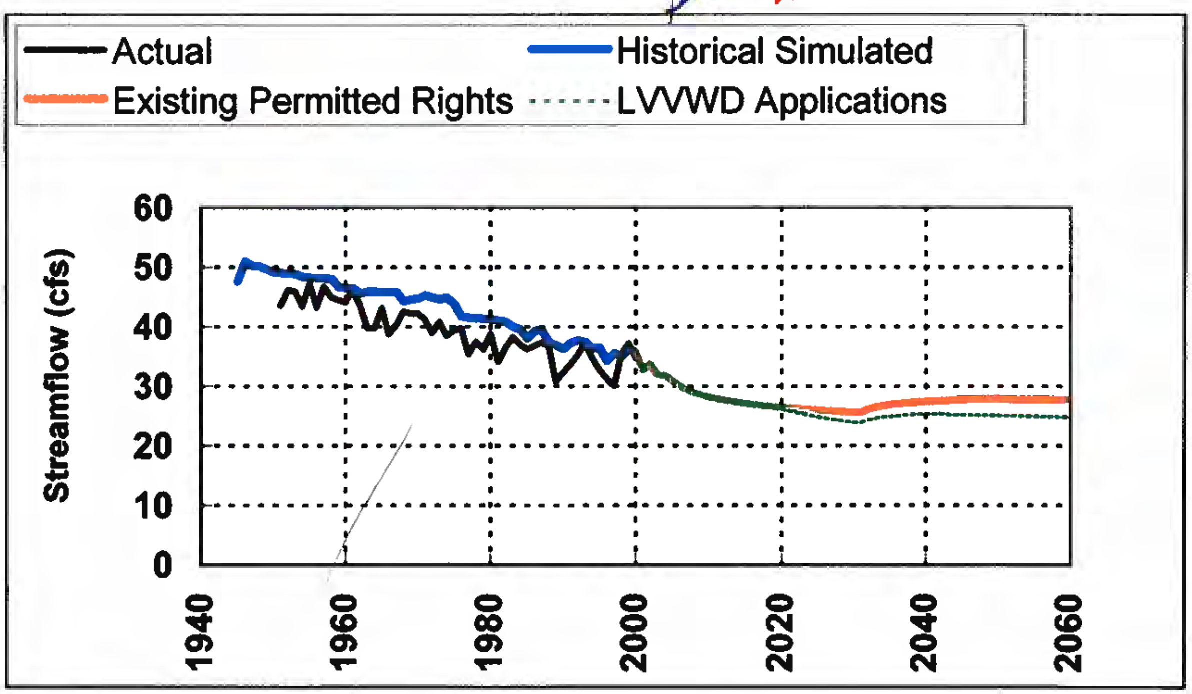

Figure 8-55 Muddy River Streamflow at Glendale Gage-Actual, Historical Simulated, Existing Permitted Rights, and LVVWD Applications.

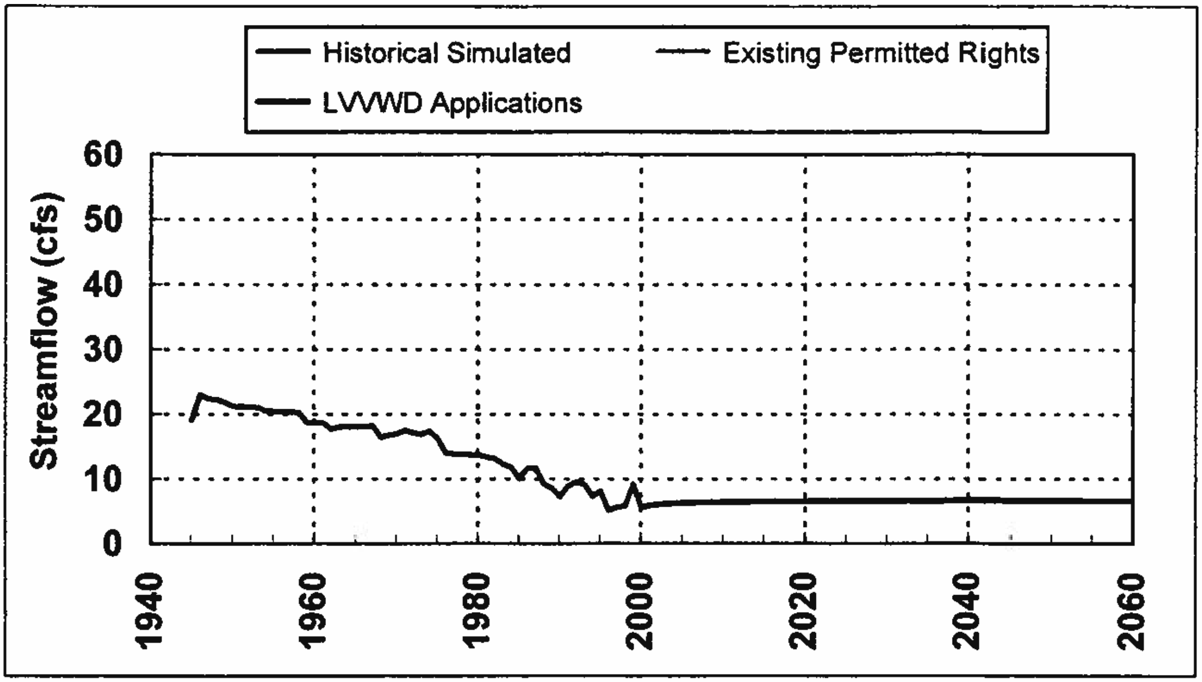

Figure 8-56. Muddy River Streamflow at Overton Gage - Historical Simulated, Existing Permitted Rights, and LVVWD Applications in Coyote Spring Valley.

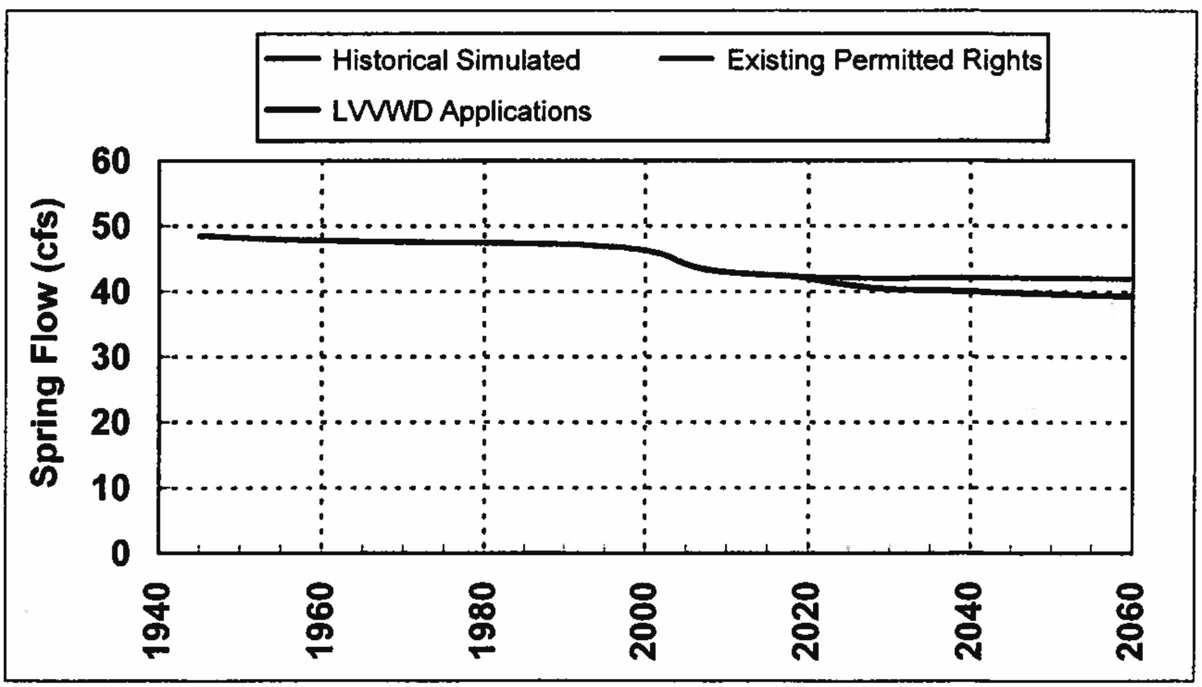

Figure 8-57. Muddy Springs Flow - Historical Simulated, Existing Permitted Rights, and LVVWD Applications in Coyote Spring Valley.

