Case No. 84739

IN THE SUPREME COURT OF THE STATE OF NEVADA

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

Appellants,

vs.

LINCOLN COUNTY WATER DISTRICT, et al.

JOINT APPENDIX

VOLUME 33 OF 49

USGS
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Geologic Map of Nevada

By A. Elizabeth Jones Crafford[1]

With a section on A Digital Conodont Database of Nevada
By Anita G. Harris[2] and A. Elizabeth Jones Crafford[1]

Prepared in cooperation with the Nevada Bureau of Mines and Geology

Pamphlet to accompany Data Series 249

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U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2007
Version 1.0

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Suggested citation:
Crafford, A.E.J., 2007, Geologic Map of Nevada: U.S. Geological Survey Data Series 249, 1 CD-ROM, 46 p., 1 plate.

Library of Congress Cataloging-in-Publication Data

Crafford, A. Elizabeth Jones,
Geologic Map of Nevada
p. cm. –(U.S. Geological Survey data series ; 249)
Includes bibliographic references.
1. Geology—Nevada.

ISBN: 978-141131812-0

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By A. Elizabeth Jones Crafford[1]

Introduction

The purpose of the Geologic Map of Nevada is to provide an integrated set of digital geologic information that can be used for regional geologic and rigorous spatial analysis. Two components of this map represent new information that has not been published in this form before. The new geology layer was created by merging into a single file individual digital Nevada county geologic maps (Hess and Johnson, 1997), published at a scale of 1:250,000. A new regional interpretation was created to unify all of the different county rock units, and then appropriate edits and modifications were made to the file to reflect additional geologic information and more current geologic interpretations. All possible sources of information were not utilized in the scope of this project, but rather the goal was to create a consistent Statewide 1:250,000-scale map that would facilitate regional geologic interpretation and be a foundation for future spatial analyses of digital data. Secondly, a new database of conodont biostratigraphic data compiled and analyzed by Anita Harris is also incorporated into the map. Information about many, but not all, of these conodont samples have been published separately elsewhere over the years, but they have not been presented together in a single digital database. Other previously published data layers are used in this map to enhance the usefulness of the geologic information. These layers include mineral deposit locations, oil well locations, and cartographic layers such as county boundaries, roads, towns, cities, rivers, water bodies, township, range and section grids, quadrangle grids, and topography. A summary of these components is given below, and complete descriptions of each layer are provided in the digital metadata.

The Digital Map

The necessary first step to create the Geologic Map of Nevada was creation of digital polygon and line coverages from the original published county geologic maps. This was done by the Nevada Bureau of Mines and Geology (NBMG) in 1996 (Hess and Johnson, 1997). Their careful creation of over 34,000 polygons of geology made possible the next step of integrating together geologic information from the different maps into a new, unified explanation. The 16 different geologic maps were created over a time span of more than 20 years by different people using different geologic standards, but all at a scale of 1:250,000. Remarkably, in spite of the large number of contributors over such a long period of time, the locational accuracy of the basic geologic polygon boundaries are good to excellent, with only a few areas needing significant modification. Interpretations of the units, however, vary significantly, and some required substantial modification on the basis of newer information, ideas, and interpretations. A new regional interpretation of the geology of Nevada is presented with this map and applied to the polygons from the county maps. The interpretation draws on the work of many, including the original State geologic map (Stewart, 1980; Stewart and Carlson, 1978). This new regional interpretation resulted in combining the thousand plus different units used on the county maps into just over 100 Statewide units. In addition to geology polygons, boundaries of the polygons with their attributes and fault traces were combined from the multiple county maps into individual Statewide layers, but they were not edited for this project. The user of the map will benefit greatly from studying the accompanying explanation presented as a separate document "Explanation for Geologic Map of Nevada.pdf."

The benefits of a digital map are many. The user can easily choose layers to turn on or off, modify those layers to suit their needs, and display or print information of particular interest at a particular scale. A digital map also introduces important caveats and responsibilities of which the user must be aware. The only layer of this map that has been spatially edited (the boundaries of the polygons themselves have been altered in some cases, and new polygons have been created) is the geology polygon layer (NevadaGeology.shp). The other two geology layers, the faults layer, and the geologic boundaries layers have not been edited yet to match the new geology polygon boundary layers. Therefore, in places where the geology has been edited, the boundaries of the polygons will *no longer match* the lines associated with the faults layer or the boundaries layer. Additionally, there are cases where one existing polygon was split into numerous pieces to improve either the location or interpretive accuracy of the

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map, with the different pieces being assigned to different units. This procedure results in a more accurate display of the geology, but also introduces spurious boundaries that have no geologic meaning. The boundaries are transparent, but the user needs to be aware that an area of a single geologic unit may be composed of several adjoining polygons. Hopefully a future release of this map will be able to address these challenging issues. These concerns, however, only apply to approximately 10 percent of the polygons on the map, and thus most boundary and fault lines still agree with the geology polygons, and should not affect general use of the map.

When combining layers of data from different sources, such as biostratigraphic or radiometric data with the geologic data, inherent variation of the spatial accuracy of the raw data from the different layers will not always match as expected. Location inaccuracies in point samples, map-scale inaccuracies of geologic polygons, and many other factors make this a significant issue. For this first release of the digital map, geologic and biostratigraphic layers are not all reconciled—in other words, for example, some Devonian conodonts plot in alluvium adjacent to the Devonian rock unit from which they were sampled, not within the boundaries of the polygon as expected. With continued support, resolution of these discrepancies is a primary goal for future releases of the map, so that data will be fully integrated and benefits of an ArcGIS system can be utilized to carry out true spatial analyses of the data. Attributes in both the geology and biostratigraphy layers attempt to document the discrepancies with the future hope of resolving them.

An important benefit of a digital map is that any number of attributes can be attached to any spatial object. This means that information about a specific polygon, such as boundary edits or value changes can easily be attached to that feature to help the user interpret the information. The user should take advantage of the many annotations included as attributes to the individual polygons explaining reference details, discrepancies, and unsolved problems for that particular polygon when interpreting the geology. The metadata that accompanies the geology file (NevadaGeology.shp) has a complete explanation of all the attributes and the meaning of their values.

The only component of the map that is ready for rigorous spatial analysis is the geology polygon layer (NevadaGeology.shp) using the GEOLOGICFM attribute field. If the user wishes to create topology for the file, they will have to input a 0.1 m cluster tolerance in order to have an error free file. Additionally, for conversion to a raster file, grouping of the Quaternary units Qya and Qal will be required to eliminate significant county boundary discontinuities. Other minor discontinuities are discussed in the file metadata.

Components of the Digital Map

To provide context for the geologic information, additional layers of geographic and geologic information are also portrayed on the map. A brief description of each of the map's components is provided below under a heading that matches the folder on the CD that contains the data. A complete listing of the files in each folder is provided in the accompanying Readmefile.txt document. Additional details including descriptions of all the attributes for each data set are provided in the metadata accompanying each data file. To access the digital map and metadata, the user needs ArcGIS 9.x software, and should open the NevadaStateDigitalGeologicMap.mxd file included on the CD-ROM. The map is accessed through ArcMap, and the .xml metadata files can be viewed through ArcCatalog.

Biostratigraphy

The biostratigraphic information presented here consists of 2,617 conodont sample locations from A.G. Harris[2], U.S. Geological Survey (USGS), emeritus in a shapefile called ConodontSamples.shp. They represent samples collected by many individuals over many years, and examined by Anita Harris. Sample locations were provided by Harris and except for a handful have not been verified for this publication. Information about many, but not all, of these samples has been published over the years in various maps and other publications, and references to USGS reports are given in the attribute table. Conodont data are displayed in seventeen different layers in the project. Fifteen layers have data broken out by sample age or age range, and colored by Conodont Color Alteration Index Minimum (CAImin) value. One layer shows samples taken from the subsurface such as drill holes or underground mine workings. Another single layer shows all of the conodonts, not differentiated by time, colored by their CAImin value. Each age or age range has a different color rim on the symbol or a different shape symbol. The CAI color scale used is intended to mimic the actual conodont color. Explanation of all the attributes for the conodont data is provided in the metadata for the file.

Cities

The CITIES_P.shp shapefile provided by the Nevada Bureau of Mines and Geology is a layer showing 101 point locations for Nevada cities and towns at 1:1,000,000 scale.

Contours

The CTOUR2.shp shapefile is a layer consisting of 150 m, 2-arc-second contours that were derived from the DLG map of Nevada, and created at the Nevada Bureau of Mines and Geology by the author and Ron Hess.

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Counties

NEVADACOUNTIES.shp is a shapefile of Nevada counties with the latest boundary locations updated. It was provided by the Nevada Department of Transportation in 2006.

Geology

Three different layers are used for the primary geologic information. All are shapefiles. The geology polygon file, NevadaGeology.shp has attributes to describe each of the polygons used on the map. The geologic boundaries shapefile (StatewideGeoBoundaries.shp) describes the characteristics of the boundaries of the geology polygons, such as whether they are known, inferred, faulted, concealed, or map boundaries. The faults layer is the shapefile StatewideFaults.shp and shows all the faults from the county maps, attributed by type of fault. The faults and boundaries layers have not been edited from their original digital version created by NBMG except to combine them into a single Statewide file. This means that in places where the geology polygon boundaries have been edited, they will no longer match the fault or contact boundaries. This only affects about 10 percent of the geology polygons. The original contact boundaries still need to be displayed (instead of the new ones) because they are attributed to make the map boundary lines invisible. While efforts have been made to check that the representation of the fault attributes is correct (such as upper plate and lower plate symbology) it has not been comprehensively examined. Errors observed should be brought to the author's attention. A summary of the geologic interpretation and details of the meaning of the codes used in the GEOLOGICFM field are provided in this document. Layer files (.lyr) have been created for virtually all layers to preserve the symbology associated with a given layer, especially the layout of all of the geologic units.

Lakes

Water bodies taken from the 1:100,000-scale topographic maps were compiled into a shapefile, lake_100.shp by the Nevada Natural Heritage Program of the Department of Conservation and Natural Resources. The geology layer (NevadaGeology.shp) includes 23 polygons attributed as water bodies (WBDY). They are not displayed on the geology layer shown in the project. The user will see a much more accurate representation of the water bodies in the State by turning on the Water Bodies layer.

Public Land Survey

The township and range grid is shapefile tr100grid.shp, and the section grid is shapefile plss100k.shp. These data sets were created and provided by the U.S. Bureau of Land Management (BLM).

Quadrangles

Two quadrangle files are included. The 1:100,000-scale quadrangles shapefile, nv_100kquads.shp, provided by the BLM, and 7.5′ (1:24,000-scale) quadrangle shapefile, NVQDP.shp, provided by the USGS.

Resources

Two different resource layers are included, Oil Wells and Gold Deposits. The Oil Wells are plotted from an edited version of a .dbf file provided by the Nevada Bureau of Mines and Geology, OFR04_1. It is current to June 2004. The SHOWEDIT attribute was cleaned up to remove duplication and symbolized. The mineral deposit information is taken from the USGS data file of MRDS deposits, mrds-fUS32.shp, now available online, updated from the 2000 version in 2005. Only those deposits that are designated as Model 19c, distal-disseminated Ag-Au, or Model 26a carbonate-hosted Au-Ag (Bliss, 1992; Cox and Singer, 1992) are currently displayed on the map, but the user can modify the display as needed by changing the definition query to show any of the Nevada sites and multiple deposit models.

Rivers

The perennial and intermittent rivers and streams in Nevada are displayed with the RIVER_TYPE attribute from the nevadarivers.shp shapefile provided by the Nevada Bureau of Mines and Geology.

Roads

The primary roads in Nevada are shown in the roads layer, ROADS_A.shp shapefile provided by the Nevada Bureau of Mines and Geology.

Summary of Regional Geologic Interpretation

A twofold challenge of creating this map was to combine the 1,000 plus county map geologic units into slightly more than 100 regional units while modifying the overall regional geologic interpretation from the original ideas in Stewart and Carlson (1978) to reflect new data and ideas. The value of a digital product is that it provides opportunity for trial and experimentation, allowing for as much iteration as necessary to create an interpretation that is as consistent with the data as possible. Many iterations were required for this interpretation.

The new regional geologic interpretation is visually presented in the accompanying file "Explanation for Geologic Map of Nevada.pdf," and discussed in this text. A separate interpretation of the tectonic history of the region is presented

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elsewhere. The rock unit designations for this new map include stratigraphic units as well as assemblages and terranes. This method was deliberately chosen to reflect more clearly both the stratigraphic and tectonic history of these rocks as an inherent component of the unit. It is the combination of lithologic and structural characteristics, not one or the other, that define a unit as distinct from other groups of rocks. The third variable in regional interpretation is always the incompleteness of our understanding of the basic geologic data in many places, which contributes significantly to how they can be reasonably grouped.

Quaternary to Pliocene sediments and rocks reflect more inconsistency from county to county than rock units from most other age periods. Some counties differentiated older and younger alluvium and some did not, so two units were used but not always designated in each county (Qal, Qya). Sand dunes, playas, and glacial moraines are also included as Quaternary units (Qs, Qpl, Qg). Only one Quaternary volcanic unit, basalt flows, (Qb) is designated. Quaternary and Pliocene sediments and sedimentary rocks include hot spring deposits (QThs), landslide deposits (QTls), older gravels (QTg), older alluvium (QToa), and volcaniclastic sediments (QTs). Apart from the Quaternary basalt, the youngest volcanic rocks in the State include late Tertiary or early Quaternary basalt flows (QTb), andesite (QTa), and rhyolite (QTr).

Most Tertiary rocks in Nevada are volcanic. Lacustrine, fluvial, and tuffaceous sedimentary rocks were deposited in Tertiary (and possibly Upper Cretaceous) basins scattered around the State. The classification of the Tertiary volcanic and sedimentary rocks in this map follows closely the scheme used in Stewart and Carlson (1978) with a few consolidations supported by new information. There are three age groupings, from youngest to oldest, T3 (6–17 Ma), T2 (18–34 Ma), and T1 (35–43). There are five primary compositional and (or) textural groupings for the volcanic and sedimentary rocks: sedimentary (Ts3, Ts2, TKs1), basaltic (Tb3, Tb2), andesitic (Ta3, Ta2, Ta1), tuffaceous (Tt3, Tt2, Tt1) and rhyolitic (Tr3, Tr2, Tr1). In addition, a few Tertiary units (Tba, Tbg, Ths) are present that cross time and compositional boundaries, and they are designated separately. Tertiary intrusive rocks are shown as phaneritic felsic or mafic composition (Tfi, Tmi), or aphanitic rhyolite (Tri). Mafic or felsic intrusive rocks of unknown age are mapped separately from Tertiary and Mesozoic intrusions (TJmi, TJfi).

Mesozoic intrusive, volcanic, sedimentary, and metamorphic rocks, including those associated with accreted terranes are all present in Nevada. These rocks formed in a variety of tectonic environments and depositional settings—they reflect many diverse structural and tectonic histories. A few Triassic (₹fi), and numerous Jurassic (Jgb, Jmi, Jfi, Ji) and Cretaceous (Kmi, Kfi, Ki) plutons of mafic, felsic, and unknown compositions are scattered across the State, with a concentration near the Sierra Nevada Mountains associated with the Mesozoic arcs. Triassic (₹vm, ₹kv), Jurassic (Jvr, Jvb), and Jurassic(?) and Triassic(?) age (J₹v) volcanic rocks also range in composition from felsic to mafic and are spread across the central part of the State. Their tectonic settings and origins are not well understood, but they are likely related to the Triassic and Jurassic arc complexes, and possibly also to the accreted terranes.

Ten different groupings of Mesozoic terranes, sedimentary rocks and assemblages are recognized. They include clastic rocks and conglomerates that unconformably overlie older, folded and faulted rocks, distinct stratigraphic sequences in the southern, eastern, and central parts of the State, and numerous different assemblages with distinct stratigraphic and structural histories that are juxtaposed in several different terranes along tectonic boundaries in the western half of the State. Mesozoic sedimentary rocks are difficult to classify because of the diversity of their structural histories, depositional settings, and basements coupled with our incomplete knowledge of their relations to each other. Generally, they can be grouped into two categories—those sequences that are deposited on a known basement, and those sequences that are strongly disrupted and their basement is either unknown or intimately deformed along with them as part of a larger terrane. In places where Mesozoic rocks have a complex deformation history, they are not grouped by formation, but rather are grouped as either terranes or assemblages. Terranes are used in the classic sense for fault-bounded geologic entities of regional extent, each characterized by a geologic history that is different from the histories of contiguous terranes (Jones, Howell, and others, 1983). Assemblage is used for a group of related rock units within a terrane, or for a unit (or units) that has a known basement, but is geographically isolated and lithologically and (or) structurally distinct from other coeval rocks. This can result in formation names being used across assemblages, but it provides a clearer picture of regional tectonic groupings of the rocks. This, in turn, provides the framework for understanding the overall tectonic evolution of these rocks and how their complex relations to one another have evolved over time. The groupings used here generally follow earlier terrane maps and discussions (Silberling, 1991; Silberling, Jones, and others, 1987; Silberling, Jones, and others, 1992) although several modifications have been made to reflect additional information. The groupings are displayed in the accompanying map sheet “Explanation of Geologic Map of Nevada.pdf.”

The disrupted rocks with unknown basement include those in:

- the *Walker Lake terrane* composed of Mesozoic carbonate, siliclastic, volcanic, and volcaniclastic rocks in Lyon, Mineral, and western Nye Counties which is divided into three distinct assemblages (WPN, WPL, WLB),

- the *Black Rock-Jackson terrane* (BRJ) that includes Mississippian to Middle Jurassic carbonate, clastic, and volcaniclastic rocks,

- the *Sand Springs terrane* (SAS), which extends from the northwestern corner of Nye County northwest into

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Washoe County, consisting mostly of volcanic rocks of Late Triassic and Early Jurassic age,

- the *Quartz Mountain terrane* (QM), a structurally disrupted unit of unknown Mesozoic or Paleozoic age in Churchill and northern Nye Counties, which is distinguished lithologically by the association of orthoquartzite with feldspathic sandstone and (or) volcanic rocks, and

- the *Jungo terrane* (JO) in west-central and northwestern Nevada consisting of Triassic to Lower Jurassic fine-grained terrigenous clastic rocks.

All of the rocks of these terranes have experienced varying degrees of deformation and metamorphism, and have complex tectonic histories.

The rocks that are deposited on a known basement include:

- *Localized clastic rocks* (TKcg, Kcg, Jcg) scattered in several places across the State,

- the *Gold Range assemblage* (JTRgor) in Mineral and western Nye Counties,

- the *Humboldt assemblage* (TRc, JTRs) in a large area of Pershing, Churchill, and Lander Counties,

- the Candelaria Formation (TRcl) of the *Siliciclastic overlap assemblage* best exposed south of Mina, and

- the *Cratonal sequence* (TRmt, JTRch, Jas) in the eastern and southern parts of the State.

Interpretation of Paleozoic rocks in Nevada has had a long and colorful history. Paleozoic rocks in Nevada are grouped into six categories that include stratigraphic sequences and lithologic assemblages, and three accreted terranes. These groupings were chosen to best represent the similarities and differences among different rock units, and are shown in the accompanying explanation. The sequence and assemblages are:

- In the eastern third of the State, the *Carbonate shelf sequence* (Pc, Psc, PℙPc, ℙMbc, Mc, Dc, Dcd, DSc, SOc, Ocq, OЄc, Єc) includes Cambrian through Permian sedimentary rocks and their metamorphosed or undivided equivalents (DЄc, DOcm, Ocqm, OЄcm). While these rocks have seen significant post-Paleozoic disruption in places, the regional pattern of these rocks is one of either continuous conformable or disconformable sequences. Major unconformities are not part of this sequence. The Carbonate shelf sequence lies conformably on Precambrian to Lower Cambrian quartzite.

- The *Siliciclastic overlap assemblage* (TRcl, Pacl, PℙPacl) is a Pennsylvanian through Lower Triassic sequence of siliciclastic and carbonate rocks lying above a major unconformity. Rocks of this assemblage unconformably overlie rocks of the Carbonate shelf sequence, the Foreland basin assemblage, lower Paleozoic rocks of the Slope and Basin assemblages, the Nolan belt, and the Dutch Flat terrane. Its sparse regional distribution but consistent stratigraphic (and structural) position makes it an important regional tectonic constraint. Lower Triassic rocks of the Siliciclastic overlap assemblage (TRcl) are only exposed in southwestern and south-central Nevada, and their relation to the underlying unit Pacl is unclear but inferred to be depositional.

- The *Foreland basin assemblage* (ℙMcl, MDcl) is an Upper Devonian through Lower Pennsylvanian siliciclastic sequence deposited on the western part of the Carbonate shelf sequence. There may be unconformities within the Foreland basin assemblage, but much of the sequence is conformable or disconformable, and lithologies above and below any breaks are similar, making them difficult to identify.

- In a north-south belt in the east-central part of the State, Ordovician through Lower Mississippian rocks are grouped into the *Slope assemblage* (MDst, DSt, DOts). Parts of this assemblage are in conformable depositional contact with Carbonate shelf sequence rocks, and fairly coherent stratigraphic sequences can be defined. In most places, however, these rocks are imbricated in thrust sheets with rocks of both the Carbonate shelf sequence and the Basin assemblage. The lithologies of the Slope assemblage reflect both slope and basin depositional settings.

- Rocks of the *Basin assemblage* (DЄs, Ss) are exposed in a belt trending southwest and south from northeastern Nevada towards Esmeralda County. These Upper Cambrian through Devonian rocks are characteristic of deep marine and base-of-slope paleogeographic settings and include both sedimentary rocks and occasionally their mafic volcanic substrate. Apart from fragments of basaltic rocks, no true basement is preserved along with these rocks, and they are everywhere structurally emplaced over other generally coeval rocks. They are imbricated with Carbonate shelf sequence rocks, Slope assemblage rocks, and rocks of the Nolan belt. The amount of displacement experienced by the rocks in this assemblage is unknown and likely highly variable.

- A belt of lower Paleozoic rocks with affinity to the continental margin but with unusual structural characteristics forms a discrete belt west and northwest of displaced rocks of the Slope and Basin assemblages, and is here named the *Nolan belt*. They are different from the other Paleozoic rocks in a number of important ways that warrant distinction as a separate group. These rocks have structural characteristics of an accreted terrane, that is, they exhibit polyphase deformation, but have stratigraphic ties to North America that suggest they have not traveled great distances laterally from the continental margin. The three principal characteristics that define the Nolan belt of rocks are that (1) lithologically they define a region of outer shelf and slope Cambrian and Ordovician rocks, originally deposited in a more proximal position to the Carbonate shelf sequence than the rocks of the Basin assemblage, some of which now lie structurally to the east of this belt, (2) unlike rocks of the Basin or most of the Slope assemblage, they are stratigraphically attached to their Precambrian to Cambrian quartzite basement, and (3) they exhibit a unique polyphase deformation history distinct from adjacent coeval rocks.

Three accreted terranes are defined for the Paleozoic rocks, including the Black Rock-Jackson terrane described in the Mesozoic section which also contains Paleozoic rocks. These terranes represent rocks that have a range of ages and lithologies, and have structural or tectonic characteristics that make them distinct from adjacent rocks. Some of these rocks may be displaced only tens of kilometers from their places of origin, while others may be displaced thousands of kilometers. The rocks in these terranes also have tectonic histories distinct from the rocks of the continental margin prior to the time of their accretion. The terranes were accreted by a combination of translational and compressional movement leading to large, steeply dipping fault zones and many imbricate slices of deformed rocks along the boundaries between these terranes and the continental margin.

- The *Golconda terrane* (GC, GChr) is a strongly deformed group of Upper Devonian through Middle Permian deep basinal sedimentary, distal shelf clastic, volcaniclastic, and volcanic rocks. The only basement known for the Golconda terrane is Mississippian to Permian slivers of ocean floor mafic and ultramafic rocks interleaved with the deep marine sedimentary and clastic rocks. It is structurally emplaced over coeval rocks of the Pennsylvanian to Triassic Siliciclastic overlap assemblage.

- The Upper Devonian *Dutch Flat terrane* (DF) is represented by the Harmony Formation, a feldspathic sandstone long thought to be Cambrian (Roberts, 1964). It is unconformably overlain by Pennsylvanian rocks of the Siliciclastic overlap assemblage providing an upper age limit. Its contacts with adjacent rock units are structural. It has a unique structural history and unique lithologic characteristics. Its origin and mode of emplacement remain unknown.

- The Paleozoic rocks of the *Black Rock-Jackson terrane* (BRJ) exposed in northwestern-most Nevada have stratigraphic and structural affinities with coeval rocks in the eastern Klamath Mountains. These rocks were accreted to other Mesozoic rocks in Nevada during Jurassic and (or) Cretaceous time.

Finally, Precambrian and Lower Cambrian clastic rocks conformably underlie the Carbonate shelf sequence in eastern and southern Nevada (ꞒZq, ꞒZqm, Zqs). They also form the stratigraphic base of the rocks of the Nolan belt. This sequence of Precambrian rocks is interpreted to represent the original rifted margin of western North America (Stewart, 1972), prior to the formation of the carbonate shelf. They rest unconformably over Proterozoic basement rocks (Yfi, Xm) that are only exposed in southernmost Nevada.

Three units are classified as Other rocks. A breccia unit of mixed breccias (br) not classifiable elsewhere identifies locally disrupted rocks. A metamorphic-igneous complex with Tertiary and Mesozoic metamorphic ages and Paleozoic to Archean protolith ages (TAgn) in Elko County is the only high-grade metamorphic rock in Nevada. Upper Paleozoic or Triassic ultramafic rocks including serpentine (ꞦPzsp) are scattered in a few places around the State adjacent to major terrane boundaries.

Detailed Explanation of Geologic Units

All of the descriptions below use information from the 1978 State map of Stewart and Carlson and from the accompanying text (Stewart, 1980), as well as material from each county map that is not always specifically referenced. Additional references are cited in the text. The county maps that were merged to create the Statewide geology layer consist of 16 different geologic maps that do not correspond exactly with the individual counties. References are commonly made in the text to the maps, not necessarily to the counties. The complete references for each county report are listed in the bibliography. The sixteen maps and the counties (or parts of counties) they represent are as follows:

Map name	County	Reference
1. Churchill	Churchill	Willden and Speed, 1974
2. Clark	Clark	Longwell, Pampeyan, and others, 1965
3. Elko	Elko	Coats, 1987
4. Esmeralda	Esmeralda	Albers and Stewart, 1972
5. Eureka	Eureka	Roberts, Montgomery, and Lehner, 1967
6. Humboldt	Humboldt	Willden, 1964
7. Lander	Lander	Stewart, McKee, and Stager, 1977
8. Lincoln	Lincoln	Tschanz and Pampeyan, 1970
9. LDC	Lyon, Douglas, and Carson	Moore, 1969
10. Mineral	Mineral	Ross, 1961
11. Nye North	Northern Nye	Kleinhampl and Ziony, 1985
12. Nye South	Southern Nye	Cornwall, 1972
13. Pershing	Pershing	Johnson, 1977
14. Washoe North	Northern Washoe	Bonham and Papke, 1969
15. Washoe South	Southern Washoe and Storey	Bonham and Papke, 1969
16. White Pine	White Pine	Hose, Blake, and Smith, 1976

Quaternary Sediments and Rocks (Holocene and Pleistocene)

Quaternary sediment and rock units reflect more inconsistency from county to county than rock units from most other age periods. Some counties differentiated older and younger alluvium and some did not, so two units were used but not always designated in each county, and their names are not consistent across county boundaries. Sand dunes, playas, and glacial moraines are also included as Quaternary units. Only one Quaternary volcanic unit, basalt flows, is designated. Quaternary and Pliocene sediments and sedimentary rocks include hot spring deposits, landslide deposits, older gravels, older alluvium, and volcaniclastic sediments. The youngest volcanic rocks in the State apart from the Quaternary basalt include late Tertiary or early Quaternary age basalt flows, andesite, rhyolite, and volcaniclastic sediments.

Sediments and Sedimentary Rocks

Qal **Alluvium, undifferentiated—**Unit is present in all counties. Some counties divided the alluvium into younger and older units, and some did not. For those that did not, or used other generalized terms for Quaternary rocks, the unit Qal has been used for the general undivided alluvium. Additionally, when polygons have been edited and changed to alluvium, Qal was used as the general value; hence it now is present in all counties

Qya **Younger alluvium—**Map unit is used in Churchill, Elko, Esmeralda, Eureka, Humboldt, Lander, and Lincoln Counties where geologic information suggests better-defined younger versus older alluvium. It is mostly interchangeable with Qal, except that it implies some specifically younger Quaternary deposits

Qs **Sand dunes—**Unit is present in Clark, Humboldt, Lincoln, Churchill, Washoe, and Pershing Counties. There may be sand dunes in other counties that are not distinguished

Qpl **Playa, lake bed, and flood plain deposits—**Map unit used in all counties for recent lake beds, playas, and flood plains. Polygons from the 1978 State map unit Qp were added where no playa was shown on the county maps

Qg **Glacial moraines—**Sediments are present in southern Washoe, northern Nye, Esmeralda, Elko, Humboldt, White Pine, and Lander Counties in high mountain ranges

Volcanic Rocks

QЬ **Basalt flows—**Basalt flows, plugs, cinder cones, basaltic ash, scoria, and basaltic sediments. They are present in Nye, Esmeralda, and Churchill Counties

Quaternary and Pliocene Sediments and Rocks

Sediments and Sedimentary Rocks

QThs **Hot spring travertine, sinter, and tufa (Holocene to Pliocene)—**Calcareous and siliceous sinter and tufa deposits that are present in Washoe, Nye, Elko, Eureka, and Lander Counties

QTls **Landslide deposits, colluvium, and talus (Holocene to Pliocene)—**Unit is mixed on the Washoe North map with basalt, tuff, diatomite, and tuffaceous sediments. It includes the units mapped as Qls from the 1978 State map. It is present in Churchill, Washoe, Nye, Esmeralda, Elko, Eureka, Humboldt, Lander, Lincoln, Mineral, and Pershing Counties

QTg **Older gravels (Pleistocene and Pliocene)—**Unit is used for pre-Lake Lahontan deposits, weakly consolidated gravel and sand, older gravels, pediment gravels, and gravel deposits. It includes all units designated as QToa on the 1978 State map. This unit is used in all counties

QToa **Older alluvium and alluvial fan deposits (Pleistocene and Pliocene)—**Unit consists mostly of older alluvium and alluvial fans. It also includes various stream deposits, gravel, fanglomerates, and older gravels. It is not very consistent in description from county to county. This is used in all counties except Clark

QTs **Tuffaceous limestone, siltstone, sandstone, and conglomerate (Holocene to Pliocene)—**Present in Esmeralda, Elko, Mineral, Lyon, Douglas, Carson, and Eureka Counties and corresponds to unit QTs on the 1978 State map

Volcanic Rocks

QTb **Basalt flows (Holocene to Pliocene)—**Olivine basalt and basaltic and andesitic rocks. This unit is present in Clark, Elko, Mineral, Esmeralda, Humboldt, Lincoln, Lyon, Douglas, Carson, Nye, Washoe, and Lander Counties. It corresponds to the 1978 State map unit QTb

QTa **Andesite flows and breccias (Holocene to Pliocene)—**Present in southern Washoe, Esmeralda, Lyon, Douglas, Carson, Mineral, and Lander Counties. It corresponds to unit QTa on the 1978 State map

QTr **Rhyolite dome (Holocene to Pliocene)—**Unit is only present in southern Washoe and Mineral Counties. It corresponds to unit QTr on the 1978 State map

Tertiary and Upper Cretaceous(?) Rocks

Most Tertiary rocks in Nevada are volcanic. There are also a few lacustrine, fluvial, and tuffaceous sedimentary rocks that were deposited in Tertiary and possibly Upper Cretaceous basins scattered around the State. Tertiary intrusive rocks are distinguished by compositional and textural characteristics.

Volcanic and Sedimentary Rocks

Map unit names of the Tertiary volcanic and sedimentary rocks on this map follow closely the scheme used in Stewart and Carlson (1978) with a few additions and consolidations. There are three age groupings, from youngest to oldest, T3 (6–17 Ma), T2 (18–34 Ma), and T1 (35–43 Ma). There are five primary compositional and textural groupings for the volcanic and sedimentary rocks; sedimentary (Ts3), basaltic (Tb3), andesitic (Ta3), tuffaceous (Tt3), and rhyolitic (Tr3). The distinction between the Ts_ units and the Tt_ units is that Ts_ represents sedimentary rocks that formed in a primary depositional environment (lake bed, fluvial, and so forth) with some amount of tuff or tuffaceous sedimentary rock as part of the sequences, while the Tt_ units are primarily volcanic in nature (welded or nonwelded tuffs) that may have interlayered tuffaceous sedimentary horizons. In addition to the scheme described above, there are a few Tertiary units (Tba, Tbg, and Ths) that cross time and compositional boundaries, and they are designated separately as described below.

Tba **Andesite and basalt flows (Miocene and Oligocene)—**Generally poorly age constrained. This unit includes rocks originally mapped as the Pyramid sequence in Washoe County, the Mizpah Trachyte in Nye County, the Malpais Basalt, Rabbit Spring Formation, and Mira Basalt in Esmeralda County, and many other poorly dated unnamed basaltic and andesitic rocks around the State. It corresponds to unit Tba on the 1978 State map

Tbg **Basalt, gravel, and tuffaceous sedimentary rocks (Miocene)—**Basalt flows, cinder and lava cones, gravel, and tuffaceous sedimentary rocks mostly in Elko and some in Humboldt Counties. This unit includes the Banbury

Formation (Stewart and Carlson, 1978) and the Big Island Formation in Elko County and other unnamed units. It corresponds to unit Tbg from the 1978 State map

Ths **Tuffaceous sedimentary rocks (middle Miocene to upper Oligocene)—**Consists of the Horse Spring Formation in Clark and southern Nye Counties. This unit corresponds to unit Ths from the 1978 State map, and likely represents a composite of units Ts3 and Ts2. It is poorly known and may include rocks of other ages including Cretaceous

Ts3 **Younger tuffaceous sedimentary rocks (Pliocene and Miocene)—**Tuffaceous and other young Tertiary sedimentary rocks. Most of these rocks are sedimentary with a strong volcanic component—a few are tuffaceous with a strong sedimentary component. This unit includes rocks originally mapped as the High Rock sequence in Washoe County; the Horse Camp Formation in northern Nye County; the Esmeralda Formation in Mineral and Esmeralda Counties; older lake beds in Lincoln County; the Belted Range Tuff; the Indian Trail Formation (now abandoned); Timber Mountain, Paintbrush, and Crater Flat Tuffs; Wahmonie and Salyer Formations in southern Nye County; the Siebert Tuff in Esmeralda County; the Muddy Creek Formation in Clark County; and the Thousand Creek and Virgin Valley “beds” in Humboldt County; and other unnamed units. It corresponds to units Ts3 and Tts from the 1978 State map. It is present in all counties

Tb3 **Basalt (Miocene)—**Basalt flows, plugs and dikes, some olivine basalt, and andesite and latitic rocks. This unit corresponds with unit Tb on the 1978 State map. It is present on the Washoe North, Washoe South, Lincoln, Clark, Elko, Eureka, Humboldt, Nye South, and Lander County maps

Ta3 **Younger andesite and intermediate flows and breccias (Miocene)—**Includes some rocks mapped as the Kate Peak and Alta Formations on the Washoe South map; Wahmonie and Salyer Formations on the Nye South map; Gilbert Andesite on the Esmeralda map; pyroxene, hornblende phenoandesite, and phenodacite on the Elko map; and other unnamed units. It corresponds to the unit Ta3 on the 1978 State map. It is present everywhere except Eureka and White Pine Counties

Tt3 **Younger silicic ash flow tuffs (Miocene)—**Includes units mapped as the High Rock sequence on the Washoe North map; the Timber Mountain, Paintbrush, Crater Flat, and Belted Range Tuffs, and Indian Trail Formation (now abandoned) on the Nye South map; the Thirsty Canyon Tuff on the Nye South and Esmeralda maps; and other unnamed units. Locally it includes tuffaceous sedimentary rocks interstratified with tuffs. It is present in the northernmost part and southernmost parts of the State, and is not exposed in the central region. It corresponds to unit Tt3 on the 1978 State map, although a few rocks also mapped as Trt on the 1978 State map also are included. It is present in Clark, Churchill, Washoe, Nye, Lincoln, Lyon, Douglas, Carson, Esmeralda, Elko, Humboldt, Pershing, and Mineral Counties

Tr3 **Younger rhyolitic flows and shallow intrusive rocks (Miocene)—**Rhyolitic flows, domes, plugs, breccias, quartz latite, rhyodacite, quartz porphyry dikes, and other shallow intrusive rocks. This unit includes rocks mapped as the Cañon Rhyolite on the Washoe North map, the Jarbidge Rhyolite and phenorhyolitic and phenodacitic flows and domes on the Elko County map, and other unnamed units. It has a distribution similar to Tt3, with exposures in the northern and southern parts of the State, but only crops out in a few places in the central region. It corresponds to unit Tr3 on the 1978 State map, and also includes a few rocks mapped as Trt on the 1978 State map. This unit is exposed in every county except White Pine

Ts2 **Older tuffaceous sedimentary rocks (lower Miocene and Oligocene)—**Locally includes minor amounts of tuff. It includes rocks mapped as the Titus Canyon Formation on the Nye South map, the Gilmore Gulch Formation on the Nye North map, lacustrine limestone in Lincoln County, and other unnamed units. This unit corresponds to unit Ts2 on the 1978 State map. It is present in Nye, Lincoln, Elko, and Lander Counties

Tb2 **Basalt, tuff, and breccia (lower Miocene and Oligocene)—**Basalt flows, basaltic tuff, tuff breccia, and andesitic rocks in Elko and Humboldt Counties. These rocks correspond to unit Tob on the 1978 State map

Ta2 **Intermediate andesite and intermediate flows and breccias (lower Miocene and Oligocene)—**Andesite flows and breccias and other related rocks of intermediate composition such as dacite, rhyodacite, quartz latite, and biotite-hornblende porphyries. This unit includes units mapped as the South Willow Formation on the Washoe North map, the Milltown Andesite on the Nye South and Esmeralda County maps, the Mizpah Trachyte on the Nye North map, and other units. It corresponds to unit Ta2 on the 1978 State map. It crops out in all counties except Clark, Eureka, Lyon, Douglas, and Carson

Tt2 **Intermediate silicic ash flow tuff (lower Miocene and Oligocene)—**Welded and nonwelded silicic ash flow tuffs. Aside from alluvium, this unit covers more of Nevada than any other rock, with over 4,000 polygons representing it on this map. It is principally exposed in the central regions of the State. It locally includes thin units of air fall tuff and sedimentary rocks. It includes rocks mapped on the Washoe South, Lyon, Douglas, and Carson Counties maps as the Hartford Hill Rhyolite Tuff (now abandoned); on the Nye South map as the tuff of White Blotch Spring, the tuffs of Antelope Springs, and the tuff of Monotony Valley; in Lander County it is mapped as the Bates Mountain Tuff, Caetano Tuff, Edwards Creek Tuff, New Pass Tuff, tuff of Hall Creek, and the tuff of McCoy Mine; in Lander and Pershing Counties it is the Fish Creek Mountains Tuff; on both of the Nye County maps it is the Fraction Tuff; it also includes the Pancake Summit Tuff, Northumberland Tuff, Shingle Pass Tuff, some outcrops of Darrough Felsite shown to be Tertiary (other outcrops have been shown to be Mesozoic or Paleozoic), tuffs of Moores station, tuffs of Peavine Canyon, tuffs of the Pancake caldera complex, the Stone Cabin Formation, tuff of Saulsbury Wash, tuff of Kiln Canyon, the Tonopah Formation, tuffs of Hannapah, tuff of Bald Mountain, the Needles Range Formation, and the Calloway Well Formation on the Nye North map; in Esmeralda County it is the Kendall Tuff and latite; and in northern Nye and Lander Counties it is the Toiyabe Quartz Latite (now abandoned), and other unnamed units. It corresponds to unit Tt2 on the 1978 State map. It crops out in every county except Clark

Tr2 **Intermediate rhyolitic flows and shallow intrusive rocks (lower Miocene and Oligocene)—**Includes rocks mapped as the rhyolite of Big Sand Springs Valley on the Nye North map, the Sandstorm Formation in Esmeralda County, rhyolite flow domes in the Sheep Creek Range in Lander County, and other units. It corresponds to unit Tr2 on the 1978 State map. It is present in Nye, Lincoln, Churchill, Esmeralda, Eureka, Mineral, Elko, Humboldt, and Lander Counties

TKs1 **Conglomerate, lacustrine, and tuffaceous sedimentary rocks (lower Oligocene to Upper Cretaceous(?))—**Includes the Sheep Pass Formation and equivalents in northern Nye, Lincoln, Elko, Eureka, Lander, and White Pine Counties. In most places the Sheep Pass Formation is Paleocene or Eocene (Fouch, Hanley, and Forester, 1979), although rocks from the Carlin-Piñon Range area that contain Late Cretaceous fossils have been included in the Sheep Pass Formation (Smith and Ketner, 1976, 1978). It corresponds to unit Ts1 on the 1978 State map

Ta1 **Older andesite and intermediate flows and breccias (lower Oligocene to middle Eocene)—**Unit includes andesite or dacite flows, flow breccias, and hypabyssal rocks in Lander County, andesitic to latitic flows, pyroclastic rocks, and phenoandesitic and phenolatitic flows in Elko County, and other undifferentiated volcanic rocks in other counties. Present in Humboldt, northern Nye, Churchill, Elko, Eureka, Lander, and White Pine Counties. It corresponds to the 1978 State map unit Ta1

Tt1 **Older silicic ash flow tuffs (lower Oligocene to middle Eocene)—**Welded and nonwelded silicic ash flow tuffs, locally includes thin units of air fall tuff and sedimentary rock. This unit corresponds with the 1978 State map unit Tt1. These rocks are present in northern Nye, Elko, Eureka, and White Pine Counties

Tr1 **Older rhyolitic flows and shallow intrusive rocks (lower Oligocene to middle Eocene)—**Includes rhyolitic lava of Portuguese Mountain in northern Nye County, rhyodacite in Elko Hills in Elko County, and other unnamed units. The rhyodacite in Elko Hills was shown on the 1978 State map as unit Tr1, and on the Elko County map as the Jurassic Frenchie Creek Rhyolite. It was subsequently renamed the Rhyodacite of Elko Mountain (Ketner, 1990) when the late Eocene radiometric age of approximately 39.5 Ma was obtained. It corresponds to unit Tr1 on the 1978 State map. This unit is present in northern Nye, Elko, Eureka, and White Pine Counties

Intrusive Rocks

The groupings for Tertiary intrusive rocks are both compositional and textural. Two phaneritic compositions, mafic (Tmi) and felsic (Tfi), and one aphanitic composition, rhyolitic (Tri), are shown. More detail on definitions of intrusive rocks is provided under Mesozoic Intrusive Rocks. A companion publication to this one with more detailed, updated, and accurate intrusive rock assignments should be consulted for northeastern Nevada (du Bray and Crafford, 2007).

Tmi **Mafic phaneritic intrusive rocks (Miocene to middle Eocene)—**Tertiary mafic intrusive rocks are widely scattered across Nevada north of Clark County. They include rocks mapped as dacite and rhyodacite, diorite, quartz latite, and numerous undivided intrusive rocks on the county maps

Tfi **Felsic phaneritic intrusive rocks (Miocene to Eocene)—**Tertiary felsic intrusive rocks are widely scattered in every county across the State. They are generally described as granitic rocks, granodiorite, monzonite, quartz monzonite, alaskitic granite, quartz diorite, dacite, and rhyodacite in the places where they are shown separately on county maps

Tri **Rhyolitic intrusive rocks with aphanitic groundmass (Miocene to middle Eocene)—**Tertiary rhyolitic intrusive rocks also are present in every county of Nevada. They include many rocks mapped as rhyolite or rhyolite porphyry, rhyolite intrusive rocks, rhyolite plugs or flows, microgranite dikes, and many other undifferentiated intrusive rocks

Miocene(?) to Jurassic(?) Intrusive Rocks

These rocks are poorly constrained in age, and are shown only as mafic or felsic phaneritic intrusive rocks. They could range in age from Miocene to Jurassic. See the description below under Mesozoic intrusions for more details about the unit definitions.

TJmi **Mafic phaneritic intrusive rocks—**Poorly dated mafic intrusions are concentrated in two regions of Nevada, northwestern and west-central to southwestern parts of the State. They crop out in northern Nye, Mineral, Esmeralda, Eureka, Humboldt, and Lander Counties, and include rocks described on the county maps as dioritic to andesitic rocks, diorite and related rocks, and granodiorite

TJfi **Felsic phaneritic intrusive rocks—**Poorly dated felsic intrusions described as granitic rocks, granite porphyry, granodiorite, quartz monzonite, and many undivided plutonic rocks are included here. They crop out in every county except Elko and northern Washoe

Mesozoic Intrusive and Volcanic Rocks

A few Triassic, and numerous Jurassic and Cretaceous plutons of various compositions are scattered across the State, with a concentration along the Sierra Nevada Mountains associated with Mesozoic arcs. Mesozoic volcanic rocks ranging in composition from felsic to mafic are spread across the central part of the State. Their tectonic settings and origins are not well understood, but they are likely related to Triassic and Jurassic arc complexes, and possibly also to accreted terranes.

Intrusive Rocks

Intrusive rocks include many Jurassic and Cretaceous plutons ranging in composition from diorite to granite—predominantly granodiorite and quartz monzonite. The classification scheme for the intrusive rocks is a designation by age (Triassic, Jurassic, or Cretaceous) and composition, and is much generalized, taken primarily from designations given in Stewart and Carlson (1978). Compositionally, rocks are designated as either *felsic* (*fi*) or *mafic* (*mi*), except for the Jurassic gabbro complex (Jgb). Where composition is poorly known, rocks are simply designated as (*i*). A more comprehensive analysis of intrusive rock compositions and textures, with updated values using actual modal data for northeastern Nevada, is presented in a separate publication (du Bray and Crafford, 2007).