EX 55 errata

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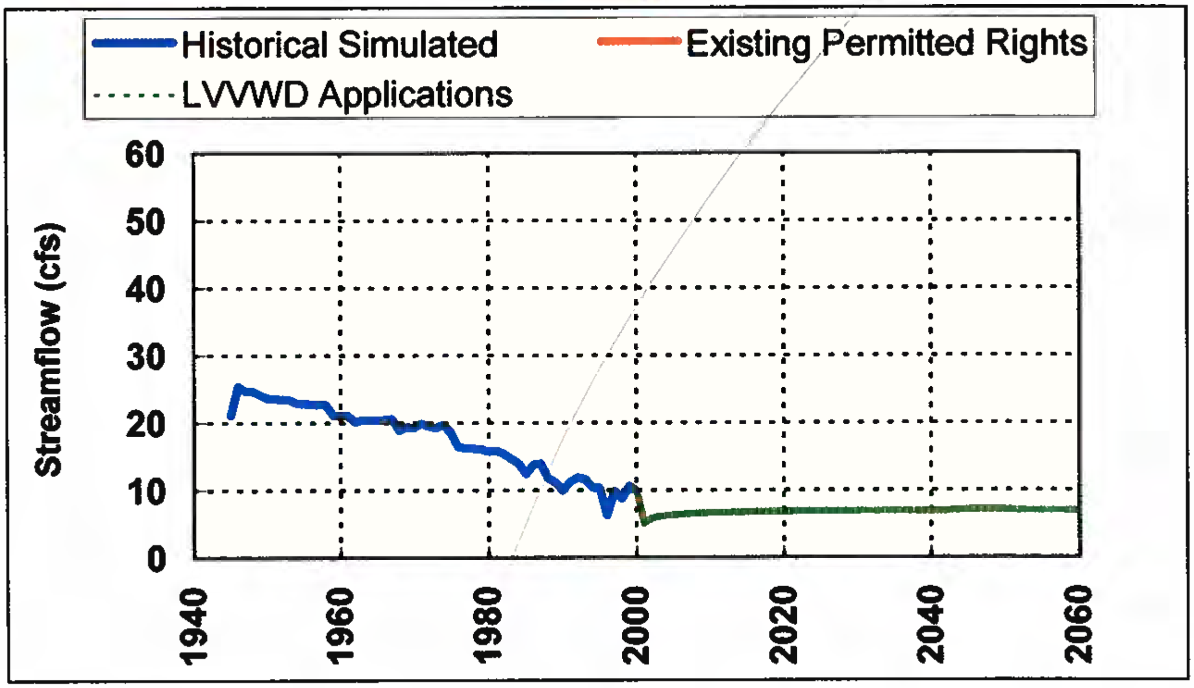

Figure 8-56 Muddy River Streamflow at Overton-Historical Simulated, Existing Permitted Rights, and LVVWD Applications.

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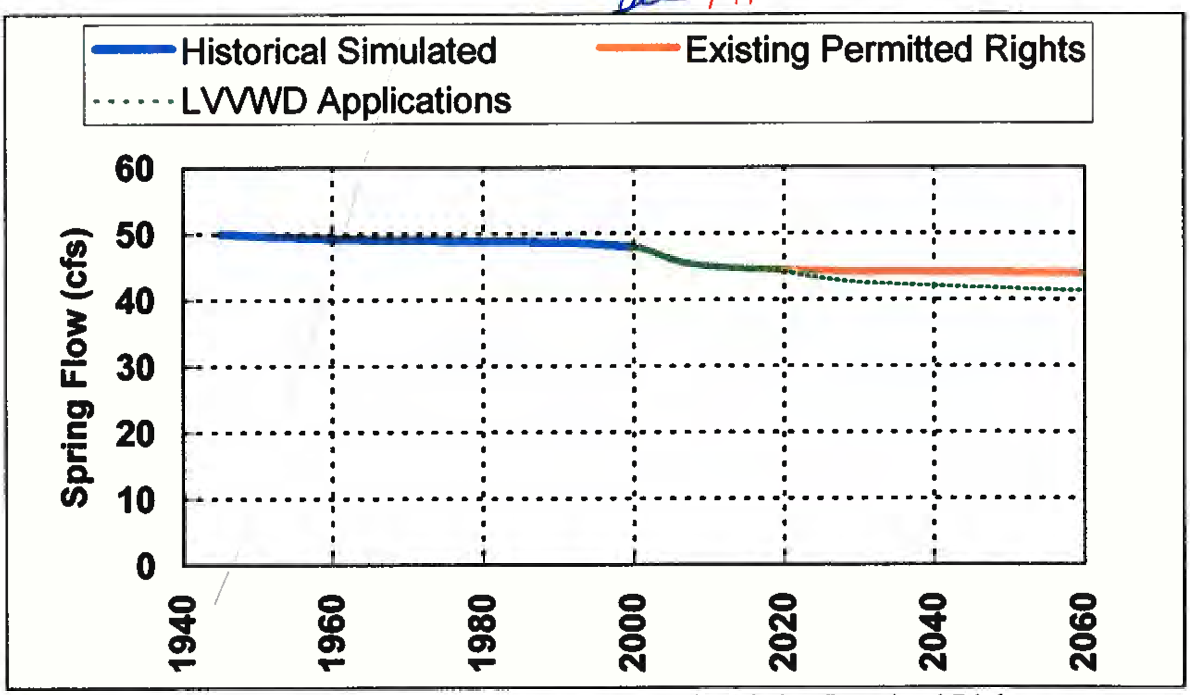

Figure 8-57 Muddy Springs Flow-Historical Simulated, Existing Permitted Rights, and LVVWD Applications.

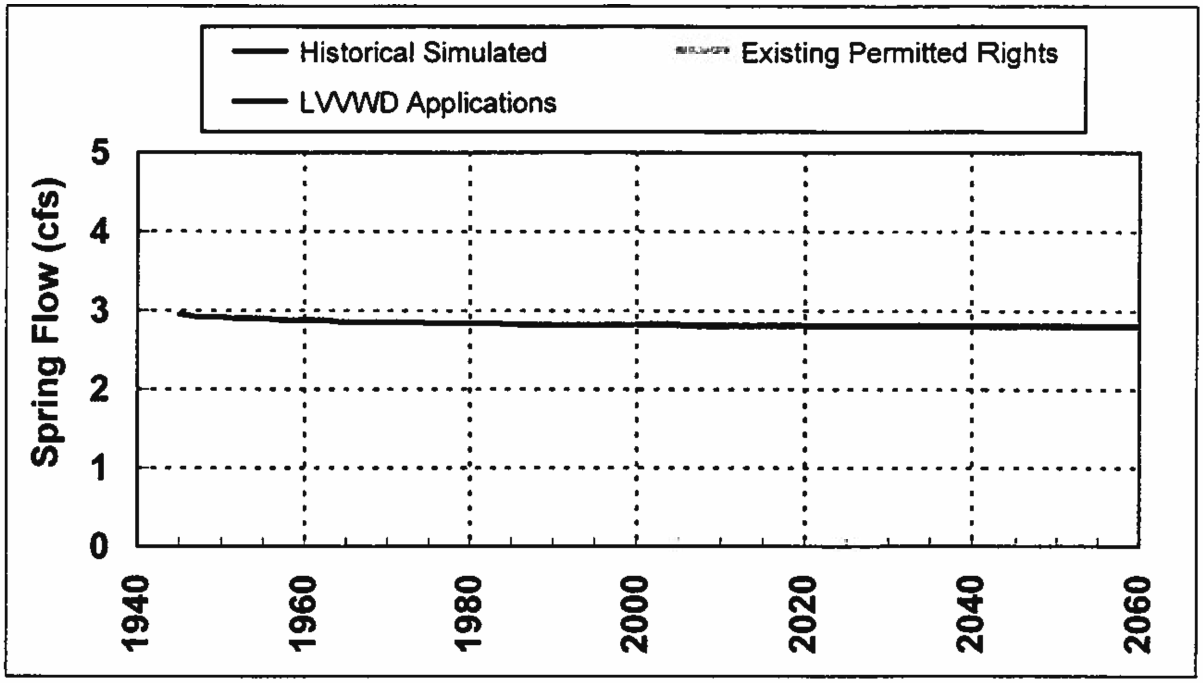

Figure 8-58. Roger and Blue Point Springs Flow - Historical Simulated, Existing Permitted Rights, and LVVWD Applications in Coyote Spring Valley.

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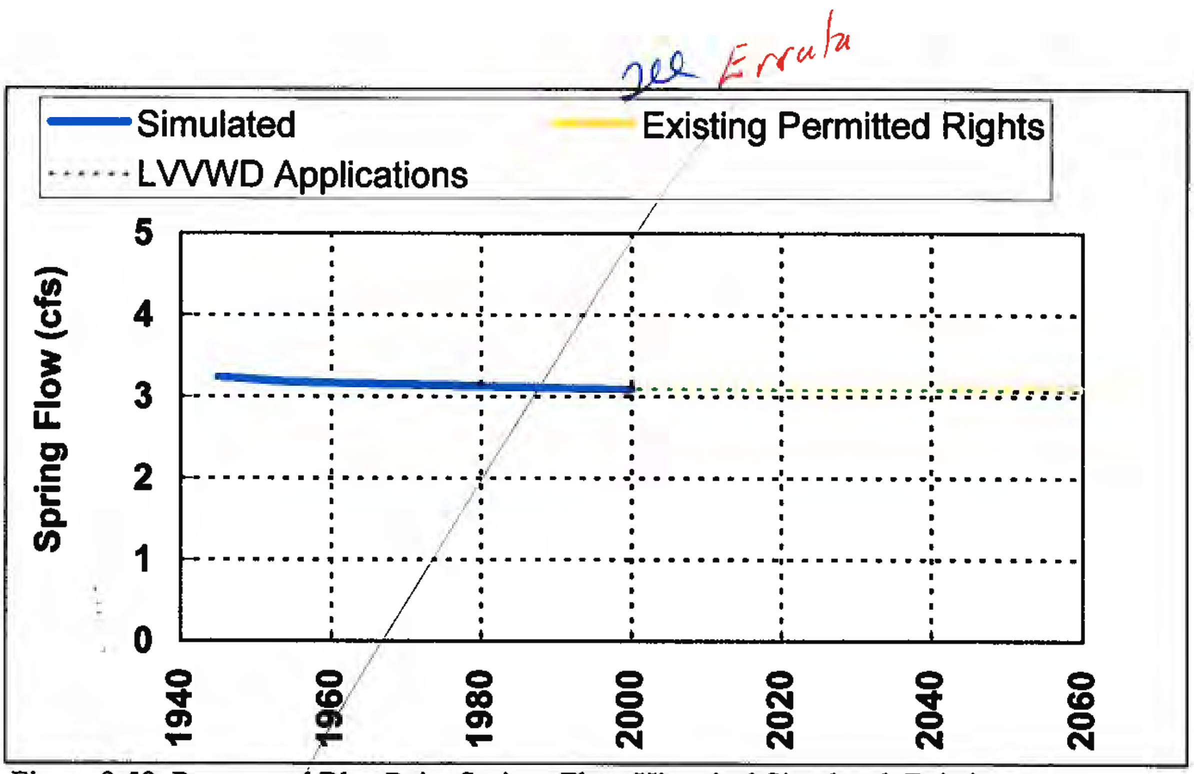