Kmi **Mafic phaneritic intrusive rocks (Cretaceous)—**Rocks mapped as Cretaceous dioritic rocks only crop out in northern Nye County in the San Antonio Mountains, and in a belt in far northwestern Nye County from the Monte Cristo Mountains east to the Shoshone Mountains

Kfi **Felsic phaneritic intrusive rocks (Cretaceous)—**Granodiorite, granite, and related rocks make up the largest group of granitic intrusions exposed in Nevada. They are present in every county, and are especially abundant in west-central Nevada in an arcuate belt along the border with California extending north and eastward towards Idaho

Ki **Dikes (Cretaceous)—**These dike rocks of unknown composition are mapped in the Shawave Mountains in Pershing County, the Osgood Mountains and Edna Mountain in Humboldt County, and just outside of Eureka

Jgb **Gabbro complex, anorthosite, and albitite (Early Cretaceous to Middle Jurassic)—**A large complex of gabbroic rocks forms a series of related intrusions in the northern parts of the Stillwater Range and Clan Alpine Mountains of Churchill County and in the West Humboldt Range of Pershing County (Willden and Speed, 1974). It also may extend into the Trinity Range and Shawave Mountains in western Churchill County (Greene, Stewart, and others, 1991). The complex contains highly differentiated facies near the periphery of the body and more homogeneous gabbro in the interior. Layered rocks near the margins include picrite, olivine gabbro, hornblende gabbro, and anorthosite. The homogeneous rocks consist largely of feldspathic hornblende gabbro and analcite gabbro. The complex is interpreted to be part of a continental Jurassic volcanic arc that is the northern continuation of a Jurassic continental margin arc that extended from the Sonora Desert region in the south to northern California in the north (Dilek and Moores, 1995; Zientek, Sidder, and Zierenberg, 2004). Biotites from several places in the gabbro have been dated by K/Ar and range from 140 to 170 Ma

Jmi **Older mafic phaneritic intrusive rocks (Jurassic)—**Unit includes diorite in northern Elko County, diorite to granodiorite in the Toquima Range of northern Nye County, and dioritic rocks in western Churchill County

Jfi **Older felsic phaneritic intrusive rocks (Jurassic)—**Concentrated in two areas of the State; common in the west-central part of the State along the California border in Mineral, Esmeralda, Lyon, Douglas, and Carson Counties. There is another more widely scattered group in eastern and central Nevada in Elko, Eureka, and White Pine Counties. Scattered occurrences also are present in Humboldt, Churchill, Lander, and Pershing Counties. Compositions are mainly granitic, granodiorite, and quartz monzonite

Ji **Phaneritic intrusive rocks (Jurassic)—**Quartz monzonite to Quartz diorite intrusions crop out in west-central Nevada in the Singatse Range in Lyon County, the Gillis Range in Mineral County, the Toquima Range on the Nye/Lander County boundary, in northern Nevada at Buffalo Mountain in Humboldt County, and in the East Range in Pershing County

ƦFi **Felsic phaneritic intrusive rocks (Triassic)—** Intrusive rocks crop out in the East Range and Humboldt Range in Pershing County associated with the Koipato Group volcanic rocks (Ʀkv). They intrude upper Paleozoic rocks of the Golconda terrane (GC) and rocks of the Koipato Group. Limited older evidence suggests that these rocks may be Triassic (Silberling and Wallace, 1967; Wallace, Silberling, and others, 1969; Wallace, Tatlock, and Silberling, 1960; Wallace, Tatlock, and others, 1969), but new data (du Bray and Crafford, 2007) suggests that most of the intrusive rocks mapped as Triassic in the East and Humboldt Ranges are Cretaceous or younger. In northern Esmeralda County between the Royston Hills and the Monte Cristo Range small exposures of Upper Triassic plutons are inferred to relate to the Lee Vining intrusive epoch in eastern California (Stewart, 1980). These rocks also intrude into the Golconda terrane (GC)

Volcanic Rocks

Triassic volcanic rocks are present only in west-central Nevada. They include the Koipato Group (Ʀkv) volcanic and sedimentary rocks which unconformably overlie the Golconda terrane in a large area of eastern Pershing County and mafic volcanic rocks (Ʀvm) in the Humboldt and East Ranges in Pershing County that are present as flows interbedded with Triassic carbonate rocks. Jurassic felsic volcanic rocks (Jvr) are isolated in the Cortez Mountains and Dry Hills around Crescent Valley in northern Eureka County near Carlin. Jurassic basaltic rocks (Jvb) are present in Churchill County in the Stillwater Range associated with Jurassic gabbro (Jgb) and quartzose sandstone (Jcg). In far western Nevada around Reno, a sequence of Triassic(?) and Jurassic(?) metamorphosed volcanic rocks (JƦv) is dissimilar to other Mesozoic rocks in the area, and may represent a distinct terrane.

Jvb **Flows, basaltic tuffs, and lapilli tuffs (Middle(?) Jurassic)—**Layered tuff, lapilli tuff, bedded agglomerate, tuff breccia, autobreccia, and lava, chiefly basaltic. Jurassic mafic volcanic rocks are present in the Stillwater Range in Churchill County, with smaller exposures in the West Humboldt Range. In the Stillwater Range they are intimately associated with gabbroic intrusive rocks (Jgb). They conformably overlie and locally are interbedded with quartz arenite (Jcg). The lavas are homogeneous basalts that contain microphenocrysts of labradorite, diopsidic augite, and talc-hematite after olivine. The groundmass is plagioclase-clinopyroxene-iron oxide (Willden and Speed, 1974). They are believed to be Middle Jurassic because they are thought to be comagmatic with the gabbro (Jgb). This unit is included within the 1978 State map unit Jgb

Jvr **Rhyolite flows, tuffs, and volcaniclastic rocks (Upper Jurassic)—**Rhyolite flows, felsic ash-flow tuffs and volcaniclastic rocks of the Pony Trail Group (Muffler, 1964) are the only recognized Jurassic felsic volcanic rocks in Nevada, cropping out in northern Eureka County in the Cortez Mountains area. They are dated as Jurassic by a radiometric date from 1972 (Smith and Ketner, 1976). The Pony Trail Group is made up of (in ascending order) the volcaniclastic Big Pole Formation; a silicic ash-flow tuff unit, the Sod House Tuff; and the boldly outcropping Frenchie Creek Rhyolite made of tuffs, volcaniclastic horizons and flows (Smith and Ketner, 1976). While some of these rocks likely are Jurassic, rocks mapped on the Elko County map as the Frenchie Creek Rhyolite exposed in the Elko Hills northeast of Elko have been shown to be Tertiary and renamed (Ketner, 1990) so it is possible that parts of the section included in the Frenchie Creek Rhyolite are not Jurassic. This unit corresponds to unit Jv on the 1978 State map

J₸v **Metavolcanic rocks (Jurassic(?) and Triassic(?))—**Metamorphosed (generally greenschist-facies) andesite and dacite flows and breccias, flow-banded rhyolite and rhyodacite, welded tuff, local hypabyssal intrusive rocks, and minor amounts of volcaniclastic sandstone and conglomerate (Greene, Stewart, and others, 1991). This unit includes the Peavine sequence in Washoe County, and other unnamed metasedimentary and metavolcanic rocks in Lyon, Douglas, Carson, and Churchill Counties. These rocks are considered distinct from the other metavolcanic and metasedimentary rocks in adjacent Mesozoic terranes. They are included in unit J₸sv on the 1978 State map

₸vm **Mafic flows and volcanic breccias (lower Upper Triassic to lower Middle Triassic)—**Amygdaloidal, nonporphyritic, massive flows and breccia, tuff, and tuffaceous argillite are interbedded with limestones in the Smelser Pass Member of the Augusta Mountain Formation in the Star Peak Group Triassic sedimentary rocks (₸c) in Pershing County (Nichols and Silberling, 1977b). They are well dated by abundant fossils from the surrounding rocks and range from lower Upper Triassic (Carnian) to lower Middle Triassic (Anisian) (Silberling and Wallace, 1969). They are not divided out on the 1978 State map from the surrounding Triassic carbonate unit ₸c

₸kv **Andesite, rhyolite, tuff, and volcaniclastic rocks (Middle and Lower Triassic)—**Andesite, rhyolite, tuff, and generally siliceous volcaniclastic rocks make up the Koipato Group, which lies unconformably below the Humboldt assemblage. The Koipato Group consists of altered porphyritic andesite flows and flow breccia of the Limerick Greenstone, altered felsite and coarse-grained tuffaceous sedimentary rocks of the Rochester Rhyolite, and quartz-rich ash-flow tuff and tuffaceous sedimentary rocks of the Weaver Rhyolite. It is present in Churchill, Humboldt, Lander, and mostly Pershing Counties where it unconformably overlies deformed rocks of the Golconda terrane (GC). The upper part of the Koipato contains late Early Triassic (Spathian) fossils (Silberling, 1973; Wallace, Tatlock, and others, 1969). It is depositionally overlain by the Star Peak Group (₸c), a sequence of carbonate platform deposits at the base of the Humboldt assemblage. Radiometric dates from the 1970s (McKee and Burke, 1972) suggest a Middle to Early Triassic age

Mesozoic Terranes, Sedimentary Rocks, and Assemblages

Ten different groupings of Mesozoic terranes, sedimentary rocks, and assemblages are recognized in the State. Mesozoic sedimentary rocks are difficult to classify because of the diversity of their structural histories, depositional settings, and basements coupled with our incomplete knowledge of their relations to one another. Generally, they can be grouped into two categories—those sequences that are deposited on a known basement, and those sequences that are strongly disrupted and their basement is either unknown or intimately deformed along with them as part of a larger terrane. In places where the Mesozoic rocks have a complex deformation history, they are not grouped by formation, but rather they are grouped as either terranes or assemblages. Terranes are used in the classic sense for fault-bounded geologic entities of regional extent, each characterized by a geologic history that is different from the histories of contiguous terranes (Jones, Howell, and others, 1983). Assemblage, an informal term, is used for a group of related rock units within a terrane or for a unit (or units) that has a known basement, but is geographically isolated and lithologically and (or) structurally distinct from other coeval rocks. This can result in traditional formation names being used across assemblages, but it provides a clearer picture of the tectonic groupings of the rocks. This, in turn, provides the framework for understanding the overall tectonic evolution of these rocks and how their complex relations to one another have evolved over time. The groupings used here generally follow earlier terrane maps and discussions (Silberling, 1991; Silberling, Jones, and others, 1987; Silberling, Jones, and others, 1992) with a few modifications.

The disrupted rocks with unknown basement include those in:

- the *Walker Lake terrane* composed of Mesozoic carbonate, siliclastic, volcanic, and volcaniclastic rocks in Lyon, Mineral, and western Nye Counties which is broken into three distinct assemblages (WPN, WPL, WLB),
- the *Black Rock-Jackson terrane* (BRJ) that includes Mississippian to Middle Jurassic carbonate, clastic, and volcaniclastic rocks,
- the *Sand Springs terrane* (SAS) which extends from the northwestern corner of Nye County northwest into Washoe County, consisting mostly of volcanic rocks of Late Triassic and Early Jurassic age,
- the *Quartz Mountain terrane* (QM), a structurally disrupted unit of unknown Mesozoic or Paleozoic age in Churchill and northern Nye Counties, which is distinguished lithologically by the association of orthoquartzite with feldspathic sandstone and (or) volcanic rocks, and
- the *Jungo terrane* (JO) in west central and northwestern Nevada consisting of Triassic to Lower Jurassic fine-grained terrigenous clastic rocks.

All of the rocks of these terranes have experienced varying degrees of deformation and metamorphism, and have complex tectonic histories.

The rocks that are deposited on a known basement include:

- *Localized clastic rocks* (TKcg, Kcg, Jcg) scattered in several places across the State,
- the *Gold Range assemblage* (JŦgor) in Mineral and western Nye Counties,
- the *Humboldt assemblage* (Ŧc, JŦs) in a large area of Pershing, Churchill, and Lander Counties,
- the Candelaria Formation (Ŧcl) of the *Siliciclastic overlap assemblage* best exposed south of Mina, and
- the *Cratonal sequence* (Ŧmt, JŦch, Jas) in the eastern and southern parts of the State.

Terranes

Walker Lake Terrane

The Walker Lake terrane is divided into three assemblages or allochthons, not two subterranes as in earlier discussions (Silberling, oral commun., 2006). The three assemblages, Pine Nut (WPN), Pamlico-Lodi (WPL), and Luning-Berlin (WLB), have similar but not identical stratigraphic characteristics, and the Pine Nut assemblage has a distinct structural history. The Pamlico-Lodi and Luning-Berlin assemblages have different degrees of similar deformation, and different stratigraphic sequences in the oldest and youngest rocks. All three assemblages are structurally bounded from one another. Together, they form a southeast-vergent accretionary complex of Triassic volcanogenic rocks, in part, interfingering with and overlain by an extensive Upper Triassic to Lower Jurassic carbonate platform assemblage that has intercalations of terrigenous and volcaniclastic rocks, and grades upward into nonmarine terrigenous clastic and volcanogenic rocks (Silberling, 1991). The upper Paleozoic andesitic rocks originally included here (Pablo Formation) are now reassigned to the Golconda terrane, and are overlain by the distinct Gold Range assemblage (JŦgor). The Sand Springs assemblage, originally included in the Paradise terrane (Silberling, Jones, and others, 1987), also has been designated as a separate terrane and is not included here. The oldest Mesozoic rocks in this terrane containing abundant quartzose and continentally derived clastic materials are latest Triassic in age; the youngest stratified rocks are partly synorogenic deposits of late Early Jurassic and possibly younger age (Silberling, 1984; Whitebread and John, 1992). Rocks in the Pamlico-Lodi and Luning-Berlin assemblages are present in numerous thrust nappes representing several major juxtaposed allochthons (Oldow, 1984a; Oldow, Satterfield, and Silberling, 1993; Silberling and John, 1989; Silberling, Jones, and others, 1992; Speed, Silberling, and others, 1989).

WPN **Pine Nut assemblage—Volcanogenic, carbonate, and clastic rocks (Middle(?) Jurassic to Middle Triassic)—**This assemblage is composed of Upper Triassic basinal-marine volcanic and carbonate rocks overlain by Lower Jurassic fine-grained, marine siliciclastic and tuffaceous sedimentary rocks, and by partly nonmarine sandstone, coarse clastic rocks, and volcanic rocks of late Early Jurassic and possibly younger age. This assemblage has stratigraphic similarities to the Luning-Berlin and Pamlico-Lodi assemblages, but shares only part of their late Mesozoic structural history, and is separated from them by the linear trace of the northwesterly trending Pine Nut fault (Oldow, 1984a; Silberling, Jones, and others, 1992). Structurally, the rocks are involved in only a single phase of

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tight to isoclinal folds with north-northwest striking axial planes, and no major internal thrust faults are known (Oldow, 1984a). The Pine Nut assemblage crops out in southern Washoe, Lyon, Douglas, Carson, and Mineral Counties, and includes rocks originally mapped as the Excelsior Formation, the Peavine sequence, and other metasedimentary and metavolcanic rocks

WPL **Pamlico-Lodi assemblage—Carbonate and volcanogenic rocks (Middle(?) Jurassic to Middle Triassic)—**The Pamlico-Lodi assemblage differs stratigraphically from the Luning-Berlin assemblage in that the Triassic carbonate sequences are interstratified with volcanic and volcanogenic rocks, not continentally derived epiclastic chert, conglomerate, sandstone, and argillite (Oldow, Satterfield, and Silberling, 1993; Silberling and John, 1989). The uppermost part of the sequence is a regionally extensive carbonate shelf like the Luning-Berlin assemblage. This is conformably overlain by quartz arenite and poorly sorted coarse clastic rocks faunally dated as Early Jurassic that grade upward into volcanogenic sedimentary and volcanic rocks (Oldow, 1984a; Oldow and Bartel, 1987). The Pamlico-Lodi assemblage has a polyphase folding history similar to the Luning-Berlin assemblage that was caused by northwest-southeast directed thrusting that displaced the rocks tens of kilometers toward the southeast (Oldow, 1984a). Compared with the Luning-Berlin assemblage to the east, however, rocks of the Pamlico-Lodi assemblage manifest much more shortening from this first deformation of southeast-directed tectonic transport (Speed, Silberling, and others, 1989). This assemblage is exposed in Churchill, Mineral, and northern Nye Counties. It includes rocks mapped as Dunlap, Excelsior, Gabbs, Sunrise, and Luning Formations

WLB **Luning-Berlin assemblage—Carbonate and terrigenous clastic rocks (Middle(?) Jurassic to Middle Triassic)—**Assemblage is underlain by the regionally extensive Luning thrust and lies structurally below the Pamlico-Lodi assemblage (WPL) (Oldow, 1984a). The Upper Triassic continental shelf sequence part of WLB consists of platform carbonate rocks and shallow-marine to deltaic-clastic rocks. Minor amounts of volcanogenic rocks are interbedded with terrigenous clastic rocks near the western margin of the assemblage (Oldow, 1984a). These are conformably overlain by Lower (Pliensbachian) to Middle Jurassic quartz arenite and coarse clastic rocks which grade upward into volcanogenic rocks (Oldow, 1984a; Oldow and Bartel, 1987). Rocks of the Luning-Berlin assemblage are involved in a complex deformational history involving first northwest-southeast thrusting, followed by second folds with north-northwest to west-northwest axial planes (Oldow, 1984a). The folding is constrained between Middle Jurassic and Late Cretaceous (90 Ma) (Oldow, 1984a). Rocks that have been assigned to the Dunlap, Gabbs, Sunrise, Luning, and Grantsville Formations are included in this assemblage (Silberling, 1984; Whitebread and John, 1992)

Black Rock-Jackson Terrane

BRJ **Basinal, island arc, carbonate, and volcanogenic rocks (Middle Jurassic to Mississippian)—**This composite terrane includes Mississippian to Middle Triassic oceanic-basin and island-arc rocks in isolated exposures in northwesternmost Nevada originally assigned to the Black Rock terrane, and Upper Triassic to Middle Jurassic volcanogenic and volcanic rocks of the Jackson terrane in the same region. These rocks crop out in southern Washoe, Humboldt, and Pershing Counties. Parts of the Black Rock terrane can be interpreted as the base of the Jackson terrane, but they are generally structurally juxtaposed throughout the region (Jones, 1990; Russell, 1984; Silberling, Jones, and others, 1987; Wyld, 1990). Rocks of this terrane have affinities with correlative rocks in the Eastern Klamath and Northern Sierra terranes in California (Silberling, Jones, and others, 1992)

Sand Springs Terrane

SAS **Basinal volcanogenic rocks and carbonate turbidites (Lower Jurassic and Upper Triassic)—**The Sand Springs terrane is a highly deformed, thick, mainly basinal volcanogenic assemblage of rocks at least partly of early Mesozoic age and possibly having affinities with rocks of the Black Rock-Jackson terrane (Silberling, 1991). The presumably oldest Mesozoic rocks are volcanogenic and carbonate turbidites interbedded with mudstone which grade upward into interbedded basinal carbonates and volcanogenic rocks containing Late Triassic faunas (Oldow, 1984a). Elsewhere, interbedded carbonate, volcanic, and volcanogenic rocks are assigned an Early to Middle Jurassic age and represent relatively shallow-marine to subaerial deposition (Oldow, 1984a). Although structural relations in the Sand Springs terrane are locally complicated by later Cenozoic deformation, the rocks appear to have been involved in major northwest-southeast shortening between the Early Jurassic and Late Cretaceous (80 Ma) (Oldow, 1984a). The rocks of the Sand Springs terrane crop out in southern Washoe, Pershing, Churchill, Mineral, and northern Nye Counties

Quartz Mountain Terrane

QM **Orthoquartzite, feldspathic sandstone, and volcanic rocks (Mesozoic or Paleozoic, possibly Jurassic)—**The Quartz Mountain terrane, of unknown Mesozoic or Paleozoic age, is distinguished lithologically by the association of orthoquartzite with feldspathic sandstone and (or) volcanic rocks (Silberling, oral commun., 2006). Other rock types include metapelite, dolomite, and locally derived coarse clastic rocks (Silberling and John, 1989). This structurally disrupted mass is intricately intruded by and structurally brecciated with igneous rocks in the Lodi Hills. The structures that bound the intrusive rocks are thought to postdate the fault or faults on which the sedimentary rocks of the Quartz Mountain terrane were originally emplaced (Silberling and John, 1989). Exposures in the La Plata quadrangle mapped as the Mountain Well sequence, have here been assigned to the Quartz Mountain terrane (John and Silberling, 1994). These rocks are exposed in Churchill and northern Nye Counties

Jungo Terrane

JO **Turbiditic, fine-grained, terrigenous clastic rocks (Middle Jurassic to Upper Triassic)—**The Jungo terrane, also called the Lovelock assemblage or Fencemaker allochthon (Oldow, Satterfield, and Silberling, 1993), consists of complexly deformed, thick basinal, turbiditic, fine-grained, terrigenous clastic rocks, mainly Norian, but also as young as Pliensbachian (Late Triassic and Early Jurassic) age. It crops out in southern Washoe, Churchill, Humboldt, and Pershing Counties. These rocks represent the basinal facies component of the Auld Lang Syne Group (Burke and Silberling, 1973; Lupe and Silberling, 1985). The Jungo terrane has no known basement and is structurally detached from coeval shelf facies (Silberling, Jones, and others, 1992). It is locally overlain unconformably by Middle or Upper Jurassic peritidal sedimentary rocks (Jcg) intruded by a gabbroic igneous assemblage (Silberling, 1991). Rocks included with the Jungo terrane were originally mapped as the Grass Valley Formation of the Auld Lang Syne Group in Humboldt and Pershing Counties; some rocks were mapped as the Happy Creek Volcanic "series" (now the Happy Creek Volcanic Complex) in Humboldt County, the Nightingale sequence in southern Washoe County, the Osobb Formation of the Auld Lang Syne Group in Churchill County, and the Winnemucca and Raspberry Formations of the Auld Lang Syne Group (Compton, 1960) in the Santa Rosa Range in Humboldt County

Sedimentary Rocks and Assemblages

Localized Clastic Rocks

Scattered occurrences of Mesozoic conglomeratic rocks and sandstone (TKcg, Kcg, Jcg) are present in several places in Nevada. They lie unconformably over older, deformed rocks thus serving as important age constraints on underlying rocks and deformation. Their isolated occurrences are significant indicators of local and regional tectonic events, but their ages are generally poorly constrained.