Figure 8-58 Rogers and Blue Point Springs Flow-Historical Simulated, Existing Permitted Rights and LVVWD Applications.

9 MONITORING

Timely and sound judgements regarding the effects and benefits of development of the regional carbonate aquifer can only be made through the use of monitoring combined with coordinated development. Extensive monitoring in the Muddy Springs Area and surrounding valleys is currently being conducted by NPC, MVWD, SNWA, and CSI. All these organizations have monitoring plans in place that require annual summaries to be submitted to the Nevada State Engineer for review. Monitoring is also being conducted by NDWR, USFS, USFWS, NPA, and the Moapa Band of Paiute Indians (MBPI). The parameters being monitored are ground-water levels, spring and streamflow discharges, and quantities of surface and ground-water diversions. **Table 9-1** outlines the number of wells and springs being monitored by each of these entities. This monitoring establishes a mechanism for all parties to better understand the complex aquifer system and protect vital water resources.

Ground-water development naturally occurs in stages due to capital investment of infrastructure and population growth. Development of existing and potential ground-water rights by LVVWD and SNWA will also occur in phases, with concurrent monitoring, modeling, and hydrogeologic investigations. However, the timing and quantities/volumes of these pumping stages will be variable, because future population growth and resulting water demand in the Las Vegas region and the I-15 corridor are not known at this time.

With so little actually known about causal relationships between pumping stresses, water level fluctuations, and spring discharge in the model area, monitoring is key to development of the carbonate aquifer system. LVVWD and SNWA as public agencies are committed to protecting the public interest and vital water resources in the model area.

Table 9-1. Summary of current ground-water and surface-water monitoring sites and data collected.

Area and Agency	Ground-Water Levels		Stream Flow	Diversion Amounts		
	Valley Fill	Carbonate	Spring/River	Springs	River	Wells
Upper Moapa Valley / Arrow Canyon						
NDWR (monthly)	6		5		2	12
NPC (continuous)	5	2			2	11
NPC (monthly)	6	1				
NPC (quarterly)			8			
MVWD (continuous)		2	4	2		2
USFWS (misc.)			5			
USGS (2 per year)			8			
USGS (continuous)[1]		1	4			
Black Mountains Area, California Wash, Garnet and Hidden Valleys						
MBPI (continuous)		6				
NPC (quarterly)		1				
NPS (monthly)		1?	1			
SNWA (quarterly)	2					
USGS (quarterly)	1					
Coyote Spring Valley						
SNWA (quarterly)	4	3				
USGS (continuous)		1				
USGS (quarterly)	4	3				
Lower Meadow Valley Wash / Lower Moapa Valley						
NDWR (monthly)						6
NPC (quarterly)	10					
USGS (continuous)			1			
Mesa/Weiser Wash						
NPC (quarterly)	2	2				

[1] *SNWA funds 50% of three of the USGS continuous gaging stations.*

SOURCES:

Johnson, C., Mifflin, M. D., Johnson, R. J., Haitjema, H., 2001, Hydrogeologic and groundwater modeling analyses for the Moapa Paiute Energy Center, 78 p.

Converse Consultants, 2000, Groundwater level monitoring program: 1999 Annual Report, Moapa, Nevada, 14 p.

MVWD, 2000, Muddy Springs Area monitoring report, 10 p.

MVWD, 1997, Muddy Springs Area monitoring plan, 28 p.

Site reconnaissance conducted 4/30/01; SNWA, USGS, TNC

10 SUMMARY AND CONCLUSIONS

To support ground-water applications 54055 through 54059 (inclusive) filed by LVVWD for an annual duty of 27,512 af in Coyote Spring Valley an extensive hydrogeologic investigation was completed for the Colorado River Basin Province in Nevada, which includes all of the White River and Meadow Valley Flow Systems. Both of these systems are in hydrogeologic continuity with each other and are tributary to the Muddy River.

The water-resources budget for the model area, including Coyote Spring Valley where the applications are located, shows 117, 000 afy of inflow. The upper valleys in the White River and Meadow Valley Flow Systems contribute 44,000 afy and 36,000 afy respectively plus local recharge of 37,000 afy. This recharge is minor compared to the vast amount of water in storage in the alluvial and carbonate rock aquifers.

The analysis shows there is about 324,000 afy of ground-water recharge throughout the entire White River and Meadow Valley Flow Systems. This is slightly more than two times the amount estimated by previous investigators. Ground-water discharge through evapotranspiration is also much greater than previously estimated. Ground-water outflow from the two flow systems (the difference between recharge and discharge) is estimated at about 50,000 afy of which 10,000 to 20,000 afy is surface water in the Muddy River that actually flows into Lake Mead.

Previous studies demonstrate there is a wide range of values in the hydrologic components used to estimate natural recharge and discharge. There is also uncertainty in aquifer properties of the regional carbonate aquifer, and conceptual flow paths of this complex system are only vaguely known. These uncertainties are compounded by the lack of data over much of the area and when combined with natural variation in the hydrologic system make a definitive interpretation of the affects of ground-water development extremely difficult. Nevertheless, this study draws on all previous investigations and using the most recent data and interpretations refines estimates of the hydrogeology of the carbonate aquifer. With a better understanding of the surface- and ground-water hydrology, geology, and geochemistry a ground-water flow model was developed for the lower part of the White River and Meadow Valley Flow Systems to assess the potential affects of ground-water development of the carbonate aquifer in Coyote Spring Valley.

The model was calibrated (for the years 1945 to 2000) to measured water levels in the carbonate aquifer, spring flow of Muddy, Rogers, and Blue Point Springs, and flow in the Muddy River and Meadow Valley Wash. The calibrated model showed predicted water levels were within a few feet of observed levels and spring and river flows were matched within three percent.

During the transient simulations the model simulated a 2 cfs decline in the Muddy Springs from 1945 to 2000. However, water level and gage data collected over nearly the last 20 years does not support this simulated 2 cfs decline which means the model is conservative, slightly over predicting impacts to the ground-water system.

The most sensitive model parameter observed in model development is the value of specific storage. The range of plausible values, based on those found in the literature, vary from 1×10^{-5} to 1×10^{-7}. A value of 1×10^{-6} produced the best model calibration, and all the simulations were run with this value.

The calibrated model evaluated impacts to the ground-water system for a 61-year period. Existing ground-water pumpage of 18,000 afy is simulated in the model area plus additional permitted rights of 16,100 afy in Coyote Spring Valley, and another additional permitted 10,000 afy scattered throughout the model area for a total of 44,000 afy. Of this total 5,000 afy is utilized for a proposed power plant that is anticipated to decrease its use in 2031.

Future impacts due to the LVVWD applications in Coyote Springs Valley for the same time period has all of the permitted water pumped, 44,000 afy, plus ground-water applications filed by LVVWD in the amount of 27,512 afy for a total of about 72,000 afy. All of the pumpage for the LVVWD applications is on line in the first 20 years. The model predicts that the additional pumpage of the applications after 61 years results in: 1) A net water level decline of about 5 ft in Coyote Spring Valley, and 2) an additional 2 ft decline in water levels in the carbonate aquifer in the Muddy Springs area, which causes a decline in spring flow of about 2.5 cfs. This decrease in flow results in a similar decrease in the flow of the Muddy River. Rogers and Blue Point Springs remain unchanged. 1800 afa

Are these values realistic? If the hydrogeology is exactly as we have estimated the answer is yes, however, we know there is great variability in the hydrologic processes that control the movement of ground water and the associated recharge and discharge. These uncertainties suggest a staged approach to ground-water development of these applications that optimizes well locations based on ground-water exploration and aquifer testing. This program, coupled with a monitoring and mitigation plan, will provide insurance against undesirable impacts to the ground-water system.