TKcg **Conglomerate and clastic rocks (Tertiary(?) and Cretaceous(?))—**These conglomeratic, tuffaceous, and other clastic rocks are not well enough constrained to be assigned either a Tertiary (unit TKs1) or Cretaceous (unit Kcg) age, so they are grouped as TKcg. Like the Cretaceous clastic unit Kcg, these rocks sit unconformably on many different age rocks. Included in this unit are units previously mapped as "Older clastic rocks" in Lincoln County; conglomerate, clastic rocks, and tuff in northern Nye County; the Gale Hills Formation in Clark County; and the Pansy Lee Conglomerate in the Krum Hills and Jackson Mountains in Humboldt County

Kcg **Siltstone, shale, conglomerate, and limestone (Cretaceous)—**Includes detrital deposits of continental origin, and locally derived fluvial and lacustrine clastic rocks, some interbedded with siltstone and freshwater limestone. Outcrops are concentrated in three separate areas of the State. In each place, limited biostratigraphic data indicate these rocks are Cretaceous. The King Lear Formation in the Jackson Mountains in Humboldt County lies unconformably on Triassic and older rocks of the Black Rock-Jackson terrane. The Newark Canyon Formation crops out mostly in Eureka and White Pine Counties but extends into Elko and Nye Counties as well, and rests unconformably on Ordovician to Permian rocks. In places it is difficult to distinguish Upper Devonian, Pennsylvanian, and Permian clastic rocks also derived from the nearby underlying bedrock from the Newark Canyon Formation, and some confusion still exists. The Willow Tank Formation in Clark County lies unconformably on Jurassic rocks and is overlain by what was mapped as the Baseline Sandstone and Overton Fanglomerate (now referred to as the Overton Conglomerate Member of the Baseline Sandstone), all of Cretaceous age

Jcg **Conglomerate, limestone, and quartz sandstone (Middle and Lower Jurassic)—**The Boyer Ranch Formation in the Clan Alpine and Stillwater Ranges in Pershing and Churchill Counties consists of a basal conglomerate overlain by partly silicified limestone that is overlain by quartz sandstone. In places it rests unconformably over Upper Triassic or younger rocks (Speed and Jones, 1969) of the Jungo terrane (JO), constraining its maximum age, and elsewhere it is faulted over Late Triassic and Early Jurassic rocks (Speed and Jones, 1969). The occurrence of conglomerate-bearing clasts of underlying units at the base of the formation supports the interpretation of unconformable basal contacts even though the unit is strongly folded (Speed and Jones, 1969). It is overlain by volcanic rocks that are comagmatic with the adjacent Middle Jurassic gabbro. In the Pamlico-Lodi (WPL) and Luning-Berlin (WLB) assemblages of the Walker Lake terrane and the Gold Range assemblage (JŦgor), a coarse clastic and shallow marine unit of Jurassic age has been mapped as the Dunlap Formation (Stewart and Carlson, 1978). It lies unconformably over both Permian and Triassic rocks (Oldow, 1981), and disconformably over other Triassic and Lower Jurassic rocks (Oldow and Bartel, 1987). Some of the rocks mapped as Dunlap likely belong in unit Jcg, however, it is not consistently defined on the Nye, Mineral, and Esmeralda County maps, and in many places rocks originally mapped as Dunlap have turned out to be a variety of other units. The Dunlap Formation therefore has not been separated from the other Mesozoic rocks on this map at this time, but it may belong with a more regional Jcg unit that defines an important mid-Mesozoic tectonic constraint

Gold Range Assemblage

JŦgor **Terrigenous clastic and volcanogenic rocks (Lower Jurassic and Upper Triassic)—**The Gold Range assemblage consists of mainly nonmarine, terrigenous clastic, and volcanogenic rocks of probable Late Triassic to Middle Jurassic ages, and local volcanic rocks having younger Mesozoic radiometric ages (Silberling, 1991). It is lying with angular unconformity over Permian rocks included in the Golconda terrane (GC). The oldest rocks are interbedded, subaerial and shallow-marine terrigenous clastic, volcaniclastic, and minor carbonate rocks overlain by shelf carbonates containing Early Jurassic pelecypods. Unfossiliferous quartz arenite and coarse clastic rocks disconformably overlie the shelf carbonate and grade upward into poorly sorted volcanogenic sandstone and coarse clastic rocks (Oldow, 1984a; Oldow and Bartel, 1987). The assemblage is deformed by northeast-trending folds associated with the overlying Luning thrust as well as younger northwest-trending folds (Oldow, 1984a). Archbold and Paul (1970) named these rocks the Gold Range Formation. They were originally mapped as the Luning Formation and in a few cases, the Excelsior Formation by early workers (Archbold and Paul, 1970, p. 6). Speed (1977a) later modified the definition of the Gold Range Formation. Oldow (1981) included some of these rocks in the Water Canyon assemblage. These rocks were included with the Paradise terrane (Silberling, Jones, and others, 1987; Silberling, Jones, and others, 1992), but have been separated here in agreement with Silberling (1991). Silberling (1991) used “Gold Range terrane” to include the unconformably underlying Permian rocks of the Mina Formation. Since the basement rocks are here included with the Golconda terrane, the term "Gold Range assemblage" is used only for the Mesozoic rocks unconformably overlying the Permian basement. The Gold Range assemblage is in the same tectonostratigraphic position as the Humboldt assemblage—both are overlying rocks of the Golconda terrane with a strong angular unconformity. While these assemblages are similar in overall age, they have different stratigraphic sequences and thus paleogeographic settings. The exact stratigraphy of the Gold Range assemblage and whether or not it includes younger Cretaceous volcanic rocks (Silberling, Jones, and others, 1987; Stewart, 1980) is not clear. This assemblage crops out in Esmeralda, Mineral, and northern Nye Counties

Humboldt Assemblage

A thick carbonate and clastic sequence of Triassic and Early Jurassic age (₮c, J₮s) was deposited on top of the Lower Triassic volcanic Koipato Group (₮kv) throughout a large area of Pershing, Churchill, and Lander Counties (Oldow, 1984a). These sedimentary rocks crop out in central Nevada and are geographically isolated and stratigraphically distinct from stratigraphic sequences to the east. They exhibit varying degrees of deformation, but can still be defined as coherent sequences of strata. They may be paleogeographically related to rocks of similar ages and facies that are part of accreted terranes now located to the west, but each terrane and assemblage has somewhat different structural and stratigraphic characteristics.

J₮s **Shale, siltstone, sandstone, and minor carbonate (Lower Jurassic to Upper Triassic)—** Rocks of the Grass Valley, Osobb, and Dun Glen Formations, and their unnamed overlying rocks elsewhere known as the Winnemucca Formation, exposed in Pershing, Churchill, Lander, and Humboldt Counties, characterize this unit. These rocks are depositional on top of the Star Peak Group carbonate and detrital rocks (₮c). Crossbedding, lode casts, and other depositional features indicate uniform northwest-trending current directions. The lithology and depositional characteristics of these rocks suggest shallow marine conditions on and around a westerly prograding delta (Silberling and Wallace, 1969). Fossils from these rocks range in age from Late Triassic (Norian) to Early Jurassic (Toarcian) (Silberling and Wallace, 1969)

₮c **Limestone, dolomite, shale, sandstone, and conglomerate (middle Upper to upper Lower Triassic (Carnian to Spathian))—**Unit consists of the Star Peak Group which lies depositionally on the volcanic and volcaniclastic rocks of the Koipato Group (₮kv). Map unit includes rocks mapped as Cane Spring, Natchez Pass, Prida, Augusta Mountain, Congress Canyon, Fossil Hill, Favret, Dixie Valley, and Tobin Formations, including Smelser Pass, Panther Canyon, and Home Station Members of the Augusta Mountain Formation. Basaltic flows and volcanic breccias (₮vm) are present in the Humboldt and northern Stillwater Ranges within the Smelser Pass Member of the Augusta Mountain Formation. The Star Peak Group includes carbonate platform deposits and grades westward into slope and basin paleogeographic environments. Complex stratigraphic patterns of carbonate and terrigenous rocks in the lower part of the group result from localized relative uplift. Widespread diagenetic secondary dolomitization of calcareous rocks complicates the stratigraphic patterns (Nichols and Silberling, 1977b). There is a major unconformity within the Star Peak Group underneath the Panther Canyon Member, which is late Ladinian (late Middle Triassic) in age. The Panther Canyon Member rests in places directly on the noncarbonate rocks of either the Koipato Group (₮kv) or the Golconda terrane (GC), and elsewhere on varying thicknesses of secondary dolomite that replaces Star Peak Group carbonate rocks. The Star Peak Group crops out in Churchill, Humboldt, Lander, and mostly Pershing Counties. Abundant fossil data from the Star Peak Group indicates this unit is latest Early (Spathian) to middle Late (Carnian) Triassic in age (Nichols and Silberling, 1977b)

Siliciclastic Overlap Assemblage

The Candelaria Formation (₮cl) is the only Mesozoic unit grouped with the Siliciclastic overlap assemblage (₮cl, Pacl, PPacl) which is discussed in detail under Paleozoic rocks.

₮cl **Shale, sandstone, and limestone (Lower Triassic)—**Shale with interbedded sandstone and minor limestone characterize the Lower Triassic Candelaria Formation (Ferguson, Muller, and Cathcart, 1954). This vertically coarsening sequence grades up into a distal volcanogenic turbidite in the middle and a proximal turbidite and breccia near the top (Stewart, 1980). The basal strata of the Candelaria are earliest Triassic (Griesbachian) and the highest are late Early Triassic (early Spathian) (Speed, Silberling, and others, 1989). It is equivalent in age to the marine Dinwoody Formation of northwestern Utah and southeastern Idaho, and possibly, to the lower part of the predominantly volcanic Koipato Group in northwestern Nevada (Poole and Wardlaw, 1978). The Candelaria Formation is mainly exposed near the old mining camp of Candelaria, located a little more than 20 mi south of Mina, in Mineral County. Another exposure also has been described from the southern Toquima Range in Nye County, and a collection of Early Triassic fauna was recovered from flaggy brown siltstone from the west side of the Toiyabe Range east of Ione (Poole and Wardlaw, 1978). Early Triassic conodonts in clastic rocks in the northern Hot Creek Range near Morey Peak suggest that some of these rocks may also be correlative with the Candelaria. These additional Early Triassic locals suggest that the Candelaria may have been more extensive, or is still unrecognized elsewhere in the central part of the State. The nature of the basal contact is critical to determining the appropriate paleogeographic setting and regional grouping for this unit. If the basal contact is a major structure, then the Candelaria likely represents a section of one of the many Mesozoic terranes that have been emplaced from the west. If the contact is fundamentally sedimentary, albeit disconformable or unconformable, then it constrains an important piece of the paleogeographic tectonic puzzle of Nevada geology. The Candelaria Formation lies on the subjacent Permian Diablo Formation where it is described as unconformable by Ferguson and others (1954), conformable by Speed and others (1977, p. 303), and nearly conformable by Page (1959). The Candelaria near Willow Spring in the Toquima Range is described as a “probable unconformity” by Poole and Wardlaw (1978). The regional map relations for this unit suggest that the base is a disconformity or slight unconformity with the underlying Diablo Formation (Ferguson, Muller, and Cathcart, 1954; Page, 1959), but not a major structure. The Diablo Formation, included here with the Permian siliciclastic overlap assemblage, lies with marked unconformity on lower Paleozoic basinal rocks of chert, argillite, and shale, as discussed below. The Candelaria Formation is unusual in that it is the oldest Mesozoic sedimentary sequence known in Nevada, and is present in a restricted area only over the Permian rocks of the Siliciclastic overlap assemblage, which also suggests that it was originally deposited directly on those rocks. The presence of volcaniclastic rocks in the upper part of the section is an important tectonostratigraphic link to the rocks of adjacent terranes. Rocks near Quinn River, Nevada that are almost as old and contain volcaniclastic rocks in the upper part of the section, belong to the Black Rock-Jackson terrane (Blome and Reed, 1995; Jones, 1990). Triassic rocks of similar age exposed south of Jarbidge in northeastern Elko County are juxtaposed with Permian rocks of the Siliciclastic overlap assemblage and may correlate with the Candelaria, but the base of the section is unknown and no volcanic facies are reported from those rocks, so they are currently included with the Cratonal sequence, ₮mt

Cratonal Sequence

Marine and continental deposits of Triassic and Jurassic rocks crop out east of 116° longitude. They can be correlated with similar deposits present to the east on the Colorado Plateau and eastward across the western United States. The older Triassic rocks are marine (₮mt) and grade upward in a depositional sequence into continentally derived rocks (J₮ch) and crossbedded sandstone (Jas).

Jas **Eolian crossbedded sandstone (Jurassic)—**Consists of the Aztec Sandstone. Unit is a friable fine- to medium-grained sandstone with conspicuous large scale cross-strata (Stewart and Carlson, 1978). It is considered eolian. Its age is wholly Jurassic and does not include Triassic rocks as indicated on the 1978 State map (Stewart, 1980). The Aztec is the westward continuation of the Navajo Sandstone of the Colorado Plateau. It crops out only in southern Nevada in Clark and Lincoln Counties

J₮ch **Continentally derived siltstone and clay (Lower Jurassic and Upper Triassic)—**These continental deposits include variegated bentonitic claystone, siltstone, and clayey sandstone, ledge-forming sandstone, and red siltstone (Stewart and Carlson, 1978). The lower part of this unit is equivalent to the Upper Triassic Chinle Formation and the upper part corresponds to the Moenave and Kayenta Formations which are now considered Lower Jurassic (Stewart, 1980). It crops out in Elko, Lincoln, and Clark Counties

Ŧmt **Marine siltstone, limestone, and conglomerate (Middle(?) and Lower Triassic)—**Unit consists of marine deposits of siltstone, sandstone, claystone, mudstone, limestone, and conglomerate (Stewart and Carlson, 1978). It includes rocks assigned to the Moenkopi and Thaynes Formations and related unnamed rocks in northern Nevada (Stewart, 1980). It crops out in the eastern part of the State in Elko, White Pine, Lincoln, and Clark Counties

Paleozoic Rocks

The interpretation of Paleozoic rocks in Nevada has had a long and colorful history that is almost as interesting as the rocks themselves. Paleozoic rocks in Nevada are here grouped into nine categories that include stratigraphic sequences, lithologic assemblages, and accreted terranes. These groupings were chosen to best represent the similarities and differences among different rock units.

- In the eastern third of the State, the *Carbonate shelf sequence* includes Cambrian through Permian rocks and their metamorphosed equivalents. While these rocks have seen significant post-Paleozoic disruption in places, the regional pattern of these rocks is one of either continuous conformable or disconformable sequences. Major unconformities are not part of this sequence.

- The *Siliciclastic overlap assemblage* is a Pennsylvanian through Lower Triassic sequence of siliciclastic and carbonate rocks that lies above a major unconformity over several other assemblages and terranes. It lies disconformably on Pennsylvanian Carbonate shelf sequence rocks and on the Foreland basin assemblage, and with major unconformity on lower Paleozoic rocks of the Slope assemblage, the Basin assemblage, the Nolan belt, and the Dutch Flat terrane. Its sparse regional distribution but consistent stratigraphic (and structural) position makes it an important regional tectonic constraint. Lower Triassic rocks of the Siliciclastic overlap assemblage only are exposed in southwestern and south-central Nevada.

- The *Foreland basin assemblage* is an Upper Devonian through Lower Pennsylvanian siliciclastic sequence deposited on the western part of the Carbonate shelf sequence. There may be unconformities within the Foreland basin assemblage, but much of the sequence is conformable or disconformable, and lithologies above and below any breaks are similar, making them difficult to identify.

- In a north-south belt in the east-central part of the State, Ordovician through Lower Mississippian rocks are grouped into the *Slope assemblage*. In places parts of this assemblage are in conformable depositional contact with Carbonate shelf sequence rocks, and fairly coherent stratigraphic sequences can be defined. In most places, these rocks are imbricated in thrust sheets with rocks of both the Carbonate shelf sequence and the Basin assemblage. The lithologies of the Slope assemblage reflect deeper slope and basin depositional settings than their coeval Carbonate shelf sequence counterparts.

- Rocks of the *Basin assemblage* are exposed in a belt trending southwest and south from northeastern Nevada towards Esmeralda County. These Upper Cambrian through Devonian rocks are characteristic of deep marine paleogeographic settings and include both sedimentary rocks and occasionally their mafic volcanic substrate. Apart from fragments of basaltic rocks, no basement is preserved with these rocks, and they are structurally emplaced over other generally coeval rocks. In many places they are intimately imbricated with Slope assemblage rocks, and in some places they are imbricated with Carbonate sequence rocks. While biostratigraphic evidence indicates that these rocks range from Upper Cambrian through Devonian, few stratigraphic sequences can be defined within these strongly deformed rocks. The amount of displacement experienced by the rocks in this assemblage is unknown and likely highly variable.

- A belt of lower Paleozoic rocks with strong affinity to the North American continental margin but with unusual structural characteristics forms a discrete belt west and northwest of displaced rocks of the Slope and Basin assemblages, and is here named the *Nolan belt*. They are different from the other Paleozoic rocks in a number of important ways that warrant distinction as a separate group. These rocks have structural characteristics of an accreted terrane, that is, they exhibit polyphase deformation, but have stratigraphic ties to North America that suggest they have not traveled great distances laterally from the continental margin. The three principal characteristics that define the Nolan belt of rocks are that (1) lithologically they define a region of outer shelf and slope Cambrian and Ordovician rocks, originally deposited in a more proximal position to the Carbonate shelf sequence than the rocks of the Basin assemblage, some of which now lie structurally to the east of this belt, (2) unlike rocks of the Basin or most of the Slope assemblage, they are stratigraphically attached to their Precambrian to Cambrian quartzite basement, and (3) they exhibit a unique polyphase deformation history distinct from adjacent coeval rocks.

Two Paleozoic terranes are included, in addition to the Black Rock terrane described in the Mesozoic terranes section which also contains Paleozoic rocks. These terranes represent groups of rocks that have a range of ages and lithologies, but share structural or tectonic characteristics that indicate they have a common structural history that is distinct from the history of adjacent rocks. Some of these rocks may be displaced only tens of kilometers from their places of origin, while others may be displaced by thousands of kilometers. The rocks in these terranes also have tectonic histories distinct from the rocks of the continental margin prior to the time of their accretion. The terranes were accreted by a combination of translational and compressional movement leading to large steeply dipping fault zones and many imbricate slices of deformed rocks along the boundaries between these terranes and the continental margin.

- The *Golconda terrane* is a strongly deformed group of Upper Devonian through Middle Permian deep basinal sedimentary, distal shelf clastic, volcaniclastic, and volcanic rocks. The only basement known for the Golconda terrane is slivers of Mississippian to Permian ocean floor mafic and ultramafic rocks interleaved with the deep marine sedimentary and clastic rocks. It is structurally emplaced over Pennsylvanian and Permian rocks of the Siliciclastic overlap assemblage.

- The Late Devonian or younger *Dutch Flat terrane* is represented by the Harmony Formation, feldspathic sandstone long thought to be Cambrian. It is unconformably overlain by Pennsylvanian rocks of the Siliciclastic overlap assemblage providing an upper age limit. Its contacts with adjacent rock units are structural. It has a unique structural history and unique lithologic characteristics. Its origin and mode of emplacement remain uncertain.

- Finally, the Paleozoic rocks of the *Black Rock-Jackson terrane* exposed in northwesternmost Nevada have stratigraphic and structural affinities with coeval rocks in the eastern Klamath Mountains. These rocks were accreted to other Mesozoic rocks in Nevada during Jurassic and (or) Cretaceous time.

Sedimentary and Metamorphic Rocks

Carbonate Shelf Sequence

In the eastern third of the State, the *Carbonate shelf sequence* includes Cambrian through Permian rocks and their metamorphosed equivalents. While these rocks have seen significant post-Paleozoic disruption in places, the regional pattern of these rocks is one of either continuous conformable or disconformable sequences. Major unconformities are not part of this sequence, although disconformities are. The Carbonate shelf sequence rocks are principally carbonate and dolomite, with lesser amounts of shale, sandstone, quartzite, and other clastic rocks typical of middle inner shelf to platform margin depositional environments. Metamorphic equivalents are also present in Cambrian through Devonian rocks and are included in the next section. Two clastic units, the Middle and Upper Ordovician Eureka Quartzite (Ocq) and the Lower Permian siltstone and sandstone (Psc), are also part of this sequence, the former serving as an important marker horizon in the Ordovician rocks, and the latter indicating a period of extended subaerial deposition during the Early Permian across the region. The area of exposure of the Carbonate shelf sequence of rocks generally defines the extent of the Paleozoic continental shelf, although locally this area has been significantly modified as the result of post-Paleozoic tectonism. The Cambrian through Devonian sequence of shelf rocks can be broken out reasonably well according to the depositional sequences discussed in Cook and Corboy (2004), which is similar to, but provides more detail than the groupings used in Stewart and Carlson (1978). Units DSc and SOc are not uniformly broken out across their area of exposure. In some places unit DSc is lumped with unit SOc, in other places unit SOc is lumped with unit O€c. The resulting local differences in the stratigraphic section are largely an artifact of the map units, but may locally be caused by the irregular distribution of these units.