APPENDIX B

B.1 BACKGROUND

Historically, ground-water development within the model boundary has generally been limited to areas located within the flood plains of the Muddy River and Lower Meadow Valley Wash in Lower Moapa Valley, Lower Meadow Valley Wash, and the Muddy River Springs area of the Upper Moapa Valley near the southeast portion of the model area. Ground water has principally been developed to supply water for agriculture in these areas. It has also been developed in the Muddy River Springs area to supply water to the Reid Gardner power-generating facility located in California Wash which is owned and operated by NPC. Pumping well locations in the area are depicted in **Figure B-1.** Until recently, there has been little to no ground-water development in the other basins comprising the remainder of the model area (Black Mountains, California Wash, Garnet Valley, Hidden Valley). However, since 1990, various commercial enterprises have been granted ground-water withdrawal permits within the Black Mountains Area, Garnet Valley, and Hidden Valley of which, only a few have been certified. The remaining sections of this appendix discuss sources of ground-water production data, methods used to compile the development history for each basin within the model boundary, and a summary of the development history and description of how the records were used in the flow model.

B.2 DATA SOURCES AND RECORD COMPILATION

Major sources of ground-water production data and information are DRI, NDWR, USGS, and various reports referenced in this appendix. Information was obtained in the form of published and unpublished documents and data sets. In addition, numerous interviews were conducted with representatives of the MVIC, MVWD, NDWR, and various consultants working within the boundaries of the model area.

Ground-water production data were compiled and transcribed into digital form for analysis and formatting such that they could be used as input into the ground-water flow model. Abstracts from the Water Rights Database administered by NDWR were used to identify permitted/certified ground-water rights. Information garnered from this process was used to construct possible ground-water production histories in areas where reported data are scarce. Much of the data for the Muddy Springs area was compiled from monitoring reports submitted to the Nevada State Engineer on behalf of MVWD and NPC. Ground-water production reports for selected wells located in the Black Mountains Area and Garnet Valley were acquired from NDWR and transcribed into digital form. Information garnered through interviews was incorporated. Land-use maps based on aerial photography and satellite imagery were developed for selected years in order to identify irrigated areas from which the magnitude of ground-water development could be approximated.

B.3 METHODS

A record of ground-water production for each basin within the model boundary was developed for the period 1945 to 2000 based on the data and informational sources noted in the previous section. Since few recorded data are available for the years prior to 1987, information garnered from literature review and the interview process, land-use maps, aerial photography, and satellite

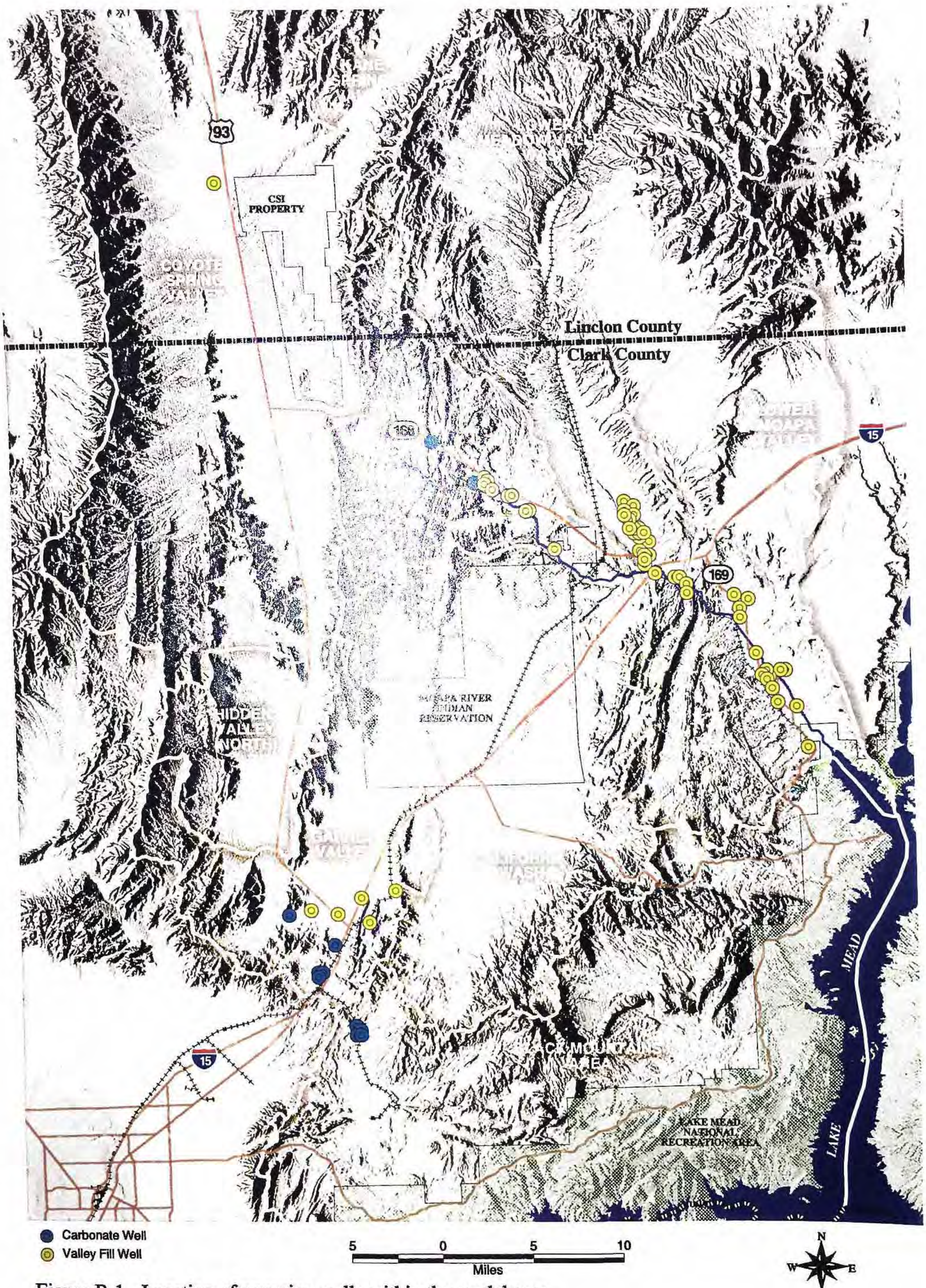

Figure B-1. Location of pumping wells within the model area.

imagery was relied upon to construct the records. The methods employed for each basin are discussed in detail in the following sections.

B.3.1 Black Mountains Area and Garnet Valley

Ground-water development in these basins began in earnest in the early 1990s to support various industrial and mining operations. The principal ground-water user in the Black Mountains Area is the Nevada Cogeneration Associates plant, and the principal users in Garnet Valley are the Chemical Lime Company, Georgia Pacific Corporation, Great Star Cement Corporation, and Republic Environmental Technologies. These users accounted for approximately 2,600 acre-feet of ground-water production in 2000.

Abstracts from NDWR's Water Rights Database were used to identify permitted rights within each basin. To construct the development history of these rights, ground-water production records were requested from NDWR. NDWR provided copies of these records for selected wells. For other wells that are known to exist in the area, information garnered from interviews with Mr. Robert Coache (Chief Engineer, NDWR) was used to estimate the extent to which the permitted rights have been developed.

B.3.2 California Wash, Coyote Spring and Hidden Valleys

California Wash, Coyote Spring and Hidden Valleys remain essentially undeveloped; however numerous ground-water permit applications have been filed with the Nevada State Engineer for proposed projects located within these basins. To date, no appreciable development has occurred.

B.3.3 Lower Meadow Valley Wash

In the southern section of Lower Meadow Valley Wash, ground water has historically been used for crop irrigation that has been generally confined to the flood plain of Lower Meadow Valley Wash. Based on interpretations of aerial photography acquired for year 2000, approximately 792 acres of cropland was irrigated in this section of the basin. Using a consumptive rate of 5 feet per acre, first published by Eakin (1964) for agriculture in the Muddy River Springs area, an estimated 3,960 acre-feet of ground water were applied in 2000. In order to distribute this quantity spatially, the volume was divided equally amongst permitted wells located on or near the irrigated fields. It was assumed that the consumptive use applied to the wells remained constant to the date the well was constructed.

In the early 1980s, NPC constructed wells at the southern tip of the basin in an effort to develop additional ground-water resources for use at their Reid Gardner facility. These wells were pumped extensively for a brief period in the early 1980s, coincident with the activation the fourth generating unit in 1983, but production was reduced in 1988 due to excessive declines in water levels and water quality (Mifflin, oral. commun. 03/2001). The annual ground-water production was reduced to approximately 310,000 gallons in 1989 as reported by Pohlmann et al. (1990, p.9). Only a negligible amount of ground water has been produced from these wells since 1990.

In the northern portions of Lower Meadow Valley Wash, above Farrier, agricultural uses are assumed to be supplied principally by surface water flowing in the wash. It is acknowledged that ground-water pumping occurs minimally in this area, but since records are non-existent or unavailable, it is assumed to be negligible for the purposes of this study.