Pc **Cherty limestone, dolomite, shale, and sandstone (Middle to Lower Permian)—**These Permian rocks include cherty limestone, dolomite, shale, sandstone, bioclastic limestone, and phosphatic limestone exposed in Elko, White Pine, Lincoln, and Clark counties. This unit includes rocks mapped as the Phosphoria Formation; the Gerster Limestone, Plympton Formation, Kaibab Limestone, and Grandeur Formation of the Park City Group; the Park City Group undivided; the Toroweap Formation; and the Coconino Sandstone. Unit Pc is disconformably overlain by Triassic unit ₮mt in scattered places in eastern and southern Nevada. It depositionally overlies unit Psc. It matches closely with unit Pc of Stewart and Carlson (1978)

Psc **Siltstone, sandstone, limestone, and dolomite (Lower Permian, Leonardian and Wolfcampian)—**This largely siliciclastic unit of siltstone, sandstone, limestone, and dolomite crops out in Elko, White Pine, Lincoln, and Clark Counties. It includes rocks originally mapped as the Arcturus Formation, Rib Hill Sandstone, undivided Kaibab Limestone, Toroweap Formation, and Coconino Sandstone in Clark County; and the Pequop Formation and red beds in Lincoln County. Unit Psc represents a strong influx of clastic material over the carbonate shelf during the Early Permian, presumably derived primarily from the craton to the east. It is depositionally overlain by unit Pc and lies conformably above unit Pℙc. At its western and northern edges it can be difficult to distinguish from Permian clastic rocks of the Siliciclastic overlap assemblage (units Pacl and Pℙacl). It follows closely with unit Psc of Stewart and Carlson (1978)

Pℙc **Limestone, dolomite, siltstone, sandstone, and shale (Lower Permian and Pennsylvanian)—**Present in Elko, White Pine, Lincoln, and Clark Counties. This unit represents mostly Upper Pennsylvanian and Lower Permian rocks that have not otherwise been separated into units Psc or ℙMbc. Unit includes unnamed Pennsylvanian and Lower Permian limestone and sandstone beds in Lincoln County, the Bird Spring Formation in Clark County, the Riepe Spring and Ely Limestones (undivided) in White Pine County, and limestone and dolomite rocks not otherwise assigned in Elko County. This unit lies depositionally below unit Psc and above the Ely Limestone (ℙMbc) where it is mapped separately. Where unit ℙMbc is not mapped separately in southern Nevada, the unit lies directly on Mississippian carbonate (Mc) and in White Pine County it rests on undivided Chainman and Pilot Shales and Joana Limestone (shown as either unit ℙMcl or MDcl)

ℙMbc **Bioclastic limestone (Pennsylvanian and Upper Mississippian)—**Mostly Lower Pennsylvanian limestone is present in Nye, Elko, Eureka, White Pine, Lincoln, and Clark Counties, and is most commonly referred to as the Ely Limestone. A ledgy gray limestone mapped as the Moleen Formation is included here. It is not mapped separately from unit Pℙc in most of White Pine County, southeastern Elko County, southern Lincoln, and western Clark Counties. Throughout most of the area of exposure unit lies conformably or disconformably beneath unit Pℙc and depositionally above unit ℙMcl. In southern Nye County this unit includes the Tippipah Limestone, and in Clark County it includes the Callville Limestone. In a north-south trending belt starting at the north end of the Pancake Range in Nye County and continuing north up through the Diamond Mountains along the Eureka-White Pine County border, Lower Pennsylvanian limestone is overlain unconformably by clastic rocks of the Siliciclastic overlap assemblage (Pacl, Pℙacl). North of the Diamond Mountains, where Lower Pennsylvanian carbonate is not recognized separately, the coeval facies are grouped with unit ℙMcl. Unit ℙMbc is primarily Pennsylvanian, but in places contains Late Mississippian fossils as well

Mc **Limestone (Mississippian)—**This unit is present in southern Nye, Lincoln, and Clark Counties. Unit includes the Monte Cristo Limestone, and Lower Mississippian rocks referred to as the Joana, Mercury, Bristol Pass, and Rogers Spring Limestones. It generally lies depositionally above Devonian carbonate rocks and beneath Pennsylvanian carbonate and clastic rocks. In the Meadow Valley Mountains in southern Lincoln County it is also shown sitting on a thin horizon of Pilot Shale and overlain by a thin Mississippian clastic unit assigned to unit ℙMcl

Dc **Limestone and minor dolomite (Upper and Middle Devonian)—**Includes generally cliff-forming, thin- to thick-bedded limestone. These rocks are mainly shallow-water subtidal, intertidal, and supratidal deposits formed on a broad inner carbonate shelf (Stewart, 1980). The Devils Gate Limestone and Guilmette Formation in northern Nevada are the principal units, and the Sultan Limestone is included from the southern part of the State. Unit is overlain (usually disconformably) by the Pilot Shale of unit MDcl except in southernmost Nevada where it is overlain by Mississippian carbonate (Mc). It depositionally overlies Middle and Lower Devonian unit Dcd. In a few places, such as southern Nevada and parts of Eureka County, regional mapping did not distinguish the Upper and Middle Devonian section from the Lower Devonian section, and all of the Devonian is included in unit Dc. Rocks mapped as the Simonson Dolomite would fit into this depositional sequence (sequences 9 and 10 of Cook and Corboy, 2004), but they are not differentiated from the underlying dolomites in White Pine or Elko Counties, so they are all included in unit Dcd here, not unit Dc. This unit crops out in Clark, Elko, Eureka, Lander, Lincoln, Nye, and White Pine Counties

Dcd **Dolomite, sandstone, and limestone (Middle and Lower Devonian)—**Crops out over the same area as unit Dc. Its primary formations are the Sevy Dolomite and the Nevada

Formation (now abandoned). In White Pine County, there may be some undivided Guilmette Formation included with unit Dcd. Also included are the Lower Devonian Tor and McMonnigal Limestones in northern Nye County. The Simonson Dolomite is also included here as it is not differentiated in White Pine and Elko Counties. These rocks correspond to depositional sequences 6, 7, and 8 of Cook and Corboy (2004). Unit Dcd is overlain by unit Dc and is depositional on DSc. In White Pine County and most of Elko County, unit DSc is not broken out from unit SOc, hence the Devonian dolomite sequence appears to rest directly on SOc

DSc **Dolomite (Lower Devonian and Silurian)—**Unit corresponds with sequence 5 of Cook and Corboy (2004) and includes the Laketown and Lone Mountain Dolomites and equivalent unnamed rocks. In White Pine County these rocks are grouped with the underlying unit SOc, but otherwise are mapped in Elko, Eureka, Nye, Lincoln, and Clark Counties. Disconformities and discontinuities are commonplace along both upper and lower contacts (Langenheim and Larson, 1973). Unit DSc is depositionally overlain by unit Dcd, except where those rocks are grouped with unit Dc. In general, unit DSc overlies unit SOc. In Clark County and parts of Elko County, unit SOc is not differentiated from unit O€c, and therefore DSc lies directly on O€c. In the Sulphur Spring Range, DSc depositionally overlies unit DSt, and in the Roberts Mountains it grades laterally and vertically down into unit DSt. The Lone Mountain Dolomite has been shown to be both primary and secondary dolomite (Nichols and Silberling, 1977a). Therefore the boundaries mapped between unit DSc and both underlying DSt and overlying Dcd are not primary depositional features in all cases, especially in the Roberts Mountains

SOc **Dolomite, limestone, and shale (Lower Silurian to Middle Ordovician)—**Ely Springs Dolomite and Hanson Creek Formation are the main formations included in this unit. Many of the rocks in this unit are not assigned to a formation. A large section of the carbonate platform from Early Devonian through latest Ordovician time is represented by dolomitic rocks. They commonly look similar, have poor biostratigraphic control, and thus are not always well differentiated on the county maps. Additionally, not all of the dolomite is primary, and thus boundaries between secondary dolomite and other rock units have been misinterpreted as primary stratigraphic boundaries, further confusing the stratigraphy of the lower Paleozoic shelf (Nichols and Silberling, 1977a). Rocks in this unit correspond to sequence 4 of Cook and Corboy (2004). This unit includes rocks deposited immediately above the Eureka Quartzite, but disconformably below the Lone Mountain and Laketown Dolomites, hence it includes the Silurian and uppermost Ordovician. Rocks included in unit SOc that are mapped as the Hanson Creek Formation are depositionally overlain by the Roberts Mountains Formation of unit DSt in the northern and western part of the exposure area. The SOc rocks mapped as Hanson Creek Formation are difficult to distinguish from units DSt and DOts, and should more appropriately be included in unit DOts, but inconsistent mapping makes this difficult. In general unit SOc is not differentiated from unit O€c in Clark County, and thus unit DSc lies directly on unit O€c. In Lincoln and Nye Counties unit SOc lies directly on the Eureka Quartzite (Ocq) and is overlain by the Laketown Dolomite (DSc). In southern Nye County, rocks mapped as Ely Springs Formation are grouped with the Eureka Quartzite as unit Ocq. In White Pine and eastern Elko Counties, the Eureka Quartzite is not mapped separately, and unit SOc therefore lies directly on unit O€c, which includes the quartzite. Also in White Pine and eastern Elko Counties, unit DSc is not differentiated from unit SOc, so SOc is overlain directly by unit Dcd. In the northern and western areas of exposure where unit SOc is mapped as Hanson Creek Formation it is overlain depositionally by unit DSt of the Slope assemblage

Ocq **Quartzite (Middle Ordovician)—**Because of its importance as a stratigraphic marker horizon, the Eureka Quartzite is depicted on this map wherever it is mapped separately from the Ordovician carbonate shelf rocks. It represents depositional sequence 3 of Cook and Corboy (2004). It is not differentiated from the rest of the Ordovician (O€c) in White Pine or Clark Counties, but is shown in Elko, Eureka, Nye, and Lincoln Counties. Rocks mapped as the Ely Springs Dolomite are included with the Eureka Quartzite in southern Nye County. The Eureka Quartzite depositionally overlies the Pogonip Group

(O€c), and is overlain by either the Hanson Creek Formation or the Ely Springs Dolomite (SOc)

O€c **Limestone, dolomite, and quartzite (Middle Ordovician to Upper Cambrian)—** Carbonate platform rocks are present in Nye, Lincoln, Elko, Eureka, Lander, White Pine, Esmeralda, and Clark Counties. This unit is primarily Ordovician in age but does include Upper Cambrian rocks at the base (Page, Lundstrom, and others, 2005). The Pogonip Group, including the Antelope Valley Limestone is the most common name used. In Clark County it also includes the Ely Springs Dolomite, and includes the Eureka Quartzite in White Pine and Clark Counties. Unit O€c corresponds to depositional sequence 2 of Cook and Corboy (2004). Where Ocq is mapped separately, it overlies O€c. Otherwise O€c is depositional under SOc, or in southern Nye and Clark Counties, it is overlain directly by DSc where SOc is not differentiated. Unit O€c depositionally overlies unit €c

€c **Dolomite, limestone, and shale (Cambrian)—** Occurs in southern and eastern Nevada. The Bonanza King and Carrara Formations are the primary formations in southern Nye County; the Dunderberg Shale in northern Nye and Lincoln Counties; the Hamburg Dolomite in Eureka County; the Nopah Formation in southern Nye and Esmeralda Counties; the Patterson Pass and Pioche Shales, the Chisholm and Highland Peak Formations, and the Lyndon Limestone in Lincoln County; the Pole Canyon Limestone and the Lincoln Peak and Windfall Formations in northern Nye County; and undifferentiated limestone and dolomite in Lincoln, Clark, White Pine, Eureka, northern Nye, and Elko Counties. This unit is conformably overlain by the Ordovician shelf rocks (O€c), and is depositional on the underlying Proterozoic-Cambrian quartzite of €Zq

Undivided and Metamorphosed Carbonate Shelf Sequence Rocks

D€c **Dolomite and limestone (Middle Devonian to Upper Cambrian)—**Lower Paleozoic dolomite and limestone present in southeastern Lincoln and Clark Counties are grouped together into unit D€c. The lower Paleozoic section is too thin to map regionally as individual units, and the structure is too complex in these rocks to accurately portray the individual units at this scale. In part of Clark County, these rocks are referred to as the Goodsprings Dolomite. In the Mormon Mountains of Lincoln County, these rocks are overlain by Mississippian carbonate (Mc). In Clark County in the Spring Mountains, they are overlain by the Devonian Sultan Limestone (Dc)

DOcm **Dolomite and graphitic marble (Devonian to Upper Ordovician)—**Occurs in the Ruby Mountains, East Humboldt Range, and Wood Hills in Elko County and overlies the metamorphosed Eureka Quartzite (Ocqm)

Ocqm **Metaquartzite (Middle Ordovician)—**The metamorphosed Eureka Quartzite is shown separately in the Ruby Mountains, East Humboldt Range, and Wood Hills in Elko County, and serves as a valuable marker horizon for the thick sequence of metamorphosed lower Paleozoic shelf rocks

O€cm **Calcite marble (Middle Ordovician to Cambrian)—**Underlies the metamorphosed Eureka Quartzite marker horizon in the Ruby Mountains, Wood Hills, and Pequop Mountains in Elko County

Terranes and Assemblages

Golconda Terrane

GC **Basinal, volcanogenic, terrigenous clastic, and minor carbonate rocks (Permian to Upper Devonian)—**The Golconda terrane is composed of deformed and imbricated thrust slices of upper Paleozoic rocks including deep-marine, pelagic and turbiditic, carbonate, terrigenous clastic and volcaniclastic rocks, radiolarian chert and argillite, and pillow basalt (Silberling, Jones, and others, 1992). While the terrane is characterized by a great diversity of rock types, all rocks are strongly deformed with an east-vergent fabric, a distinguishing characteristic of this terrane (Brueckner and Snyder, 1985; Jones, 1991a; Miller, Kanter, and others, 1982; Murchey, 1990; Stewart, Murchey, and others, 1986). It crops out in a long sinuous belt, up to 100 mi wide in places. Southwest of Mina, the belt trends east from the California border to just north of Tonopah, and then bends north-south to the west of Longitude 117° to about 50 mi north of Winnemucca, where it bends again, sharply to the east-north of Tuscarora with significant exposures eastward and to the northern border of the State. Outcrops of the Golconda terrane are present in Mineral, Esmeralda, northern Nye, Churchill, Elko, Humboldt, Lander, and Pershing Counties. It includes some rocks originally mapped as Banner and Nelson Formations in Elko County; rocks originally mapped as the Excelsior Formation in Mineral and Esmeralda Counties, later assigned to the Black Dyke and Mina Formations by Speed (1977b); the original Havallah and Pumpernickel Formations (Muller, Ferguson, and Roberts, 1951; Roberts, 1964; Silberling and Roberts, 1962), later revised to structural sequences (Murchey, 1990; Stewart, MacMillan, and others, 1977; Stewart, Murchey, and others, 1986; Theodore, 1991; 1994) in Elko, Humboldt, Lander, and Pershing Counties; the Inskip Formation in Pershing County; the Mitchell Creek Formation in Elko County; the Pablo Formation in northern Nye County; and the Schoonover Formation (see unit GChr) in Elko County.

In all of the places where rocks of the Golconda terrane were originally believed to form a stratigraphic sequence, detailed mapping and biostratigraphic analysis with radiolarians and conodonts has demonstrated that it is characterized by complex imbrications of rocks ranging from mid-Permian through latest Devonian age (Holdsworth, 1986; Jones, 1991b; Miller, Holdsworth, and others, 1984; Murchey, 1990; Stewart, MacMillan, and others, 1977). In Pershing County, the Golconda terrane is unconformably overlain by Triassic volcanic rocks of the Koipato Group (T̄Rkv) which form the stratigraphic base to the Humboldt assemblage (T̄Rc, JT̄Rs). In Mineral and Esmeralda Counties, it is unconformably overlain by the Gold Range assemblage (JT̄Rgor) of mainly nonmarine, terrigenous clastic, and volcanogenic Upper Triassic and younger rocks. Elsewhere in northern and southwestern Nevada, it is structurally overlain by Mesozoic accreted terranes.

Across the length of its exposure from the Independence Mountains north of Elko to the Candelaria region south of Mina, the base of the Golconda terrane has a remarkably consistent structural emplacement relationship with adjacent rocks. It commonly lies on a low-angle structure above Permian and Pennsylvanian rocks of the Siliciclastic overlap assemblage. In places where these rocks are missing, it is faulted directly onto either the nearby lower Paleozoic Basin assemblage, the Nolan belt rocks, or the Harmony Formation of the Dutch Flat terrane. The type locality of this regional feature, the Golconda thrust is well exposed along Interstate Highway 80 at Edna Mountain near the town of Golconda (Ferguson, Roberts, and Muller, 1952), and in the open pits of mines near Battle Mountain (Theodore, T., oral commun., 2006). In southwestern Nevada, the lower Lower Triassic rocks of the Candelaria Formation overlie Permian and Pennsylvanian Siliciclastic overlap assemblage rocks, and the Golconda terrane is exposed nearby, but not observable directly on top of the Candelaria because of younger cover rocks. Elsewhere, there is no youngest age constraint for the age of emplacement. In several places, notably in the Osgood Mountains and the Toiyabe Range, it is also bounded by large, steeply dipping, mélange-like shear zones against older rocks of the Nolan belt. Stratigraphic and structural studies within the terrane have locally identified lithostratigraphic groupings (Erickson and Marsh, 1974a, b; Jones, 1991a; Murchey, 1990), but only the Home Ranch subterrane can presently be distinguished on a regional scale (GChr). Interpretations of the size and character of the late Paleozoic basin where these rocks formed and the nature of its Late Permian or Early Triassic accretion are as varied as the lithologic and structural characteristics of the terrane itself (see references above)

GChr **Home Ranch subterrane (Mississippian)—** Limestone, basalt, chert, and volcaniclastic rocks. The Home Ranch subterrane of the Golconda terrane shares similar structural characteristics with the rest of the Golconda terrane, but it has more specific age and lithologic features. It is restricted to Mississippian age (generally Early) and consists of shallow-water fossiliferous limestone, black chert, basalt, and volcaniclastic rocks. Olistostromal debris flows of basalt and limestone, indicative of steep paleotopography, are a distinguishing characteristic (Jones, 1991a). The depositional setting for this subterrane can be interpreted as a seamount. It includes rocks in Elko County mapped as the Banner and Nelson Formations, at least parts of the Inskip Formation in the East Range in Pershing County, the Goughs Canyon Formation in the Osgood Mountains, similar rocks in the Hot Springs Range in Humboldt County, and likely includes Mississippian limestone in the San Antonio Mountains in northern Nye County. To what extent these rocks have a history distinct from other rocks of the Golconda terrane is unclear. They are present structurally in a position outboard or west of most other exposures of the Golconda terrane, and are separated in the northern part of the State from other exposures of the terrane by the Nolan belt

Siliciclastic Overlap Assemblage

The Siliciclastic overlap assemblage is a discontinuous sequence of Pennsylvanian, Permian, and Triassic siliciclastic and carbonate rocks deposited with marked unconformity, usually with a basal conglomerate, over variably deformed Paleozoic rocks of the Dutch Flat terrane (DF), the Nolan belt (OЄtd, Єtd), the allochthonous Basin and Slope assemblages (Ss, DЄs, DOts, DSt, MDst), the Foreland basin assemblage (ℙMcl, MDcl), and Pennsylvanian carbonates of the Carbonate shelf sequence (ℙMbc). The exposures are scattered over a wide area as far west as the Osgood Mountains in Humboldt County and as far east as the HD Range in northeastern Elko County. Exposures are present as far south and west as Candelaria in Mineral County and as far southeast as the Hot Creek Range and possibly into the Pancake Range in eastern Nye County. Outcrops are spotty and discontinuous regionally, but the geologic relations are always very consistent. The regionally significant characteristics of this group are (1) it lies with marked unconformity on deformed older Paleozoic rocks, (2) it is a mixed sequence of siliciclastic and carbonate rocks, commonly with locally derived conglomeratic horizons, (3) it has multiple internal disconformities and unconformities, and (4) it is structurally overlain by rocks of the Golconda terrane (GC) along a low angle structure in many places. The oldest rocks of the assemblage are Middle Pennsylvanian (Atokan), and the youngest rocks of the sequence are Late Permian age, except in southwestern Nevada where the Permian rocks are overlain disconformably by Lower Triassic rocks (unit Ŧcl is described above under Mesozoic sedimentary rocks). All of the section is not present at all exposures; there is a significant unconformity within the section such that Permian rocks are commonly lying directly on deformed lower Paleozoic rocks. Everywhere except where the rocks lie on the Foreland basin assemblage and Pennsylvanian Carbonate shelf sequence, the unconformity is pronounced and the time gap ranges from as large as Permian overlying Cambrian to as small as Middle Pennsylvanian overlying Devonian or possibly Lower Mississippian rocks. Where the rocks overlie the Foreland basin assemblage, in some areas the unconformity is marked, such as in Carlin Canyon (Dott, 1955; Trexler, Cashman, and others, 2004), but the lithologies are similar above and below the unconformity—making it difficult to distinguish in areas of poor exposure, and the time gap is much smaller with Middle or Upper Pennsylvanian rocks sitting on Lower or possibly Middle Pennsylvanian rocks (Trexler, Cashman, and others, 2004). Because this assemblage overlaps so many different rocks with distinct tectonic histories, it serves as an important regional age constraint for a number of major Paleozoic tectonic events (Theodore, Moring, and others, 2003). This assemblage is broken into three units that include rocks that are Lower Triassic (Ŧcl), Permian (Pacl), and Pennsylvanian to Lower Permian (PℙacI). Disconformities or unconformities are present between each of these units. In places where this assemblage has not been broken into separate units it is grouped into unit Pℙacl. See above under Mesozoic sedimentary rocks for a description of unit Ŧcl.

Pacl **Sandstone, siltstone, limestone, conglomerate, and carbonaceous limestone (Permian)—** Unit is mapped in Elko, Mineral, Humboldt, Lander, Eureka, White Pine, northern Nye, and Esmeralda Counties. Included in this unit are the Carbon Ridge Formation in Eureka and White Pine Counties, parts of the Carlin sequence of Coats (1987), the sandstone and siltstone of Horse Mountain in Elko County, the Edna Mountain Formation in Humboldt and Elko Counties, the Garden Valley Formation in Eureka County, and the Diablo Formation in northern Nye, Mineral, and Esmeralda Counties. In the Candelaria area south of Mina, unit Pacl rests unconformably on deformed Upper Cambrian through Devonian Basin assemblage (DЄs) and is overlain by the Lower Triassic Candelaria Formation (Ŧcl). In the Toiyabe Range, it lies unconformably on deformed Cambrian through Ordovician rocks of the Nolan belt (OЄtd). In the Simpson Park Mountains and the Sulphur Spring Range, it rests unconformably on Ordovician and Devonian Slope assemblage rocks (DOts). In the Diamond Mountains it rests unconformably on the Ely Limestone (ℙMbc). In the Eureka area, Pacl unconformably overlies the Ely Limestone (ℙMbc) and the Diamond Peak Formation (ℙMcl) and is unconformably overlain by Cretaceous conglomerate (Kcg). Near Golconda it unconformably overlies Pℙacl. In the Adobe Range in Elko County it overlies Foreland basin assemblage rocks (ℙMcl, MDcl) and PPacl, and in the Snake Mountains and HD Range of northeast Nevada it lies unconformably on lower Paleozoic Slope and Basin assemblage rocks (D€s, Ss, DOts) and on older Siliciclastic overlap assemblage rocks (PPacl)

PPacl **Conglomerate, sandstone, siltstone, and limestone (Permian to Middle Pennsylvanian)—**Unit represents rocks that are stratigraphic sequences that include both Lower Permian and Pennsylvanian rocks, and also sections that have not been broken out regionally into younger and older Permian and Pennsylvanian units. The Antler sequence (Roberts, 1964) rocks are present in Humboldt and Lander Counties and include the Antler Peak Limestone, the Highway Limestone, the Battle Formation or Battle Conglomerate, and the Etchart Limestone. The Brock Canyon Formation of Permian or Pennsylvanian age is in the Cortez Mountains in Eureka County and the siliciclastic and carbonate Strathearn Formation is exposed in Elko County (Theodore, Moring, and others, 2003). Scattered remnants of conglomerate, sandstone, siltstone, and limestone in Nye County, and unnamed limestone and dolomite in Elko County are also included. In the northern Hot Creek Range in Nye County, PPacl is faulted with lower Paleozoic Carbonate shelf sequence rocks. Additionally, Early Triassic fossils in the area have caused reassignment of some of the rocks to the Candelaria Formation (Ƚcl). In the Pancake Range, PPacl lies on the Ely Limestone (PMbc). In the Toquima Range, the Pennsylvanian Wildcat Peak Formation lies unconformably on Slope assemblage rocks (DOts). In the Monitor Range and in Lander County, this unit lies unconformably on the lower Paleozoic Basin assemblage rocks (D€s). At Battle Mountain the Antler sequence lies unconformably on both the Harmony Formation, which is the Dutch Flat terrane (DF), and the Valmy Formation of Basin assemblage unit D€s. At Edna Mountain near Golconda and in the Osgood Mountains it lies unconformably on Cambrian and Late Proterozoic quartzite (€Zq) and Cambrian phyllite and shale (€td) of the Nolan belt, as well as on units of the Basin and Slope assemblages (D€s, DOts). In the Cortez Mountains of northern Eureka County, it lies unconformably on Basin and Slope assemblage rocks (D€s, DOts). In the Adobe Range and the Sulphur Spring Range, it lies unconformably on Pennsylvanian and Mississippian Foreland basin rocks (PMcl) (Trexler, Cashman, and others, 2004). In northern Elko County in the Bull Run and Copper Mountains, it lies unconformably on strongly deformed Ordovician to Cambrian rocks of the Nolan belt (O€td). In the Snake Mountains and the HD Range, the Pennsylvanian Quilici Formation lies unconformably on the Basin and Slope assemblages (D€s, DOts, Ss) and is unconformably overlain by the Permian Siliciclastic overlap assemblage rocks (Pacl). In far northeastern Nevada, upper Paleozoic rocks around Contact are very poorly known, but are similar to the Siliciclastic overlap assemblage rocks recognized in the HD range, and are thus included in this group

Foreland Basin Assemblage

The Foreland basin assemblage is a sequence of Upper Devonian through Lower Pennsylvanian siliciclastic and carbonate rocks deposited disconformably on older Paleozoic rocks of the Carbonate shelf sequence. The boundaries between the Foreland basin assemblage and coeval rocks of the Carbonate shelf sequence migrated east and west as a result of the changing tectonic and depositional settings during this time. Disconformities may be part of this assemblage but are often difficult to identify in these rocks, some of which have limited biostratigraphic control and consist largely of reworked siliciclastic rocks. The primary distinction with coeval rocks to the east in the Carbonate shelf sequence is the principally siliciclastic nature of the units, with a secondary carbonate component. In addition, the source of much of the siliciclastic component is interpreted to be material from the west, as well as from the east. Because of significant Mesozoic and younger structural disruption of these rocks, original stratigraphic relations can be difficult to determine.

PMcl **Shale, siltstone, sandstone, and conglomerate (Middle Pennsylvanian to Lower Mississippian)—**Unit crops out across all of eastern Nevada, generally east of 116° west longitude, and somewhat farther west in the southern half of the State. It includes rocks mapped as the Chainman Shale in Elko, northern Nye, and Lincoln Counties; the Diamond Peak Formation in northern Nye, Elko, Eureka, and White Pine Counties; the Scotty Wash Quartzite in Lincoln County; the upper part of the Eleana Formation in Nye County; and undivided sedimentary rocks in Eureka and Lincoln Counties. Clastic and carbonate rocks mapped in

Elko County, including undivided Moleen and Tomera Formations (the Tomera Formation includes Middle Pennsylvanian rocks) are also grouped here. Most of these rocks are Upper Mississippian and Lower Pennsylvanian in age, but unit ℙMcl also includes Lower Mississippian rocks, overlapping with unit MDcl where they have not been clearly distinguished. In places the Chainman Shale is time transgressive into the Diamond Peak Formation, and in other places they represent different coeval facies, based on limited biostratigraphic data. Where possible, younger siliciclastic rocks have been separated from the older sequence that includes the Pilot Shale and Joana Limestone because of significant differences in the character of the rocks. Unit ℙMcl is overlain conformably or disconformably in the eastern part of its exposure by carbonate rocks of units Pℙc and (or) ℙMbc. In the northern and western parts of its exposure it is overlain unconformably by Permian and Upper Pennsylvanian clastic rocks of the Siliciclastic overlap assemblage (Pacl or PℙPacl). Assignment of siliciclastic Pennsylvanian units to either unit ℙMcl or the unconformably overlying PℙPacl is challenging unless biostratigraphic data are available and outcrop observations reveal the presence of the unconformity such as in Carlin Canyon (Dott, 1955). Unit ℙMcl lies either conformably or disconformably above unit MDcl

MDcl **Siltstone, limestone, shale, and sandstone (Lower Mississippian and Upper Devonian)—** Unit crops out across all of eastern Nevada, generally east of 116° west longitude. It includes rocks mapped primarily as Pilot Shale, Joana Limestone, Chainman Shale, and their equivalents. This also includes the Tripon Pass Limestone in Elko County, the Cockalorum Wash Formation (now abandoned) in northern Nye County, the Mercury and Bristol Pass Limestones in Lincoln County, and some of the rocks mapped as Monte Cristo Limestone in Clark County. While it may be desirable to separate out the different lithologies, they are not well enough differentiated at this regional map scale. The Chainman, Joana and Pilot are grouped in White Pine County, and the Joana and Pilot are grouped in Elko County. The Pilot Shale lies depositionally (both conformably and disconformably) on Upper Devonian carbonate rocks (Dc) and signals a major change in the depositional setting across most of the carbonate platform which has long been attributed to the onset of deformation attributed to the Antler orogeny. The Pilot Shale is generally recognized as carbonaceous shale, overlain by the cliff-forming Joana Limestone. Siliciclastic quartz-bearing grit, chert, quartz sand, and siltstone in a calcareous matrix become increasingly common as the section turns into the Chainman Shale and other equivalent siliciclastic rocks. The sequence is interrupted by disconformities in a number of places, but structural disruption and poor age control hinder determination of the nature of the contacts between the distinct lithologies. Unit MDcl is overlain by unit ℙMcl, but there are places where the age and distinction between the units is poorly constrained. In southernmost Nevada, in Clark and southeastern White Pine Counties, Devonian carbonate is overlain by Mississippian carbonate (Mc) with little or no intervening Pilot Shale equivalent and few overlying siliciclastic rocks with western-derived source material. North and west of the area of exposure of unit MDcl, fault-bounded slivers of Lower Mississippian and Upper Devonian platform margin and slope facies rocks with siliciclastic horizons have been grouped into unit MDst and separated from unit MDcl

Dutch Flat Terrane

DF **Feldspathic sandstone, shale, and turbiditic limestone (Upper Devonian)—**The Dutch Flat terrane is the Late Devonian Harmony Formation. It consists of coarse-graded feldspathic sandstone and siltstone with rare quartzose turbiditic limestone interbeds that have yielded sparse, reworked Late Devonian and post-Ordovician conodonts and conodont fragments (Jones, 1997a; Ketner, Crafford, and others, 2005). The age of the Harmony has never been well constrained. It was originally interpreted as Mississippian(?) because of its position unconformably beneath Pennsylvanian conglomerate at Battle Mountain (Ferguson, Roberts, and Muller, 1952; Roberts, 1951). Cambrian fossils were later found in close proximity to the unusual feldspathic sandstone and became the most commonly assumed age (Hotz and Willden, 1964), although the Cambrian fossils have since been recognized to be part of a structurally disrupted upper Paleozoic section (Jones, 1991b; Jones, Wrucke, and others, 1978; McCollum and McCollum, 1991). Ordovician microfossils from the Harmony Formation in the Sonoma Range (Madden-McGuire, Hutter, and Suczek, 1991) turned out to be unreliable as well. In 1994, a single Late Devonian *Palmatolepis* sp. conodont was recovered from a calcareous turbidite interbedded with the feldspathic sandstone in the Hot Springs Range (Jones, 1997a), and has remained the most convincing lower-age constraint thus far. Subsequent post-Ordovician conodont fragments also recovered from the Hot Springs Range have confirmed that the unit is clearly post-Ordovician in age (Ketner, Crafford, and others, 2005). The Dutch Flat terrane crops out in Humboldt, Lander, and Pershing Counties. In the Hot Springs Range, it is structurally bounded to the northwest by the Golconda terrane and on the southeast by unit D€s of the Basin assemblage. In the Osgood Mountains, it has been structurally dismembered into mélange blocks that are part of an upper Paleozoic matrix of argillite and shale associated with the Golconda terrane (Jones, 1991b). In the Sonoma and East Ranges, much of it is mélange-like in character and has additionally been folded and faulted with Triassic and Ordovician rocks (Silberling, 1975). At Battle Mountain (Doebrich, 1994; Theodore, Murchey, and others, 1994), it is interpreted as faulted over adjacent rocks of the Basin assemblage (D€s), and is also unconformably overlain by the Pennsylvanian rocks of the Siliciclastic overlap assemblage, providing a critical constraint on the timing of its accretion to adjacent rocks. Because it is structurally bounded everywhere, its stratigraphic relation to other units in Nevada remains uncertain, although it has lithologic features in common with rocks of the Golconda terrane and the lower Paleozoic Basin assemblage (Ketner, Crafford, and others, 2005). In places it has west vergent folding throughout (Jones, 1993; Stahl, 1987), while in other places the formation is characterized by east vergent folding (Evans and Theodore, 1978). Interpretations of the origin of the rocks of the Harmony Formation and its tectonic history (Gehrels, Dickinson, and others, 2000; Ketner, Crafford, and others, 2005; Smith and Gehrels, 1994) have yet to fully explain its significant role in the mid-Paleozoic tectonism that affected Nevada. Its varied structural characteristics and enigmatic lithology suggest that this terrane is far traveled and has had a complex history of interaction with other Paleozoic rocks in Nevada

Slope Assemblage

The Slope assemblage rocks consist of limestone, argillaceous limestone, carbonaceous shale, calcareous siltstone, shale, argillite, quartzite, and bedded chert, with siliciclastic and conglomeratic horizons of chert clasts and quartz in places. The environment of deposition of this group of rocks is actually quite varied—in a number of cases the rocks are more typical of a “basin” environment. Slope facies rocks are difficult to identify because of their varied lithologic characteristics. These varied characteristics result from complex ocean chemistry variations through time, composition of rocks of adjacent margin(s), and tectonic setting of the margin. These factors all affect composition of sediment deposition along the slope of a continental margin through time. Nonetheless, a distinct group of rocks that was not deposited strictly in either a carbonate shelf environment or an ocean basin environment can clearly be identified in Nevada (Cook and Corboy, 2004). These rocks tend to be present in regions of naturally steep gradients along a margin, and thus do not commonly have the lateral extent that is seen in Carbonate shelf sequence rocks or Basin assemblage facies rocks. Many of these rocks are found today in structurally bounded sequences, but in a few important places, rocks of the Slope assemblage are tied depositionally to rocks of the Carbonate shelf sequence.

The slope of the margin was an important locus of disruption during mid-Paleozoic and later tectonism; these rocks were intimately involved in folding and thrusting of the margin during the Paleozoic and again during the Mesozoic. Many of these rocks are also compositionally ideal hosts for sediment-hosted gold deposits (Cook and Corboy, 2004) and have a known gold endowment of over 100 million ounces (Christensen, 1993), giving them global economic significance. In a number of cases, Slope assemblage rocks are not currently adequately distinguished at a regional map scale from Basin assemblage rocks. Three Slope assemblage rock units are designated on this map, and two other units with “slope” affinity are treated separately under the *Nolan belt*. Units MDst and DOts always occur in structurally bounded settings and cannot be tied to a specific place on the continental margin, except to say that they formed in proximity to a continental margin, or possibly on the slope of an oceanic feature such as a seamount. They contain significant horizons of siliciclastic material derived from a cratonal setting, and common turbiditic horizons suggesting significant sediment transport down a slope. Although units MDst and DOts are structurally bounded and have complex deformational histories involving imbricate thrusting, they usually contain definable stratigraphic sequences and important marker horizons (Cluer, Cellura, and others, 1997; Finney, Perry, and others, 1993; Noble, Cellura, and Cluer, 1999), and tend to be only locally altered or metamorphosed from mineralizing systems or igneous rocks. Unit DSt of the Slope assemblage is mapped as depositional on Ordovician and Silurian rocks of the Carbonate shelf sequence in a number of places, and is also involved in imbricate thrusting with Basin assemblage and Carbonate shelf sequence rocks. While great progress has been made in biostratigraphic dating of these rocks, in many areas further work is required to separate similar looking, different age rocks that have long been assumed to be part of a stratigraphic sequence, but are in fact structural imbrications of varied ages.

MDst **Shale, graywacke, siltstone, chert, conglomerate, and limestone (Lower Mississippian and Devonian)**—Carbonaceous shale, black chert and argillite, graywacke, chert-pebble conglomerate, and detrital limestone are the primary lithologies described from all of the rocks assigned to this unit, representing a mixed slope and basinal facies. On other maps these rocks have been included in a variety of units including the foreland basin and Devonian siliceous and transitional rocks. Mapping and new biostratigraphic data gathered in the last 30 years have shown that many of these rocks mapped only as Devonian also contain Early Mississippian fossils, thus making it difficult to distinguish them from known lithologically similar Lower Mississippian rocks. Although this unit is everywhere structurally bounded by faults, a stratigraphic link to older Slope assemblage rocks is possible. These rocks are imbricated with units D€s, ⱣMcl, O€c, Ocq, DSt, Dc, and MDcl. Whether there is a definable continuous Early Mississippian through Devonian sequence within this unit is unknown, but is suggested in the Carlin-Piñon Range (Smith and Ketner, 1978). The Slaven Chert first described in the Shoshone Range (Gilluly and Gates, 1965) is black chert with carbonaceous shale beds 4–10 feet thick, limy brown-weathering sandstone as much as four ft thick with coarse fragments of chert, shale, greenstone, limestone, graywacke, feldspathic siltstone, and brown-weathering limestone 2–20 ft thick, and contains Late Devonian radiolarians (Boundy-Sanders, Sandberg, and others, 1999). The Mississippian Waterpipe Canyon Formation is a similar formation with basal medium-grained graywacke with interlayered black, carbonaceous shale; chert-pebble conglomerate; and bedded chert grading upward into sandstone layers with black, well-rounded quartz and a black, pyritic, phosphate- and barite-bearing, argillaceous matrix interlayered with black, platy, quartz siltstone and fine-grained graywacke interbeds. It contains Early Mississippian radiolarians (Peters, Armstrong, and others, 2003). In the HD Range in northeastern Elko County, an undated, light-gray weathering, brittle, black shale, structurally underlies the other thrust sheets and was referred to as the Chainman Shale by Riva (1970), but is included here in unit MDst. In the Windermere Hills a fissile black argillite with sporadic interbeds of quartz-chert arenite is poorly exposed with variable dips suggesting a complex structure (Oversby, 1972). In the Cockalorum Wash quadrangle along the Eureka-Nye County boundary, a pale yellow-brown, organic-detrital limestone contains quartz and chert grains locally interbedded with and succeeded upward by light-colored siliceous mudstone, claystone, and siltstone. The basal limestone contains mixed Mississippian and Devonian faunas; a thin chert from a higher zone has Osagean radiolarians (Hose, 1983). In the northern Adobe Range, this unit is recognized as dark siliceous rocks consisting of shale, argillite, and bedded chert. They are faulted and folded with sparse collections of Kinderhookian and Famennian radiolarians and conodonts (Ketner and Ross, 1990). The Webb Formation in the Carlin-Piñon Range is a gray siliceous mudstone with black to gray, tan-weathering, dense limestone in lenses near the top (Smith and Ketner, 1978). The argillite of Lee Canyon is a black siliceous argillite with a little black chert and very little conglomerate and sandstone near the top (Smith and Ketner, 1978). In the Sulphur Spring Range, the Bruffey sequence (Carlisle and Nelson, 1990) is a black chert pebble to boulder conglomerate and well-bedded gritty limestone, chert and limestone conglomerate, gray limy shale, and minor sandstone. Smith and Ketner (1978) describe the same rocks as gray limestone, sandy limestone, chert, and chert-pebble conglomerate. The Woodruff Formation from the same area is described by Carlisle and Nelson (1990) as a gray fissile shale, dolomitic siltstone, and black and brown bedded chert. Smith and Ketner (1978) describe the Woodruff as dark gray to black siliceous mudstone and chert, with lesser amounts of shale, siltstone, dolomitic siltstone, dolomite, and limestone. In the Shoshone Range, pale-red to pale-brown weathering, platy, silty dolomite interbedded with black chert in the basal 50 ft of rocks referred to as the Pilot Shale by both Gilluly and Gates (1965) and Wrucke (1974) is included here. In the southern Independence Range, this unit consists of fine-grained limestone, bedded chert, shale, conglomerate, and prominent ledges of limy sandstone with Famennian and Frasnian (Late Devonian) conodonts (Ketner, 1998). In Welches Canyon northwest of Carlin, this unit is gray to black limestone, fine grained, and thin to thick bedded with common sand- and silt-size clasts of quartz and chert grains. It also contains pebbles and cobbles of chert, and interlayered chert and siliceous shale as much as 50 feet thick (Evans, 1974). In the Snake Mountains, the unit is dark carbonaceous limestone apparently overlain by a light-gray, siliceous platy siltstone. Other outcrops that belong with unit MDst, but are not mapped separately on a regional scale from Slope or Basin assemblage units D€s and DOts include the Pinecone sequence in the Toquima Range (Coles and Snyder, 1985), and gold-bearing chert (Theodore, T., oral commun., 2006) mapped informally as the "Rodeo Creek Formation" (Peters, 1997b) in the Carlin area

DSt **Platy limestone, dolomite, and chert (Lower Devonian to Silurian)—**Platy limestone, dolomite and chert are characteristic of the auriferous Roberts Mountains Formation in Nye, Elko, Eureka, and Lander Counties and of the Masket Shale and Gatecliff Formation in northern Nye County. This unit lies with depositional contact over the Hanson Creek Formation of unit SOc of the Carbonate shelf sequence (unit O€c in southern Nevada), and is also structurally imbricated with Carbonate shelf sequence rocks (O€c) and other Slope and Basin assemblages rocks (units D€s, DOts, MDst) across its area of exposure. In the Carlin area, rocks assigned to the Popovich Formation and the informal Bootstrap Limestone (Berger and Theodore, 2005; Jory, 2002) are also included. In the Monitor Range, the Roberts Mountains, and the Sulphur Spring Range, unit DSt is mapped as stratigraphically overlain by unit DSc. To what extent this "overlying" dolomite is truly a stratigraphic unit as opposed to an alteration product of this unit (Nichols and Silberling, 1977a) is unclear. A stratigraphic contact with unit MDst in the Carlin area is possible based on recent mapping (Berger and Theodore, 2005; Theodore, Moring, and others, 2003)

DOts **Calcareous shale, siltstone, chert, quartzite, and greenstone (Devonian to Ordovician)—**Calcareous shale, siltstone, sandstone, chert, quartzite, and greenstone in the Vinini Formation in Lander, Eureka, Elko, and northern Nye Counties, and the Clipper Canyon Group in the northern Toquima Range are the core rocks of unit DOts. Difficulties in identifying distinct paleogeographic settings within Ordovician slope facies rocks are discussed in Finney and Perry (1991) and Finney and others (1993). On a regional scale, the distinction between this unit and rocks traditionally mapped as the Valmy Formation (D€s) is the preponderance of shale and siltstone of cratonal derivation that is present in the Vinini rocks but less common in the Valmy rocks. Both rock units contain bedded chert, massive quartzite, and greenstone (Finney and Perry, 1991) in many places. Many lower Paleozoic rocks grouped here likely formed in a basinal rather than slope setting, but the presence of more common siliciclastic horizons of shale, siltstone, and sandstone distinguish them as a regional grouping from the lower Paleozoic Basin assemblage rocks. Whether this is a function of distinct paleogeographic settings of coeval units as interpreted by early workers, or is actually an age distinction of older (Valmy) versus younger (Vinini) Ordovician rocks, as suggested more recently for at least the Roberts Mountains (Finney, Perry, and others, 1993), remains to be determined on a regional scale. Originally thought to be primarily Ordovician, studies and biostratigraphic data have demonstrated that this unit consists of tightly imbricated Devonian, Silurian, and Ordovician rocks (Coles and Snyder, 1985; Noble and Finney, 1999). The distinction between units DOts and D€s as currently mapped on a regional scale is ambiguous in many places. Identifying the numerous occurrences of Devonian and Silurian rocks that are embedded within this unit on a regional scale would significantly enhance our understanding of the complex structural history of these rocks. These rocks are everywhere in structural contact with other Paleozoic rocks including units PMcl, Pacl, Dc, MDst, DSt, DSc, and Dcd. Stratigraphic correlation has been made between rocks of the Vinini Formation and the Carbonate shelf sequence in Nevada (Finney and Perry, 1991) on the basis of occurrence of quartzite that is coeval with the shelf unit Ocq. While this does suggest a connection between the Ordovician rocks of this composite unit and North America, the quartzite was deposited along a 1,000-mile length of the margin (Ketner, 1986) and thus does not constrain the rocks of unit DOts to deposition along a specific section of the margin. These rocks are unconformably overlain sporadically by units Pacl and PPacl, and post-Paleozoic cover rocks

Basin Assemblage

Basin assemblage rocks range from latest Cambrian through Devonian in age and represent rocks that formed primarily in a basin or lower continental-slope setting. Common rock types include chert, argillite, feldspathic siltstone and shale, quartzite, greenstone, and minor carbonate. Because of complex deformation in all of these rocks, it has been difficult to subdivide them into Ordovician, Silurian, and Devonian units, and they have generally been grouped together into larger units that represent a wide range of age and lithologic characteristics on regional maps. Distinguishing the numerous occurrences of Ordovician, Silurian, and Devonian rocks that are embedded within this unit on a regional scale would significantly enhance our understanding of the complex structural history of these rocks. These rocks are all displaced from their place of origin, and the amount of displacement relative to the continental margin is unknown, although in every place that structural studies have been done, these rocks show evidence of regional east-directed transport (Evans and Theodore, 1978; Oldow, 1984b; Peters, 1997a, b, c). Thick beds of massive quartzite are common and the timing of their deposition corresponds to at least some of the influx of quartz sand along the continental shelf suggesting a connection to the North American craton in places (Miller and Larue, 1983). Quartz sand was deposited along much of the western margin of North America more than once during the Ordovician (Finney and Perry, 1991; Gehrels, Dickinson, and others, 2000; Ketner, 1986). The Basin assemblage may consist of several distinct terranes, but regional mapping can't yet clearly distinguish them.