B.3.4 Lower Moapa Valley

Records of ground-water production for this basin are either unavailable or do not exist, and therefore had to be estimated based on information garnered from the interview process. According to MVWD (03/2001, oral. commun.), ground-water development has generally been limited to selected wells located in the valley that have been used to supply water to meet peak agricultural demands during the summer months when diversions from the Muddy River have been either insufficient or untimely. Ground-water development was at its maximum between 1970 and the late-1980s, after which it began to decrease as agricultural lands were replaced with housing developments. This trend has continued to the present, and ground-water development is now much less prevalent.

The ground-water production record for this basin was developed based on an estimated consumptive use rate of 5-6 cfs for four months out of the year (MVWD, 03/2001, oral commun.). An average rate of 5.5 cfs equates to approximately 1,325 afy, which was distributed by dividing the volume equally amongst 21 permitted wells located in the valley in 1988. It was assumed that the consumptive use applied to the wells remained constant from the date the well was constructed. After 1988, the consumptive-use rate applied to each well was reduced to account for an observed increase in housing development and reduced irrigated acreage. It is assumed in the record that by 1991 the maximum consumptive use that occurred in the late-1980s had been reduced by 66 percent to account for changes in land use from agriculture to housing developments.

B.3.5 Muddy River Springs Area

Few records of ground-water production in the Muddy River Springs area existed prior to 1989 when Nevada Power Company first established their ground-water-monitoring program for the area. However, it is known that the first well was completed in the area in 1947 (NDWR Well Log Database) and it is assumed, for the purposes of this study, that little to no ground water had been developed prior to this time. After 1947, ground water was developed primarily for agricultural purposes. Eakin (1964) first estimated that 2,000 to 3,000 afy were used to irrigate 400 to 500 acres in the Muddy River Springs area prior to 1964. By 1965, NPC completed construction of its Reid Gardner facility and had acquired water rights in the Muddy River Springs area through the purchase of the Lewis wells. NPC continues to be the primary user of ground water in the area. For this report, data compilation focuses primarily on NPC and MVWD since they have been, and continue to be, the principal users of ground water in the area. It is acknowledged that there have been, and still are, other minor uses of ground water within the area. However, since these uses are small and no records exist to determine the exact amount, they were not accounted for in this study.

B.3.5.1 Nevada Power Company

Maxey et al. (1966) reported that NPC pumped 1,931 afy in 1962 and 1,681 afy in 1963 from their Lewis well field. They also reported that the total volume pumped in 1962 was the largest on record at that time, suggesting that although the area had been extensively developed for agricultural purposes, the annual production had not exceeded 1,931 afy prior to 1962. Ground-water production records for the period 1964 to 1986 either do not exist or are unavailable, and therefore had to be estimated.

Table B-1 provides data reported to the Nevada State Engineer by NPC for the period 1987 to 2000, and ground-water production estimates for the period 1945 to 1986. Included in **Table B-1** are reported NPC Muddy River diversions for the periods 1978 to 1985 (USGS, Water Resources Data for Nevada) and 1988 to 2000 (NPC), and estimated diversions for the periods 1965 to 1977 and 1986 to 1987.

The estimated values for NPC Muddy River diversions and ground-water production are based on an assumed total water demand related to the total generating capacity of the Reid Gardner facility. According to the 1994 NPC Re-filed Resource Plan, the facility's four generating units came on-line in 1965, 1968, 1976, and 1983 with the following generating capacities: No.1 110 megawatts (MW), No.2 110 MW, No.3 110 MW, and No.4 255 MW. The generating capacity of the Reid Gardner facility for the period 1989 to 2000 is estimated to have been 605 MW, during which time the average annual water use was 7,366 afy. This equates to approximately 12 acre-feet per megawatt generating capacity. Knowing the generating capacity and date each unit came on-line, this factor can then be used to estimate NPC's annual water demand for the period 1965 to 1986 by multiplying it by the generating capacity estimated for each year. NPC's annual ground-water demand can be approximated for this period by subtracting their annual surface-water diversions from their estimated annual water demand. This method takes into account typical facility operations and maintenance schedules.

Abstracts from NDWR's Water Rights Database were reviewed to develop a history of the ground-water and surface-water rights within the Muddy River Springs area. This information was used to distribute NPC's approximated annual ground-water demand to the wells listed in **Table B-1.**

B3.5.2 Moapa Valley Water District

MVWD has used ground water pumped from the Muddy River Springs area to supplement its spring diversions since 1986. In 1986, MVWD completed construction of water storage tanks and began pumping ground water from the MX-6 well to meet peak demand during four summer months (MVWD, 3/26/01, oral. commun.) MVWD estimates that from 1986 to 1992 the MX-6 well was pumped an average of 450 gpm, or approximately 245 afy. In January 1991, MVWD completed the Arrow Canyon well. Although, the well was pumped for hydraulic testing during 1991, it was not until 1992 that the well was pumped for water supply purposes. In 1992, MVWD estimates that an estimated 531 acre-feet was pumped from the well. **Table B-2** provides data reported by MVWD for the period 1993 to 2000. Included in **Table B-2** are estimates of annual ground-water withdrawals by MVWD from 1986 to 1992.

B.5 GROUND-WATER PRODUCTION DATA SET

The ground-water development history discussed in the preceding section was used to develop a data set for input into the ground-water flow model for the period 1945 to 2000. The data set is provided in **Table B-3.**

Table B-1. Estimated and reported NPC ground-water production in the Muddy River. Springs area for the period 1945 to 2000, in acre-feet per year

	NPC WATER DEMAND		SURFACE DIVERSIONS		NPC GROUND-WATER PRODUCTION				
YEAR	NPC GENERATING CAPACITY	ESTIMATED NPC WATER DEMAND[1]	MUDDY RIVER DIVERSION[2]	APPROX. NPC GROUNDWATER DEMAND[3]	BEHMER[4]	PERKINS[4]	LEWIS WELLS[5]	LDS WELLS[4]	LOWER MEADOW VALLEY WASH[6]
1945	0	0		0	0	0	0		0
1946	0	0		0	0	0	0		0
1947	0	0		0	0	855	0		0
1948	0	0		0	0	855	0		0
1949	0	0		0	0	855	329		0
1950	0	0		0	0	855	658		0
1951	0	0		0	0	855	658		0
1952	0	0		0	0	855	658		0
1953	0	0		0	0	855	658		0
1954	0	0		0	0	855	987		0
1955	0	0		0	0	855	987		0
1956	0	0		0	0	855	987		0
1957	0	0		0	0	855	987		0
1958	0	0		0	0	855	987		0
1959	0	0		0	0	855	1316		0
1960	0	0		0	0	855	1316		0
1961	0	0		0	0	855	1316		0
1962	0	0		0	0	855	1931		0
1963	0	0		0	0	855	1681		0
1964	0	0		0	0	855	1645		0
1965	110	1320	0	1320	0	855	1645		0
1966	110	1320	0	1320	0	855	1645		0
1967	110	1320	0	1320	0	855	1645		0
1968	220	2640	1200	1440	0	855	1440		0
1969	220	2640	2000	640	0	855	640		0
1970	220	2640	2000	640	0	855	640		0
1971	220	2640	2000	640	0	855	640		0
1972	220	2640	2000	640	0	855	640		0
1973	220	2640	2000	640	0	855	640		0
1974	220	2640	2000	640	0	855	640		0
1975	220	2640	2000	640	200	855	500		0
1976	330	3960	2900	1060	300	855	800		0
1977	330	3960	2900	1060	300	855	800		0
1978	330	3960	2890	1070	300	855	800		0
1979	330	3960	2899	1061	300	855	800		0
1980	330	3960	2347	1613	400	855	1200		0
1981	330	3960	2805	1155	400	855	800		0
1982	330	3960	2752	1208	400	855	900		0
1983	605	7260	1885	5375	628	855	2400		2347
1984	605	7260	1720	5540	628	855	2400		2512
1985	605	7260	2731	4529	628	855	2400		1501
1986	605	7260	2000	5260	628	855	2400		1377
1987	605	7260	3000	4260	0	816	1188	300	1956
1988	605	7260	2164	5096	33	910	1524	1842	787
1989	605	7260	2012	5248	834	910	1679	1691	1
1990	605	7260	3526	3734	0	834	1476	1501	0

Table B-1. Estimated and reported NPC ground-water production in the Muddy River. Springs area for the period 1945 to 2000, in acre-feet per year

	NPC WATER DEMAND		SURFACE DIVERSIONS		NPC GROUND-WATER PRODUCTION				
YEAR	NPC GENERATING CAPACITY	ESTIMATED NPC WATER DEMAND[1]	MUDDY RIVER DIVERSION[2]	APPROX. NPC GROUNDWATER DEMAND[3]	BEHMER[4]	PERKINS[4]	LEWIS WELLS[5]	LDS WELLS[4]	LOWER MEADOW VALLEY WASH[6]
1991	605	*7260*	**3625**	*3635*	**319**	**910**	**1179**	**1309**	**0**
1992	605	*7260*	**2942**	*4318*	**0**	**777**	**1160**	**1413**	**0**
1993	605	*7260*	**2871**	*4389*	**138**	**910**	**1410**	**958**	**0**
1994	605	*7260*	**2462**	*4798*	**0**	**886**	**2075**	**1467**	**0**
1995	605	*7260*	**2950**	*4310*	**0**	**581**	**1299**	**1583**	**0**
1996	605	*7260*	**3219**	*4041*	**224**	**910**	**1522**	**2097**	**0**
1997	605	*7260*	**2494**	*4766*	**0**	**726**	**1195**	**2175**	**0**
1998	605	*7260*	**2296**	*4964*	**0**	**804**	**2259**	**2903**	**0**
1999	605	*7260*	**2585**	*4675*	**0**	**482**	**1876**	**2390**	**0**
2000	605	*7260*	**3063**	*4197*	**573**	**471**	**1736**	**4705**	**0**