D€s **Shale, chert, quartzite, greenstone, and limestone (Devonian to Upper Cambrian)—**Includes the Valmy Formation in Eureka, Humboldt, Lander, and Pershing Counties; Devonian to Upper Cambrian mudstone, shale, chert, siltstone, and gray quartzite in Elko County (Leslie, Isaacson, and others, 1991); Devonian to Ordovician slate, chert, limestone, and sandstone in Mineral County; Devonian to Upper Cambrian rocks in Eureka County (Finney, Perry, and others, 1993); some rocks originally mapped as the Palmetto Formation in Esmeralda County (Albers and Stewart, 1972; Ferguson and Cathcart, 1954); and the Sonoma Range Formation (Ferguson, Muller, and Roberts, 1951) in the Sonoma Range in Humboldt County (later included with the Valmy Formation). The distinctions between these rocks and rocks of the Slope assemblage (DOts) are (1) a more complex and varied history of deformation; (2) less well-defined internal stratigraphic characteristics, which may be a function of structural complexity; (3) fewer shale, siltstone, and sandstone interbeds; (4) less carbonate; and (5) in the Roberts Mountains at least, the Ordovician rocks of this unit are older than the Slope assemblage Ordovician rocks. Like unit DOts, no basement is preserved with these rocks, making it difficult to determine where they were originally laid down, and how far they have been transported. This unit includes Devonian, Silurian, Ordovician, and uppermost Cambrian rocks imbricately faulted and folded together. In a few places, Silurian rocks are defined regionally and broken out separately (Ss), but for the most part they are included in this unit. Likewise, significant exposures of Devonian rocks have been included in unit MDst, but many more are not differentiated from this unit. A great variety of depositional settings are present in ocean basins, and this diversity is represented in these rocks (Watkins and Browne, 1989). While these rocks share a common deformation history indicative of east-directed transport from folding and thrusting along regional structures in different areas of Nevada, these rocks have been subject to additional distinct tectonic events during the Mesozoic and the Paleozoic resulting in significant spatial variability in the structure of these rocks (Evans and Theodore, 1978; Oldow, 1984b)

Ss **Feldspathic sandstone, siltstone, shale, and chert (Silurian)—**In the HD Range in northeastern Elko County, the Noh Formation was described by Riva (1970) and consists of a basal, dark-gray chert and light-gray shale, light-brown weathering, siliceous and tuffaceous siltstone and shale, and tan- and light-brown-weathering, thin-bedded siltstone, sandstone, and minor shale. It contains a large and diagnostic Wenlockian (Early Silurian) graptolite fauna, and is partly coeval with the base of the Roberts Mountains Formation (DSt) which also has a conspicuous basal chert ledge. The similar age Elder Sandstone in Lander and Eureka Counties was named for moderately cemented sandstones exposed in the Shoshone Range (Gilluly and Gates, 1965). It is primarily a fine-grained, silty sandstone, sandy siliceous and tuffaceous shale, and thin, platy, light brown chert. Much of the sandstone and siltstone is notably feldspathic, including abundant angular fragments of potassium feldspar, and has reportedly interbedded rhyolite in places (Theodore, T., oral commun., 2006). It is grouped with unit D€s or DOts in many places. Its unusual lithologic characteristics warrant a separate grouping where it can be separated from these units (Noble, Finney, and Cluer, 2000). Zircon studies have suggested that the feldspathic source material for these rocks was not located adjacent to the Nevada part of the continental margin, but is derived from a source either farther to the north or in Mexico (Gehrels, Dickinson, and others, 2000). Likewise, tuffaceous source material for the shale described in the Noh Formation is not known from the Nevada continental margin of this time. Like most other rocks of the Slope and Basin assemblages, unit Ss is everywhere in structural contact with other Paleozoic rocks. It is structurally imbricated with units D€s, DOts, and MDst. Whether these rocks have traveled a significant distance either toward or along the margin as discrete tectonic blocks or as sediment transported in offshore turbidity systems is not known, but no basement is preserved with them, and they are unconformably overlain by the Pennsylvanian and younger Siliciclastic overlap assemblage

Nolan Belt

A belt of lower Paleozoic rocks with strong affinity to the North American continental margin but with unusual structural characteristics form a discrete belt west and northwest of displaced rocks of the Slope and Basin assemblages. Earlier maps included these rocks in either “Transitional” or “Siliceous” groupings (Roberts, Hotz, and others, 1958). They are different from the other Paleozoic rocks in a number of important ways that warrant distinction as a separate group. These rocks have structural characteristics of an accreted terrane, that is, they exhibit polyphase deformation, but have stratigraphic ties to North America that suggest they have not traveled great distances laterally from the continental margin. The origin of the name of this group is for T.B. Nolan, whose early paper defined many of these rocks as part of an important “geanticline” during the later Paleozoic long before such concepts had any grounding in modern tectonic understanding (Nolan, 1928), and prior to recognition of the magnitude of displacement that has affected adjacent Paleozoic rocks and terranes.

The distinguishing characteristics of the Nolan belt of rocks are (1) lithologically they define a region of outer shelf and slope Cambrian and Ordovician rocks, originally deposited in a more proximal position to the Carbonate shelf sequence than the rocks of units D€s or DOts, which now lie east, or inboard of many exposures of units O€td and €td, (2) unlike rocks of units DOts, D€s or Ss, they are stratigraphically attached to their Cambrian to Precambrian quartzite basement (€Zq), otherwise exposed only much farther to the east, (3) they have a varied and complex structural history that in at least some cases clearly involves multiple pre-Pennsylvanian deformation events with both east-vergent and west-vergent deformation (Crafford and Grauch, 2002; Ehman, 1985; Means, 1962; Oldow, 1984b), (4) like rocks of the Basin, Slope, and Foreland basin assemblages, they are unconformably overlain by Pennsylvanian and younger rocks of the Siliciclastic overlap assemblage, constraining the age of much of their deformation to pre-Middle Pennsylvanian, and (5) rocks of the Nolan belt have been much more deeply buried than coeval and lithologically similar rocks that crop out farther east, as witnessed by the metamorphic character of the slates, phyllites, and schists, and by the Conodont Color Alteration Index of the rocks (Crafford and Harris, 2005). Two units are included in this group, units O€td, and €td. The basement rocks are treated separately because they are common to the base of both the Nolan belt and the Carbonate shelf sequence.

O€td **Shale, chert, phyllite, quartzite, and limestone (Ordovician to Cambrian)—**Rocks included in this unit have been mapped as the Broad Canyon Formation and Crane Canyon sequence in Lander County (Means, 1962), the Palmetto Formation in Esmeralda and Nye Counties (Ferguson and Cathcart, 1954), the Van Duzer Limestone in northern Elko County (Coats, 1971; Coats, Howard, and Greene, 1984; Decker, 1962; Ehman, 1985), and many other unnamed and locally named rocks. These rocks are strongly deformed, although the nature of the deformation is variable across the belt (Oldow, 1984b) and not well understood regionally. This unit is usually shown both in fault contact with adjacent units Ꞓtd and ꞒZq and gradational with them. Unit Pacl of the Siliciclastic overlap assemblage is shown unconformably deposited on this unit in Wall Canyon of the Toiyabe Range in Nye County. In a few cases, this unit is a stratigraphic continuation from Ꞓtd, but in most places it represents undifferentiated rocks of both Ordovician and Cambrian age that overlap with Ꞓtd, or whose age is poorly constrained

Ꞓtd **Phyllite, schist, shale, thin-bedded limestone, chert, and siltstone (Cambrian)—**Shale, thin-bedded limestone, phyllite, hornfels, quartzite, chert, and siltstone are typical of this Cambrian unit which exhibits regional metamorphism suggesting significant burial depths have heated and recrystallized many of these rocks. This unit includes rocks mapped informally as the Bull Run Dolomite and Edgemont Formation in northern Elko County by Ehman (1985); the Crane Canyon sequence in the Toiyabe Range; some regions mapped as Dunderberg Shale; and the Swarbrick Formation in northern Nye County, the Emigrant Formation in southern Nye and Esmeralda Counties, the Mule Spring Limestone in Esmeralda County, the Preble Formation in Humboldt and Pershing Counties (Madden-McGuire, 1991), the Paradise Valley Chert in Humboldt County, and the Schwin Formation (Gilluly and Gates, 1965) in the Shoshone Range in Lander County. In most exposures this unit lies transitionally above the Cambrian-Precambrian quartzite unit ꞒZq. In places this unit is transitional into OꞒtd. This unit is also in structural contact with DꞒs, DOts, OꞒc, OꞒtd, ꞒZq, the Golconda terrane (GC), and the Dutch Flat terrane (DF). In the Osgood Mountains (Boskie and Schweickert, 2001; Crafford and Grauch, 2002; Madden-McGuire and Marsh, 1991), the Bull Run Mountains (Ehman, 1985), the Toiyabe Range (Means, 1962), and the Miller Mountain area (Oldow, 1984b) these rocks exhibit complex polyphase deformation with a strong west-vergent component. At Edna Mountain near Golconda in Humboldt County, these rocks are unconformably overlain by both Pacl and PPacl of the Siliciclastic overlap assemblage

Precambrian And Other Rocks

Lower Cambrian to Latest Proterozoic Clastic Rocks

Precambrian to Lower Cambrian clastic rocks form the base of the Carbonate shelf sequence in eastern and southern Nevada. They also form the stratigraphic base of the rocks of the Nolan belt. They are part of a large sequence of Precambrian rocks that represent the original rifted margin of western North America (Stewart, 1972). They rest unconformably over older Proterozoic basement that is only exposed in southernmost Nevada.

ꞒZq **Crossbedded quartzite, siltstone, and phyllite (Lower Cambrian and latest Proterozoic)—**These lowermost Cambrian to Precambrian strata are scattered over much of central and eastern Nevada and form the base of the Phanerozoic part of the continental margin stratigraphic section. They include the Campito, Deep Spring, Harkless, and Poleta Formations, and the Reed Dolomite in Esmeralda County; the Gold Hill Formation in northern Nye County; unnamed quartzite and shale in White Pine County; the Osgood Mountain quartzite in Humboldt County; the Prospect Mountain Quartzite in northern Nye, Lincoln, Eureka, and Elko Counties; unnamed quartzite and shale in Lander and Clark counties; and the Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite in southern Nye County. In a number of places, these rocks are depositional on Late Proterozoic unit Zqs. In southernmost Clark County, ꞒZq is lying unconformably directly on Early Proterozoic gneiss (Xm). In the east-central part of Nevada, ꞒZq is overlain depositionally by Cambrian carbonate (Ꞓc) of the Carbonate shelf sequence. In the Nolan belt, these rocks are depositionally overlain by unit Ꞓtd. In the Osgood Mountains in Humboldt County, Permian and Pennsylvanian rocks of the Siliciclastic overlap assemblage (PPacl, Pacl) rest unconformably directly on the Osgood Mountain Quartzite

ꞒZqm **Metaquartzite (Lower Cambrian and latest Proterozoic)—**This highly metamorphosed equivalent of ꞒZq crops out in the Ruby Mountains and East Humboldt Range in Elko County, in the Toquima and Monitor Ranges in northern Nye County, and at the northern tip of the White Mountains in Mineral and Esmeralda Counties. In the Ruby Mountains it is transitional into

O€cm, and in the White Mountains it is transitional into O€td

Zqs **Quartzite, siltstone, conglomerate, limestone, and dolomite (Late Proterozoic)—**Limestone, quartzite, dolomite, siltstone, conglomerate, and metamorphic rocks crop out in the southeastern, east-central, and northeastern regions of the State as part of Zqs. It forms the Proterozoic base of the continental margin stratigraphic section. This unit includes the Johnnie Formation in southern Nye and Lincoln Counties, schist in Elko County, the McCoy Creek Group metamorphic rocks in Elko and White Pine Counties, and the Wyman Formation in Esmeralda and southern Nye Counties. This rock is overlain by €Zq. Its base is not exposed

Proterozoic Basement Rocks

Yfi **Felsic phaneritic intrusive rocks (Middle Proterozoic)—**This porphyritic rapakivi granite is present only in Clark County where it intrudes Proterozoic gneiss and schist (Xm)

Xm **Gneiss and schist (Early Proterozoic)—**Exposed mostly in Clark and Lincoln Counties, with two small outliers in southern Nye County

Other Rocks

Other rocks include a breccia unit of mixed breccias that identifies locally disrupted rocks; a gneiss, schist, and migmatite in Elko County, the only high-grade metamorphic rock in Nevada; and ultramafic rocks with serpentine that are scattered in a few places around the State adjacent to major Paleozoic and Mesozoic terrane boundaries.

br **Mixed breccias including volcanic, thrust, jasperoid, and landslide megabreccia (Tertiary to Jurassic)—**Breccias of various origins are scattered across Clark, Nye, Lincoln, Elko, Eureka, Lander, and White Pine Counties. Most are interpreted to be Tertiary in age, but have tectonic, volcanic, and metamorphic origins, and include jasperoids, brecciated tuffs, exotic slide blocks, landslide deposits, megabreccia, thrust breccia, and debris beds

TAgn **Metamorphic-igneous complex (Oligocene, Cretaceous, and Jurassic with Paleozoic, Proterozoic, and Archean protolith)—**In the Ruby Mountains and East Humboldt Range in Elko County, this unit is an orthogneiss with amphibolite and paragneiss. It includes granodiorite and quartz monzonite gneiss, granitic to dioritic gneiss, biotite and muscovite schist, quartzitic schist, quartzite, calc-silicate rocks, marble, migmatitic Oligocene granodiorite, and Cretaceous and Jurassic granite. The protoliths for the East Humboldt Range orthogneiss include Archean through Paleozoic rocks (Lush, McGrew, and others, 1988; McGrew, Peters, and Wright, 2000)

ŦPzsp **Ultramafic rocks and serpentine (Triassic or upper Paleozoic)—**Ultramafic rocks are present in very small belts or lenses in a few places across the State. In the Candelaria Hills along the Mineral-Esmeralda County boundary, they crop out in a thrust complex that overlies the Candelaria Formation (Ŧcl). At Willow Spring, at the southern end of the Toquima Range south of Manhattan, serpentine is exposed again adjacent to the Candelaria Formation and deformed lower Paleozoic rocks (O€td). A few small outcrops also are present on the east side of the Toquima Range near Belmont adjacent to lower Paleozoic rocks. In the Toiyabe Range in Nye County, scattered outcrops of serpentine form a narrow north-south trending belt adjacent to the Golconda terrane (GC), deformed lower Paleozoic rocks (O€td, €td), and the Siliciclastic overlap assemblage. An early Triassic conodont was recovered near the serpentine near Marysville Canyon (Poole and Wardlaw, 1978), although the Candelaria Formation does not show on the map in this area. All of these exposures of ultramafic rocks are in a similar relative tectonic position above deformed lower Paleozoic rocks and the Siliciclastic overlap assemblage, and below the structurally overlying Golconda terrane. A narrow belt of serpentine and gabbro is exposed at the northern edge of the Golconda terrane in the Hot Springs Range in Humboldt County. In this case, the ultramafic rock is structurally above the Golconda terrane, and beneath the overlying Mesozoic Jungo terrane (JO)

Map References

References used in editing the geologic map in addition to the 1978 State map and the individual county maps are shown in the "Refs" attribute column of the geology layer. The codes and references used are listed here and shown in complete form in the references section.

Map reference code	Reference
Abase	Henry, Chris, unpublished radiometric database of Nevada, Nevada Bureau of Mines and Geology
Barnes and others, 2001	Barnes, Burton, and others, 2001
Cohen, 1980	Cohen, 1980
CONO	Harris, Anita, ConodontSamples.shp, this map
Ehman, 1985	Ehman, 1985
GSA SP 163	Silberling, 1975
Heidrick, 1965	Heidrick, 1965
Lovejoy, GSA Bull 70, p. 539	Lovejoy, 1959
Means, 1962	Means, 1962
Miller and others, 1984	Miller, Holdsworth, and others, 1984
NBMG FS Map 12	Henry, 1996
NBMG FS Map 14	Jones, 1997b
NBMG FS Map 21	Miller, Gans, and others, 1999
NBMG FS Map 4	Mueller, 1993
NBMG Map 104	Martin and Naumann, 1995
NBMG Map 143	Theodore, Moring, and others, 2003
NBMG Map 35	Fritz, 1968
NBMG Map 97	Carlisle and Nelson, 1990
NBMG OFR 03-4	Thorman, Brooks, and others, 2003
NBMG OFR 04-9	Thompson, Teal, and Meeuwig, 2002
Neff, 1969	Neff, 1969
Oldow, 1984	Oldow, 1984a
OSS, 1993	Oldow, Satterfield, and Silberling, 1993
Oversby, 1972	Oversby, 1972
PandW, 1978	Poole and Wardlaw, 1978
Peters and others, 2003	Peters, Armstrong, and others, 2003
Riva, 1970	Riva, 1970
Rowley, 1980	Rowley, 1980
SandS, 1989	Speed, Silberling, and others, 1989
Sayeed, 1973	Sayeed, 1973
Speed-Diablo-77	Speed, MacMillan, and others, 1977
Stewart, 1980	Stewart, 1980
Thurber, 1982	Thurber, 1982
USGS B 1162-B	Ketner and Smith, 1963
USGS B 1312-P	Wells and Elliott, 1971
USGS B 1439	Coats, Green, and others, 1977
USGS B 1988-D	Ketner, Murchey, and others, 1993
USGS GQ-1117	Evans, 1974
USGS GQ-1174	Erickson and Marsh, 1974a
USGS GQ-1307	McKee, 1976a
USGS GQ-1710	John and Silberling, 1994
USGS GQ-1721	Anderson and Hintze, 1993
USGS GQ-1758	Miller, Grier, and Brown, 1995
USGS GQ-1759	Hintze and Axen, 1995
USGS GQ-656	Gilluly, 1967
USGS I-1028	Smith and Ketner, 1978

Map reference code	Reference
USGS I-1410	Hose, 1983
USGS I-1578	Ekren and Byers, 1985
USGS I-1866	Loucks, Tingey, and others, 1989
USGS I-1902	Ketner and Evans, 1988
USGS I-2081	Ketner and Ross, 1990
USGS I-2082	Ketner, 1990
USGS I-2097	Smith, Ketner, and others, 1990
USGS I-2394	Wallace, 1993
USGS I-2409	Whitebread, 1994
USGS I-2629	Ketner, 1998
USGS I-612	Nolan, Merriam, and Brew, 1971
USGS I-667	Evans and Ketner, 1971
USGS I-793	Nolan, Merriam, and Blake, 1974
USGS MF-1877-J	John, 1987
USGS MF-2062	Silberling and John, 1989
USGS MF-2154-A	Greene, Stewart, and others, 1991
USGS MF-2327	Shawe, 2002
USGS OFR 03-236	Sloan, Henry, and others, 2003
USGS OFR 68-260	Stewart and McKee, 1968
USGS OFR 84-644	Coats, Howard, and Greene, 1984
USGS OFR 91-429	Theodore, 1991
USGS OFR 94-664	Doebrich, 1994
USGS PP 575-D, p. 56–63	Stewart and Palmer, 1967
USGS PP 592	Silberling and Wallace, 1969
USGS PP 668	Lee and Van Loenen, 1971
USGS PP 931	McKee, 1976b
USGS SI-2814	Page, Lundstrom, and others, 2005
Wyld, 2002	Wyld, 2002

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Acknowledgments

A compilation and reinterpretation of this scope would not be possible without a great deal of input from many people. The author is greatly indebted to the following people for their invaluable assistance, insight and important information; Ron Hess and Gary Johnson for the original digital work on the county maps; Norm Silberling, Mesozoic and Paleozoic terranes; John Oldow, Mesozoic terranes; Alan Wallace, Dave John, and Chris Henry, Tertiary volcanic rocks; Ed du Bray and Steve Ludington, Intrusive rocks; Keith Howard, Metamorphic rocks; Anita Harris, Conodonts; and David Jones, Paleozoic and Mesozoic terranes and tectonics. Most thoughtful and thorough reviews of geologic content by Ted Theodore, digital content by Doug Yager, geologic names review by Tom Judkins, and final editing by Gayle Dumonceaux are gratefully acknowledged. Paul Denning provided critical GIS support in the final stages of the map, and Gary Raines offered valuable insight and advice for the digital content and metadata. The author takes full responsibility for errors and omissions, and is grateful to the many individuals whose insight and observations provided the ingredients for revised interpretations presented herein. Financial support that made this project possible was provided by AngloGold, North America; Anita Harris; Nevada Bureau of Mines and Geology; and Al Hofstra and the Metallogeny of the Great Basin team of the U.S. Geological Survey. Thank you one and all.

Journal of Hydrology, 119 (1990) 357–388
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

[2]

A DEUTERIUM-CALIBRATED GROUNDWATER FLOW MODEL OF A REGIONAL CARBONATE–ALLUVIAL SYSTEM

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(Received March 22, 1989; accepted after revision December 16, 1989)

ABSTRACT

Kirk, S.T. and Campana, M.E., 1990. A deuterium-calibrated groundwater flow model of a regional carbonate–alluvial system. J. Hydrol., 119: 357–388.

The White River Flow System (WRFS), a regional carbonate–alluvial groundwater system in southeastern Nevada, U.S.A., contains large amounts of water in storage, especially in the underlying carbonate reservoir. As the population of Nevada grows, it may become necessary to tap the resources of this and other regional carbonate systems. Because of the depth to the carbonate reservoir and, until now, lack of motivation to collect detailed hydrogeological data on it, the state of knowledge of flow in the carbonate system is poor. However, a simple mixing-cell flow model of the WRFS can be constructed and calibrated with the spatial distribution of the stable isotope deuterium. This type of model subdivides the system into carbonate and alluvial cells and routes water and deuterium through the entire cell network. It provides estimates of recharge rates, groundwater ages and volumes of water in storage. Transience in recharge rates and their deuterium signatures are unaccounted for by the model.

The lack of constraints on the system mandates the calibration of three different flow scenarios, each of which differs slightly from the other. Despite these differences, some consistent quantitative results are obtained. Foremost among these are: (1) the carbonate aquifer may contain as much as 752 km^3 of water in storage; (2) recharge from the Sheep Range to Coyote Spring Valley is at least 90% greater than previously believed; (3) Lower Meadow Valley is part of the WRFS and contributes underflow to Upper Moapa Valley; (4) underflow with an average value of 0.163 $m^3 s^{-1}$ flows westward out of the system along the Pahranagat Shear Zone; (5) recharge to the alluvial system is greater than that to the carbonate system; (6) groundwater mean ages range from 1600 to 34 000 years, with the oldest waters exceeding 100 000 years old. The results also demonstrate that deuterium can be used to calibrate simple flow models and provide groundwater ages.

Despite the uncertainties and lack of constraints in mixing-cell models, they provide first approximations to information which, until now, has been difficult, if not impossible, to obtain. These models are especially useful for analyzing sparse-data systems, testing different flow hypotheses with minimal effort, providing ranges in parameter estimates, guiding future data collection and serving as precursors for the development of more sophisticated models.