Note: Shaded cells represent estimated years in which well(s) was used for agricultural water supply based on abstracts from NDWR Water Rights Database

1. *Demand based on the average annual water demand per megawatt generating capacity during the period 1989 to 2000*
2. *Diversions for 1978 to 1985 reported by USGS; 1988 to 2000 reported by NPC*
3. *Approximated as the difference between the estimated water demand (¹) and Muddy River diversion (²)*
4. *Data from 1987 to 2000 from NPC monitoring reports submitted to Nevada State Engineer's Office; 1945 to 1986 estimated data based abstracts from NDWR Water Rights Database*
5. *Data from 1962 and 1963 from Maxey et al. (1966); Data from 1987 to 2000 from NPC Hydrologic Impacts reports; stimated data based abstracts from NDWR Water Rights Database*
6. *Data from 1982 to 1988 estimated as the volume of water needed by NPC, in addition to other the sources, to meet their estimated water demand (¹)*

Table B-2. Estimated and reported MVWD ground-water production in the Muc River Springs area for the period 1986 to 2000, in acre-feet per year

Year	MX-6	Arrow Canyon	Total
1986	245	-	245
1987	245	-	245
1988	245	-	245
1989	245	-	245
1990	245	-	245
1991	245	0	245
1992	245	513	758
1993	141	1,204	1,345
1994	390	504	894
1995	374	304	678
1996	431	274	705
1997	307	501	808
1998	40	1,517	1,557
1999	145	2,434	2,579
2000	130	2,777	2,908

Sources: 1986 to 1992 estimates based on MVWD interviews (MVWD, oral commun., 03/2001)
1993 to 1996 NPC Hydrologic Impacts reports
1997 to 2000 MVWD Muddy Springs Area Monitoring Reports

Table B-3. Ground-water production data set as used in the ground-water flow model.

WELL_ID	OWNER/OPERATOR	UTM_X	UTM_Y	DATE COMPLETED	ELEV	HSU	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955
MUDDY SPRINGS AREA							0	0	855	855	1184	1513	1513	1513	1513	1842	1842
ARROW_CANYON	MVWD	701233	4067521	01/25/91	1875	C											
LEWIS-1	NEVADA POWER COMPANY	702136	4068021	05/16/49	1828	VF					329	329	329	329	329	329	329
LEWIS-3	NEVADA POWER COMPANY	702424	4067549	05/15/62	1827	VF											
LEWIS-2	NEVADA POWER COMPANY	702409	4067707	07/15/59	1821	VF											
LEWIS-5	NEVADA POWER COMPANY	702248	4067290	02/16/54	1822	VF										329	329
LEWIS-4	NEVADA POWER COMPANY	702104	4067418	06/07/50	1822	VF						329	329	329	329	329	329
LDS-WEST	NEVADA POWER COMPANY	702799	4066922	1986	1787	VF											
LDS-CENTRAL	NEVADA POWER COMPANY	704189	4066366	1986	1811	VF											
LDS-EAST	NEVADA POWER COMPANY	704537	4066400	1986	1715	VF											
MX-6	MVWD	697525	4071193	05/21/81	2275	C											
BEHMER	NEVADA POWER COMPANY	706031	4065080			VF											
NPC-PP	NEVADA POWER COMPANY	705735	4065016	06/16/88	1771	VF			855	855	855	855	855	855	855	855	855
LOWER MOAPA VALLEY							0	0	0	0	0	0	0	0	0	0	0
MV-2	NEVADA POWER COMPANY	716092	4061037	08/27/62	1538	VF											
73		718701	4059068	10/12/71	1524	VF											
MV-7	LEWIS, PAUL	719123	4059078	05/31/60	1552	VF											
MV-3	EWING, JAMES L	716113	4060205	02/15/80	1544	VF											
MV-5	C X PRODUCTS CORP	717002	4059425	11/26/73	1565	VF											
MV-9	LEWIS, PAUL R & PATRICIA	719735	4058477	01/11/75	1540	VF											
MV-10	LEWIS, PAUL R & PATRICIA	719755	4057676	01/11/75	1496	VF											
MV-12	LAS VEGAS CEMENT	724010	4057508	11/18/85	1500	VF											
MV-16	FAY, BOB	725237	4057139	07/15/80	1466	VF											
MV-13	STREET, KEVIN	724463	4056317	02/10/97	1431	VF											
MV-14	MOAPA VALLEY WATER CO	724484	4055516	04/24/67	1415	VF											
MV-21	ROBINSON, L H	725836	4052344	07/01/67	1367	VF											
MV-37	STRINGHAM, STANLEY	728364	4050807	02/12/78	1368	VF											
85		727941	4050795	03/21/74	1342	VF											
MV-29	HORN, ERIC	726937	4050183	03/18/67	1314	VF											
MV-26	MARSHAL, KARL	726723	4050763	02/11/76	1314	VF											
MV-23	SEBAUGH, FRANK	726311	4050352	02/27/76	1314	VF											
MV-28	METCALF, M B	726744	4049962	12/10/66	1314	VF											
MV-30	LAHM, ROBERT LEE & EVELYN	727188	4049172	05/05/73	1304	VF											
MV-33	PERKINS, W V	727643	4047950	09/26/74	1288	VF											
MV-40	MOAPA VALLEY DAIRY FARMS	729295	4047593	03/23/88	1250	VF											
MV-42	SIMPLOT SILICON PRODUCTS	730213	4043978	05/25/76	1292	VF											
37	MVWD-1	724484	4055516	04/24/67	1415	VF											
LOWER MEADOW VALLEY WASH							0	0	0	0	0	0	0	0	0	0	0
LMVW-72	NEVADA POWER COMPANY	715252	4063822	12/31/63	1564	VF											
LMVW-75	NEVADA POWER COMPANY	716086	4062240	09/30/81	1552	VF											
LMVW-76	NEVADA POWER COMPANY	716508	4062250	11/01/63	1541	VF											
LMVW-14	NEVADA POWER COMPANY	716514	4061048	08/27/62	1532	VF											
LMVW-34	LEWIS, PAUL	715669	4063031	11/1/1971	1573	VF											
LMVW-41	WHITNEY, R C	715684	4061428	11/13/1996	1545	VF											
135	PERKINS, ROBERT	708203	4061613	1/9/1975	1660	VF											
LMVW-49	MEADOW VALLEY FARMLAND IRR CO	714407	4065806	3/25/1988	1587	VF											
LMVW-50	MEADOW VALLEY FARMLAND IRR CO	715236	4065425	2/25/1988	1584	VF											
LMVW-53	SCHLARMAN, HENRY T	715659	4063432	4/23/1971	1566	VF											
LMVW-56	HENRIE, PAUL	714402	4065004	3/1/1969	1583	VF											
LMVW-57	MEADOW VALLEY FARMLAND IRR CO	715231	4064624	3/3/1988	1561	VF											
LMVW-60	LEWIS, PAUL	715679	4062630	2/12/1974	1577	VF											
LMVW-64	EMBRY, MILTON	715247	4063020	9/13/1974	1609	VF											
LMVW-66	LEAVITT, GARY & DIANE	716092	4061037	4/1/1974	1538	VF											
LMVW-67	STEWART, MARK	715669	4063031	11/1/1971	1573	VF											
LMVW-68	PERKINS, ROBERT	715237	4063421	9/28/1971	1586	VF											
LMVW-70	LEWIS, PAUL	716102	4060636	2/19/1974	1538	VF											
LMVW-71	MCKNIGHT, JAMES D	714820	4064212	3/1/1969	1564	VF											
LMVW-74	HENRIE, PAUL	714412	4064603	3/1/1969	1574	VF											
163	STEWART, MARK	716091	4063042	2/28/1977	1565	VF											
164	CUTLER, KEITH	714840	4063411	3/18/1970	1593	VF											
GARNET VALLEY							0	0	0	0	0	0	0	0	0	0	0
46	U S LIME	685798	4029433	06/17/71	2273	VF											
47	U S LIME	688174	4029084	07/22/71	2155	VF											
GV-KERR-1	KERR-MCGEE CHEMICAL CORP	683838	4028991	02/07/90	2405	C											
49	GEORGIA PACIFIC CORP	686317	4023833	10/23/92	2464	C											
50	GEORGIA PACIFIC CORP	686716	4023842	08/19/90	2415	C											
51	GEORGIA PACIFIC CORP	686326	4023432	09/30/86	2455	C											
GV-GSC-1	GREAT STAR CEMENT CORP	693337	4031201	03/30/87	2293	VF											
GV-USLIME-1	U S LIME	690310	4030549	09/13/63	2073	VF											
GV-ET-1	ENVIRONMENTAL TECHNOLOGIES	690982	4028343	03/23/89	2321	VF											
202	U S LIME	687850	4026300	06/01/99		C											
BLACK MOUNTAINS							0	0	0	0	0	0	0	0	0	0	0
60	BONNEVILLE ENERGY	689589	4019063	12/24/91	2485	C											
BM-BE-2	BONNEVILLE ENERGY	689997	4018671	12/30/91	2434	C											
BM-BE-3	BONNEVILLE ENERGY	689606	4018262	08/16/91	2391	C											
BM-BE-1	BONNEVILLE ENERGY	690006	4018271	06/12/90	2442	C											

Table B-3. Ground-water production data set as used in the ground-water flow model.

WELL_ID	OWNER/OPERATOR	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
MUDDY SPRINGS AREA		1842	1842	1842	2171	2171	2171	2786	2536	2500	2500	2500	2500	2295	1495	1495	1495	1495	1495
ARROW_CANYON	MVWD																		
LEWIS-1	NEVADA POWER COMPANY	329	329	329	329	329	329	386	336	329	329	329	329	288	128	128	128	128	128
LEWIS-3	NEVADA POWER COMPANY							386	336	329	329	329	329	288	128	128	128	128	128
LEWIS-2	NEVADA POWER COMPANY				329	329	329	386	336	329	329	329	329	288	128	128	128	128	128
LEWIS-5	NEVADA POWER COMPANY	329	329	329	329	329	329	386	336	329	329	329	329	288	128	128	128	128	128
LEWIS-4	NEVADA POWER COMPANY	329	329	329	329	329	329	386	336	329	329	329	329	288	128	128	128	128	128
LDS-WEST	NEVADA POWER COMPANY																		
LDS-CENTRAL	NEVADA POWER COMPANY																		
LDS-EAST	NEVADA POWER COMPANY																		
MX-6	MVWD																		
BEHMER	NEVADA POWER COMPANY																		
NPC-PP	NEVADA POWER COMPANY	855	855	855	855	855	855	855	855	855	855	855	855	855	855	855	855	855	855
LOWER MOAPA VALLEY		0	0	0	0	63	63	126	126	126	126	189	378	378	378	378	441	441	567
MV-2	NEVADA POWER COMPANY							63	63	63	63	63	63	63	63	63	63	63	63
73																	63	63	63
MV-7	LEWIS, PAUL					63	63	63	63	63	63	63	63	63	63	63	63	63	63
MV-3	EWING, JAMES L																		
MV-5	C X PRODUCTS CORP																		63
MV-9	LEWIS, PAUL R & PATRICIA																		
MV-10	LEWIS, PAUL R & PATRICIA																		
MV-12	LAS VEGAS CEMENT																		
MV-16	FAY, BOB																		
MV-13	STREET, KEVIN																		
MV-14	MOAPA VALLEY WATER CO												63	63	63	63	63	63	63
MV-21	ROBINSON, L H												63	63	63	63	63	63	63
MV-37	STRINGHAM, STANLEY																		
85																			
MV-29	HORN, ERIC												63	63	63	63	63	63	63
MV-26	MARSHAL, KARL																		
MV-23	SEBAUGH, FRANK																		
MV-28	METCALF, M B											63	63	63	63	63	63	63	63
MV-30	LAHM, ROBERT LEE & EVELYN																		63
MV-33	PERKINS, W V																		
MV-40	MOAPA VALLEY DAIRY FARMS																		
MV-42	SIMPLOT SILICON PRODUCTS																		
37	MVWD-1												0	0	0	0	0	0	0
LOWER MEADOW VALLEY WASH		0	0	0	0	0	0	0	0	0	0	0	0	0	660	880	1760	1760	1760
LMVW-72	NEVADA POWER COMPANY																		
LMVW-75	NEVADA POWER COMPANY																		
LMVW-76	NEVADA POWER COMPANY																		
LMVW-14	NEVADA POWER COMPANY																		
LMVW-34	LEWIS, PAUL																		
LMVW-41	WHITNEY, R C																220	220	220
135	PERKINS, ROBERT																		
LMVW-49	MEADOW VALLEY FARMLAND IRR CO																		
LMVW-50	MEADOW VALLEY FARMLAND IRR CO																		
LMVW-53	SCHLARMAN, HENRY T																		
LMVW-56	HENRIE, PAUL																220	220	220
LMVW-57	MEADOW VALLEY FARMLAND IRR CO														220	220	220	220	220
LMVW-60	LEWIS, PAUL																		
LMVW-64	EMBRY, MILTON																		
LMVW-66	LEAVITT, GARY & DIANE																		
LMVW-67	STEWART, MARK																		
LMVW-68	PERKINS, ROBERT																220	220	220
LMVW-70	LEWIS, PAUL																220	220	220
LMVW-71	MCKNIGHT, JAMES D																		
LMVW-74	HENRIE, PAUL														220	220	220	220	220
163	STEWART, MARK														220	220	220	220	220
164	CUTLER, KEITH															220	220	220	220
GARNET VALLEY		0	0	0	0	0	0	0	50	50	50	50	50	50	50	50	150	150	150
46	U S LIME																		
47	U S LIME																50	50	50
GV-KERR-1	KERR-MCGEE CHEMICAL CORP																50	50	50
49	GEORGIA PACIFIC CORP																		
50	GEORGIA PACIFIC CORP																		
51	GEORGIA PACIFIC CORP																		
GV-GSC-1	GREAT STAR CEMENT CORP																		
GV-USLIME-1	U S LIME																		
GV-ET-1	ENVIRONMENTAL TECHNOLOGIES								50	50	50	50	50	50	50	50	50	50	50
202	U S LIME																		
BLACK MOUNTAINS		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	BONNEVILLE ENERGY																		
BM-BE-2	BONNEVILLE ENERGY																		
BM-BE-3	BONNEVILLE ENERGY																		
BM-BE-1	BONNEVILLE ENERGY																		

Table B-3. Ground-water production data set as used in the ground-water flow model.

WELL_ID	OWNER/OPERATOR	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
MUDDY SPRINGS AREA		1495	1555	1955	1955	1955	1955	2455	2055	2155	3883	3883	3883	4128	2249	4554	5359
ARROW_CANYON	MVWD																
LEWIS-1	NEVADA POWER COMPANY	128	100	160	160	160	160	240	160	180	480	480	480	480	238	305	336
LEWIS-3	NEVADA POWER COMPANY	128	100	160	160	160	160	240	160	180	480	480	480	480	238	305	336
LEWIS-2	NEVADA POWER COMPANY	128	100	160	160	160	160	240	160	180	480	480	480	480	238	305	336
LEWIS-5	NEVADA POWER COMPANY	128	100	160	160	160	160	240	160	180	480	480	480	480	238	305	336
LEWIS-4	NEVADA POWER COMPANY	128	100	160	160	160	160	240	160	180	480	480	480	480	238	305	336
LDS-WEST	NEVADA POWER COMPANY															614	564
LDS-CENTRAL	NEVADA POWER COMPANY															614	564
LDS-EAST	NEVADA POWER COMPANY															614	564
MX-6	MVWD								0	0	0	0	0	245	245	245	245
BEHMER	NEVADA POWER COMPANY		200	300	300	300	300	400	400	400	628	628	628	628	0	33	834
NPC-PP	NEVADA POWER COMPANY	855	855	855	855	855	855	855	855	855	855	855	855	855	816	910	910
LOWER MOAPA VALLEY		819	819	1008	1008	1071	1071	1197	1197	1197	1197	1197	1260	1260	1260	1323	1102
MV-2	NEVADA POWER COMPANY	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
73		63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-7	LEWIS, PAUL	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-3	EWING, JAMES L							63	63	63	63	63	63	63	63	63	52
MV-5	C X PRODUCTS CORP	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-9	LEWIS, PAUL R & PATRICIA	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-10	LEWIS, PAUL R & PATRICIA	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-12	LAS VEGAS CEMENT												63	63	63	63	52
MV-16	FAY, BOB							63	63	63	63	63	63	63	63	63	52
MV-13	STREET, KEVIN																
MV-14	MOAPA VALLEY WATER CO	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-21	ROBINSON, L H	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-37	STRINGHAM, STANLEY					63	63	63	63	63	63	63	63	63	63	63	52
85		63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-29	HORN, ERIC	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-26	MARSHAL, KARL			63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-23	SEBAUGH, FRANK			63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-28	METCALF, M B	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-30	LAHM, ROBERT LEE & EVELYN	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-33	PERKINS, W V	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	52
MV-40	MOAPA VALLEY DAIRY FARMS															63	52
MV-42	SIMPLOT SILICON PRODUCTS			63	63	63	63	63	63	63	63	63	63	63	63	63	52
37	MVWD-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOWER MEADOW VALLEY WASH		2640	2860	2860	3080	3080	3080	3080	3080	3080	5427	5592	4581	4457	5036	4527	3874
LMVW-72	NEVADA POWER COMPANY										587	628	375	344	489	197	33
LMVW-75	NEVADA POWER COMPANY										587	628	375	344	489	197	33
LMVW-76	NEVADA POWER COMPANY										587	628	375	344	489	197	33
LMVW-14	NEVADA POWER COMPANY										587	628	375	344	489	197	33
LMVW-34	LEWIS, PAUL	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-41	WHITNEY, R C																
135	PERKINS, ROBERT		220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-49	MEADOW VALLEY FARMLAND IRR CO															220	220
LMVW-50	MEADOW VALLEY FARMLAND IRR CO															220	220
LMVW-53	SCHLARMAN, HENRY T	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-56	HENRIE, PAUL	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-57	MEADOW VALLEY FARMLAND IRR CO															220	220
LMVW-60	LEWIS, PAUL	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-64	EMBRY, MILTON	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-66	LEAVITT, GARY & DIANE	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-67	STEWART, MARK	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-68	PERKINS, ROBERT	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-70	LEWIS, PAUL	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-71	MCKNIGHT, JAMES D	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
LMVW-74	HENRIE, PAUL	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
163	STEWART, MARK				220	220	220	220	220	220	220	220	220	220	220	220	220
164	CUTLER, KEITH	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220	220
GARNET VALLEY		150	150	150	150	150	150	150	150	150	150	150	150	200	378	378	446
46	U S LIME	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
47	U S LIME	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
GV-KERR-1	KERR-MCGEE CHEMICAL CORP																
49	GEORGIA PACIFIC CORP																
50	GEORGIA PACIFIC CORP																
51	GEORGIA PACIFIC CORP													50	50	50	50
GV-GSC-1	GREAT STAR CEMENT CORP														178	178	178
GV-USLIME-1	U S LIME	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
GV-ET-1	ENVIRONMENTAL TECHNOLOGIES																68
202	U S LIME																
BLACK MOUNTAINS		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	BONNEVILLE ENERGY																
BM-BE-2	BONNEVILLE ENERGY																
BM-BE-3	BONNEVILLE ENERGY																
BM-BE-1	BONNEVILLE ENERGY																

Table B-3. Ground-water production data set as used in the ground-water flow model.

WELL_ID	OWNER/OPERATOR	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
MUDDY SPRINGS AREA		4056	3963	4109	4762	5322	4142	5458	4904	7524	7327	10393
ARROW_CANYON	MVWD		0	513	1204	504	304	274	501	1517	2434	2777
LEWIS-1	NEVADA POWER COMPANY	295	236	232	282	415	260	304	239	452	375	275
LEWIS-3	NEVADA POWER COMPANY	295	236	232	282	415	260	304	239	452	375	468
LEWIS-2	NEVADA POWER COMPANY	295	236	232	282	415	260	304	239	452	375	317
LEWIS-5	NEVADA POWER COMPANY	295	236	232	282	415	260	304	239	452	375	427
LEWIS-4	NEVADA POWER COMPANY	295	236	232	282	415	260	304	239	452	375	249
LDS-WEST	NEVADA POWER COMPANY	500	437	471	319	489	528	699	725	968	797	2622
LDS-CENTRAL	NEVADA POWER COMPANY	500	437	471	319	489	528	699	725	968	797	967
LDS-EAST	NEVADA POWER COMPANY	500	437	471	319	489	528	699	725	968	797	1116
MX-6	MVWD	245	245	245	141	390	374	431	307	40	145	130
BEHMER	NEVADA POWER COMPANY	0	319	0	138	0	0	224	0	0	0	573
NPC-PP	NEVADA POWER COMPANY	834	910	777	910	886	581	910	726	804	482	471
LOWER MOAPA VALLEY		881	441	441	441	552	517	569	462	462	462	462
MV-2	NEVADA POWER COMPANY	42	21	21	21	21	21	21	21	21	21	21
73		42	21	21	21	21	21	21	21	21	21	21
MV-7	LEWIS, PAUL	42	21	21	21	21	21	21	21	21	21	21
MV-3	EWING, JAMES L	42	21	21	21	21	21	21	21	21	21	21
MV-5	C X PRODUCTS CORP	42	21	21	21	21	21	21	21	21	21	21
MV-9	LEWIS, PAUL R & PATRICIA	42	21	21	21	21	21	21	21	21	21	21
MV-10	LEWIS, PAUL R & PATRICIA	42	21	21	21	21	21	21	21	21	21	21
MV-12	LAS VEGAS CEMENT	42	21	21	21	21	21	21	21	21	21	21
MV-16	FAY, BOB	42	21	21	21	21	21	21	21	21	21	21
MV-13	STREET, KEVIN								21	21	21	21
MV-14	MOAPA VALLEY WATER CO	42	21	21	21	21	21	21	21	21	21	21
MV-21	ROBINSON, L H	42	21	21	21	21	21	21	21	21	21	21
MV-37	STRINGHAM, STANLEY	42	21	21	21	21	21	21	21	21	21	21
85		42	21	21	21	21	21	21	21	21	21	21
MV-29	HORN, ERIC	42	21	21	21	21	21	21	21	21	21	21
MV-26	MARSHAL, KARL	42	21	21	21	21	21	21	21	21	21	21
MV-23	SEBAUGH, FRANK	42	21	21	21	21	21	21	21	21	21	21
MV-28	METCALF, M B	42	21	21	21	21	21	21	21	21	21	21
MV-30	LAHM, ROBERT LEE & EVELYN	42	21	21	21	21	21	21	21	21	21	21
MV-33	PERKINS, W V	42	21	21	21	21	21	21	21	21	21	21
MV-40	MOAPA VALLEY DAIRY FARMS	42	21	21	21	21	21	21	21	21	21	21
MV-42	SIMPLOT SILICON PRODUCTS	42	21	21	21	21	21	21	21	21	21	21
37	MVWD-1	0	0	0	0	112	77	129	0	0	0	0
LOWER MEADOW VALLEY WASH		3740	3740	3740	3740	3740	3740	3960	3960	3960	3960	3960
LMVW-72	NEVADA POWER COMPANY	0	0	0	0	0	0	0	0	0	0	0
LMVW-75	NEVADA POWER COMPANY	0	0	0	0	0	0	0	0	0	0	0
LMVW-76	NEVADA POWER COMPANY	0	0	0	0	0	0	0	0	0	0	0
LMVW-14	NEVADA POWER COMPANY	0	0	0	0	0	0	0	0	0	0	0
LMVW-34	LEWIS, PAUL	220	220	220	220	220	220	220	220	220	220	220
LMVW-41	WHITNEY, R C							220	220	220	220	220
135	PERKINS, ROBERT	220	220	220	220	220	220	220	220	220	220	220
LMVW-49	MEADOW VALLEY FARMLAND IRR CO	220	220	220	220	220	220	220	220	220	220	220
LMVW-50	MEADOW VALLEY FARMLAND IRR CO	220	220	220	220	220	220	220	220	220	220	220
LMVW-53	SCHLARMAN, HENRY T	220	220	220	220	220	220	220	220	220	220	220
LMVW-56	HENRIE, PAUL	220	220	220	220	220	220	220	220	220	220	220
LMVW-57	MEADOW VALLEY FARMLAND IRR CO	220	220	220	220	220	220	220	220	220	220	220
LMVW-60	LEWIS, PAUL	220	220	220	220	220	220	220	220	220	220	220
LMVW-64	EMBRY, MILTON	220	220	220	220	220	220	220	220	220	220	220
LMVW-66	LEAVITT, GARY & DIANE	220	220	220	220	220	220	220	220	220	220	220
LMVW-67	STEWART, MARK	220	220	220	220	220	220	220	220	220	220	220
LMVW-68	PERKINS, ROBERT	220	220	220	220	220	220	220	220	220	220	220
LMVW-70	LEWIS, PAUL	220	220	220	220	220	220	220	220	220	220	220
LMVW-71	MCKNIGHT, JAMES D	220	220	220	220	220	220	220	220	220	220	220
LMVW-74	HENRIE, PAUL	220	220	220	220	220	220	220	220	220	220	220
163	STEWART, MARK	220	220	220	220	220	220	220	220	220	220	220
164	CUTLER, KEITH	220	220	220	220	220	220	220	220	220	220	220
GARNET VALLEY		496	497	547	549	553	549	542	523	578	717	952
46	U S LIME	50	50	50	50	50	50	50	50	50		
47	U S LIME	50	50	50	50	50	50	50	50	50		
GV-KERR-1	KERR-MCGEE CHEMICAL CORP	0	1	1	2	7	3	0	0	9	4	4
49	GEORGIA PACIFIC CORP			50	50	45	45					
50	GEORGIA PACIFIC CORP	50	50	50	50	65	65	145	126	131	149	150
51	GEORGIA PACIFIC CORP	50	50	50	50	40	40					
GV-GSC-1	GREAT STAR CEMENT CORP	178	178	178	178	178	178	178	178	178	178	178
GV-USLIME-1	U S LIME	50	50	50	50	50	50	50	50	50		
GV-ET-1	ENVIRONMENTAL TECHNOLOGIES	68	68	68	68	68	68	68	68	111	386	470
202	U S LIME										150	150
BLACK MOUNTAINS		0	0	582	1400	1563	1528	1613	1429	1408	1569	1693
60	BONNEVILLE ENERGY			194	350	391	382	403	357	352	392	423
BM-BE-2	BONNEVILLE ENERGY			194	350	391	382	403	357	352	392	423
BM-BE-3	BONNEVILLE ENERGY			194	350	391	382	403	357	352	392	423
BM-BE-1	BONNEVILLE ENERGY				350	391	382	403	357	352	392	423

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Ex. 55 Errata

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Ex. 55 Sorata