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0022-1694/90/$03.50

INTRODUCTION

Long-term water supply needs in southern and eastern Nevada, U.S.A., have rekindled interest in regional carbonate flow systems within the Paleozoic miogeosynclinal belt of eastern Nevada. This paper describes the quantification of various flow properties of one such system, the White River Flow System (WRFS), shown in Fig. 1. The WRFS was originally defined by Eakin (1966),

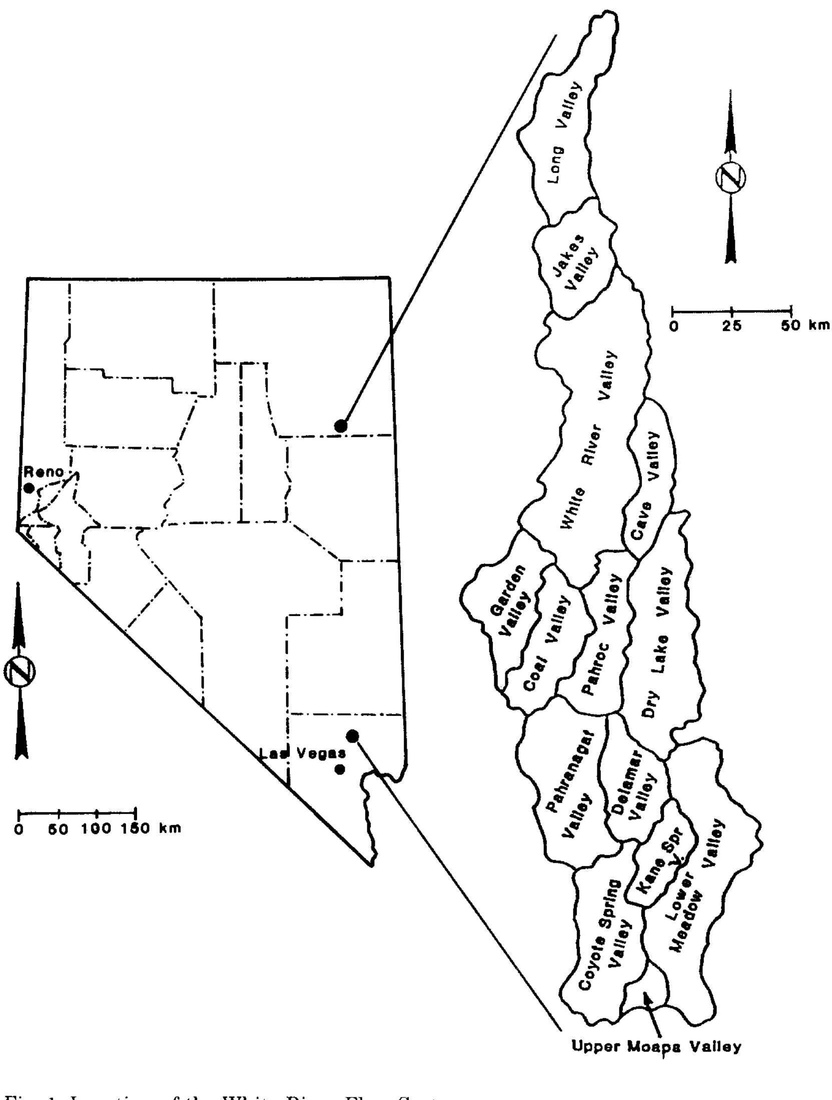

Fig. 1. Location of the White River Flow System.

who used a water-budget approach to delineate the system boundaries. Because of the areal extent of this flow system (20 000 km^2), sparse data, and uncertainties in the hydrogeological parameters (saturated thicknesses, porosities, and recharge volumes), it is difficult to use a conventional flow model to obtain quantitative estimates of the system's properties. However, a simple mixing-cell model, which requires fewer data, can yield estimates of storage volumes, groundwater residence times, and recharge rates. The application and hydrological implications of such a model vis-à-vis the WRFS are the subject of this investigation.

As originally defined by Eakin (1966), the WRFS includes thirteen topographic basins and extends 400 km from north to south, encompassing an area of $> 18\,000\,km^2$. Eakin's original flow system excluded Lower Meadow Valley, which is included in our model. The land surface slopes to the south, with valley floor elevations decreasing from 1700 m above mean sea level (msl) in the north to 550 m above msl in the vicinity of Muddy River Springs, the distal end of the system. In the northern part of the study area, the crests of the mountain ranges commonly exceed 2400 m in elevation and locally exceed 3000 m. In the southern part, mountain crests exceed 2400 m only locally and generally are < 2100 m above msl.

The objectives of this study were to:

(1) simulate flow in a large regional aquifer system using a simple mixing-cell model calibrated with the environmental stable isotope deuterium;

(2) use this model to estimate the aquifer system's storage volume, average annual recharge rates and flow distributions;

(3) document the ability of the stable isotope-calibrated model to estimate groundwater age distributions.

These objectives will be accomplished by use of three different flow scenarios, each of which may be feasible, given the lack of detailed hydraulic and hydrologic information on the WRFS.

GEOLOGY

The regional geology of the WRFS is dominated by Basin and Range horst and graben structure, formed by high-angle normal faults, oriented north–south. The intermontane basins (grabens) have been filled with alluvium eroded from the mountain blocks (horsts). As this study deals with regional groundwater flow, the geological description will be kept to a minimum.

Exposed rocks in the WRFS generally fall into three groups: Precambrian to Triassic igneous, metamorphic, and sedimentary rocks; Cenozoic sedimentary rocks; and Cenozoic volcanic rocks. Paleozoic rocks belong to the carbonate or eastern assemblages which were formed in shallow marine, intertidal, and supertidal depositional environments (Stewart, 1980).

Mesozoic sedimentary rocks were eroded during the period from the late Triassic uplift to late Jurassic or Cretaceous thrust faulting. Throughout the Tertiary, a huge outpouring (perhaps 1000 km^3) of volcanic material occurred.

These Tertiary volcanic rocks, largely tuffs, are predominantly exposed in the southern half of the WRFS. Volcanism was followed by late Cenozoic Basin and Range faulting and deposition of valley-fill sediments (Tschanz and Pampeyan, 1970).

The geological structure of the region was formed by compression during the Mesozoic–early Tertiary Sevier Orogeny, and extension during the Miocene–Holocene. Normal faults underlying valleys of the WRFS can serve as areas of spring discharge. The WRFS is divided by a regional lineament, the Pahranagat Shear Zone, composed of a series of parallel northeast–southwest trending strike-slip faults. This zone, exposed in the Pahranagat Range, which forms the western boundary of Pahranagat Valley, is composed of distinct parallel faults: the Arrowhead Mine, Buckhorn, and the Maynard Lake Faults. Northeast–southwest trending lineaments have also been mapped in the Arrow Canyon Range at the southern end of the WRFS and identified as deep-seated structural anomalies which serve as conduits for regional groundwater flow (McBeth, 1986).

HYDROGEOLOGY

Hydrostratigraphy

Three distinct hydrostratigraphic units occur in the WRFS: (1) Paleozoic carbonates; (2) Tertiary volcanics; (3) Tertiary and Quaternary valley fill. A map of these rock types is shown in Fig. 2.

Large quantities of groundwater are known to flow through the Paleozoic carbonate rocks in eastern Nevada (Eakin, 1966). Transmissive properties of the Paleozoic carbonates are facilitated by secondary porosity as a result of faults, joints, fractures and solution channels (Hess and Mifflin, 1978). Locally, the stratigraphic section of the Paleozoic carbonates exceeds 9000 m (Kellog, 1963). Within these Paleozoic rocks are low-permeability clastic rocks, primarily quartzite and shale, which act as aquitards. Knowledge of the total thickness of the transmissive section of the Paleozoic carbonates and corresponding effective porosity is difficult to obtain because of the paucity of deep borehole data.

Tertiary volcanics are extensive in the region. The primary porosity of these rocks is low but secondary porosity exists, as a result of joints and fractures. In many places, Tertiary volcanics lie between Paleozoic carbonates and valley fill.

Valley-fill alluvium was deposited in the north–south trending grabens and is composed of fine-grained lacustrine or playa deposits or Quaternary gravels, sand, silts and clay laid down in stream channels, alluvial fans and playa environments. Unconsolidated sand and gravel deposits of the younger valley-fill and alluvial fans are capable of transmitting water freely (Eakin, 1966).

Thicknesses of valley-fill deposits vary greatly. In Coyote Spring Valley the average thickness of the valley fill is 100 m, whereas in Dry Lake Valley the estimated maximum thickness, based on gravity surveys, is 3000 m.

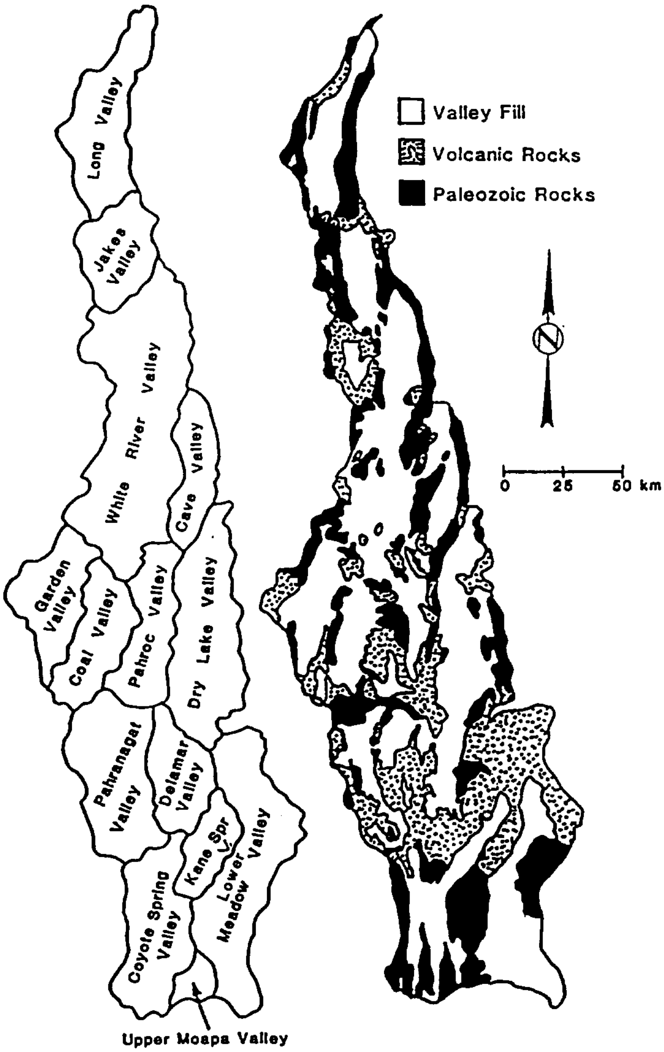

Fig. 2. Hydrostratigraphic units in the White River Flow System.

Groundwater

The occurrence of groundwater in the WRFS is generally confined to the three hydrostratigraphic units previously defined. Regional movement of groundwater in the WRFS was originally proposed by Eakin (1966), who based his conceptual model upon: (1) relative hydraulic properties of the major rock groups; (2) regional movement of groundwater as inferred from hydraulic gradients; (3) relative distribution and quantities of estimated recharge and discharge; (4) chemical quality of water discharged from major springs. Flow paths defined by Eakin are shown in Fig. 3; arrows indicate the general direction of groundwater flow.

In defining the boundaries of the WRFS, Eakin assumed that: (1) the mountain bedrock is virtually impermeable and lateral movement of water conforms to the general slope of the surface topography; (2) topographic axes of mountain ranges are coincident with structural trends which act as barriers to groundwater flow; (3) groundwater divides are coincident with topographic

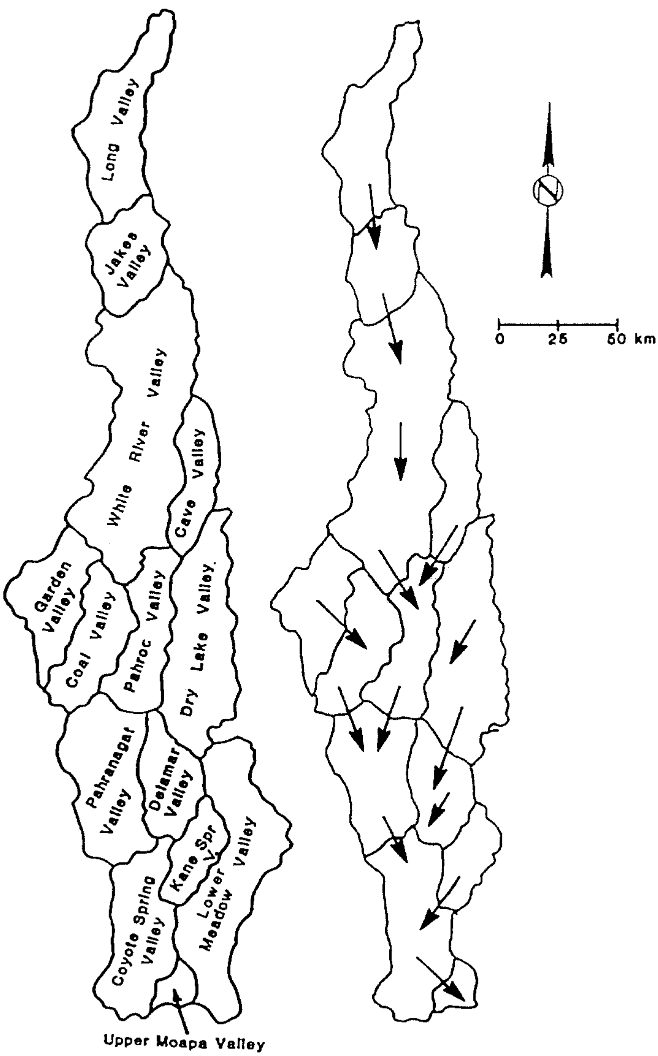

Fig. 3. Flow paths in the White River Flow System according to Eakin (1966).

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divides. The first and last assumptions can be in error for certain instances where hydraulic gradients in a regional aquifer are not coincident with those in the overlying alluvial aquifer and with the gradient of the topography. However, given the paucity of hydrologic data available to Eakin, his assumptions were reasonable. Horizontal hydraulic gradients were obtained from water levels in alluvial wells and springs. Eakin assumed that hydraulic gradients in the regional aquifer were somewhat less than in the overlying alluvial aquifer. Estimates of recharge volumes were obtained with the Maxey–Eakin method of recharge estimation (Maxey and Eakin, 1949).

Discharge from the WRFS occurs principally as spring discharge. Major spring discharge occurs in three areas: (1) White River Valley, where discharges of $\sim 0.861\,m^3\,s^{-1}$ of warm water ($> 20°C$) and $\sim 0.548\,m^3\,s^{-1}$ of cold water occur; (2) Pahranagat Valley, where a discharge of $\sim 0.978\,m^3\,s^{-1}$ of warm water occurs; (3) Muddy River Springs in Upper Moapa Valley, where a discharge of $\sim 1.408\,m^3\,s^{-1}$ of warm water occurs. Very little variation in discharge has been noted for these springs. Evaporation of discharge from Pahranagat Valley springs occurs principally from Pahranagat and Maynard Lakes.

Discharge of groundwater by evapotranspiration (ET) in valleys not associated with regional springs is $\sim 0.196\,m^3\,s^{-1}$ and occurs principally in Long ($0.086\,m^3\,s^{-1}$), Garden ($0.078\,m^3\,s^{-1}$), and Cave ($0.008\,m^3\,s^{-1}$) Valleys (Eakin, 1966). Evapotranspiration estimates are considered rough approximations. This study has adopted the ET estimates of Eakin as the more rigorous approach of phreatophyte mapping was beyond the scope of this study.

Winograd and Friedman (1972) postulated several changes to Eakin's conceptual model and questioned the validity of a water-budget-based model in light of environmental isotopic data in the region. They concluded that: (1) significant underflow from Pahranagat Valley via the Pahranagat Shear Zone exists; (2) discharge from Muddy River Springs may be derived from the Spring Mountains, west of Las Vegas, rather than the WRFS, despite the groundwater barrier effects of the Las Vegas Shear Zone; (3) the 13‰ difference between the observed deuterium value at Pahranagat Springs in Pahranagat Valley and Muddy River Springs is because of variation of deuterium recharge concentration with time.

Welch and Thomas (1984) proposed other modifications to Eakin's model of the system. Results of mass-balance calculations using deuterium isotope data and recharge and discharge estimates reveal greatly reduced flow past areas of major discharge in the White River and Pahranagat Valleys.

Other contributions to hydrologic data of the WRFS have been made by Eakin (1962, 1963a, b, 1964), Mifflin (1968), and Mifflin and Hess (1979). Potentiometric mapping of the region by Thomas et al. (1985) has resulted in the elimination of Long Valley from the flow system, assuming that hydraulic gradients in the alluvium are similar to those in the underlying carbonate aquifer.

DISCRETE-STATE COMPARTMENT MODEL

A discrete-state compartment (DSC) model (Simpson and Duckstein, 1976) was used to simulate flow in the WRFS. The DSC code was developed by Campana (1975) and applied to the Tucson Basin by Campana and Simpson (1984), and the Edwards aquifer by Campana and Mahin (1985).

Discrete-state compartment models are nothing more than sophisticated mixing-cell models, which represent the given hydrogeological system as a network of interconnected cells, through which water and dissolved materials are transported. A recursive form of the conservation of mass equation governs the transport of water and dissolved matter. For any given cell, the basic equation of the DSC model is (Simpson and Duckstein, 1976)

$$S(N) = S(N-1) + [\mathrm{BRV}(N) \times \mathrm{BRC}(N)] - [\mathrm{BDV}(N) \times \mathrm{BDC}(N)] \quad (1)$$

where: $S(N)$ is the cell state at iteration N, the mass or amount of tracer in the cell; BRV(N) is the boundary recharge volume at iteration N, the input volume of water to the cell; BRC(N) is the boundary recharge concentration at iteration N, the input concentration of tracer; BDV(N) is the boundary discharge volume at iteration N, the output volume of water from the cell; BDC(N) is the boundary discharge concentration at iteration N, the output concentration of tracer.

The tracer concentration in the water, or in this case, the deuterium value of the recharge water, entering a boundary cell from outside the model's boundaries, is referred to as a system boundary recharge concentration (SBRC). The volume of recharge water entering a boundary cell is referred to as a system boundary recharge volume (SBRV).

Equation (1) is applied successively to each cell in the network during a given iteration. As a result, boundary discharge volumes and concentrations from 'upstream' cells become boundary recharge volumes and concentrations to 'downstream' cells. The BDC(N) term is the only unknown on the right side of eq. (1). Its value can be ascertained by specifying one of two mixing rules: the simple mixing cell (SMC) rule or the modified mixing cell (MMC) rule. The former rule simulates perfect mixing within a cell, and the latter imitates some middle ground between perfect mixing and pure piston flow. For the SMC

$$\mathrm{BDC}(N) = \{S(N-1) + [\mathrm{BRV}(N) \times \mathrm{BRC}(N)]\}/[\mathrm{VOL} + \mathrm{BRV}(N)] \quad (2)$$

where VOL is the volume of water in the cell.

For the MMC

$$\mathrm{BDC}(N) = S(N-1)/\mathrm{VOL} \quad (3)$$

The MMC approaches pure piston flow as the BRV approaches VOL, and approaches perfect mixing as the BRV approaches zero. This study used both options. As the model approached calibration, the model-derived deuterium values were almost identical for both SMC and MMC options.

Each cell in the DSC model depicts a region of the hydrogeological system; regions are differentiated based upon their hydrogeological uniformity and the availability of the data. Variability within the system is distributed between cells. Cells can be of any desired size and can be arranged in a one-, two-, or three-dimensional configuration.

Discrete-state compartment models permit the user to specify the flow paths between cells and the discharge from the system. To do so requires an initial estimate of the flow system, such that an initial set of specifications can be established. During the calibration process, these parameters are adjusted by the modeler to obtain agreement between the simulated and observed tracer concentrations.

DEUTERIUM AS A GROUNDWATER TRACER

The stable isotope deuterium (^2H or D) was chosen as the tracer in the DSC model. Deuterium is a useful groundwater tracer because it: (1) is part of the water molecule; (2) does not decay with time; (3) is not removed from water by exchange processes during movement through most aquifer materials; (4) experiences no hydrodynamic dispersion. The deuterium content of precipitation varies with latitude and elevation. Variations are caused principally by the history of isotopic fractionation that occurred during changes of state of water between vapor, liquid, and solid. These variations serve to 'fingerprint' water masses, which is reflected by the spatial distribution of deuterium in concentrations in groundwater.

The measurement of deuterium content is made with a mass spectrometer. As absolute quantities of stable isotopes are difficult to measure, the isotopes of hydrogen are measured as the ratio between the element's heavy and light isotopic species. The relative permil (‰, i.e. parts per thousand) deviation of the sample isotopic ratio from that of the standard is defined as

$$\delta D = 1000[(D/H)_{\text{sample}} - (D/H)_{\text{standard}}]/(D/H)_{\text{standard}} = 1000(R_D - 1) \tag{4}$$

where R_D is the ratio between the heavy to light isotope ratio of the sample to that of the standard. A depletion of heavy isotopes in the sample, measured with respect to the standard, corresponds to a negative δD value. The abbreviation is usually understood to represent permil units. In this study, the standard is Vienna Standard Mean Ocean Water (V-SMOW).

In using deuterium as a groundwater tracer, the following assumptions are implicit: (1) recharge waters can be assigned a characteristic deuterium value; (2) the deuterium signature of recharge is a function of the geographic location (latitude, elevation, distance from the ocean, and temperature); (3) deuterium is a conservative tracer. With regard to the first two assumptions, deuterium samples from high-altitude springs were assumed to be representative of recharge waters from a given mountain range. The third assumption is critical to the successful use of deuterium as a groundwater tracer. This assumption can be invalid if fractionation or isotopic exchange has occurred subsequent to recharge. Although exchange of deuterium may occur in some hydrogen-bearing clays, it is not considered a significant process in this system.

The question of the time invariance of deuterium signatures of the recharge water and the recharge rate itself is a valid one. Paleoclimatically induced shifts in each quantity have no doubt occurred in the past. With the exception of preliminary work by Winograd et al. (1985), which dealt with waters older than the groundwaters in the WRFS, no quantitative investigations have been undertaken to determine these paleoclimatically induced shifts in eastern Nevada. Claassen (1983) interpreted the distribution of δD plotted against ^{14}C-derived ages as an indication of a deviation from the mean annual temperature. Mifflin and Wheat (1979) estimated, based on Pleistocene lake levels in the Great Basin, a mean annual temperature decrease of 5°C and a mean annual precipitation increase of ~68% during the lacustrine episodes. These studies suggest possible paleoclimatically induced shifts in both deuterium signatures and recharge rates. As quantitative shift data are lacking, the model described herein assumed time-invariation recharge rates and deuterium signatures.

Seventy-four deuterium values were used in this study, 34 of which were used for SBRC (recharge signature) determination and the remainder for calibration. Of the total, 25 samples were collected and analyzed by the Desert Research Institute (DRI). Eighteen of the DRI samples were collected in June 1986 as a part of this study. The remaining data were selected from the United States Geological Survey (USGS) data base in Reston, VA. The complete data suite can be found in Kirk and Campana (1988).

DEVELOPMENT OF THE WHITE RIVER FLOW SYSTEM DSC MODEL

Flow scenarios

Because of the dearth of data on the WRFS, the uncertainties in the information available (saturated thicknesses, recharge volumes, effective porosities, etc.) and the large number of degrees of freedom in the DSC model, three different flow scenarios were simulated. This approach leads to estimates of the range in a certain parameter (e.g. volume of storage in the carbonate aquifer) as opposed to a single value. Although a large number of flow scenarios could be specified, the three selected were designed to address the following aspects of the WRFS: (1) the differences in deuterium concentration between the Pahranagat Valley springs (average: −108‰) and the carbonate wells in Coyote Spring Valley (average: −101‰); (2) the differences in deuterium concentration between the carbonate wells of Coyote Spring Valley and Muddy River Springs (−98‰); (3) distribution of groundwater flow in the White River Valley; (4) existence of underflow from Long Valley into Jakes Valley. Each scenario consists of an overlying alluvial aquifer (tier 1) and an underlying carbonate aquifer (tier 2).

Scenario 1 divides the WRFS into 22 cells (Fig. 4), composed of two tiers. Alluvial (tier 1) and carbonate (tier 2) aquifers were specified for Jakes, White River, Cave, Coal/Garden, Dry Lake, and Delamar Valleys. Alluvial aquifers were not specified for Pahroc, Pahranagat, Coyote Spring, Kane Springs, Lower Meadow and Upper Moapa Valleys, because of the relatively small

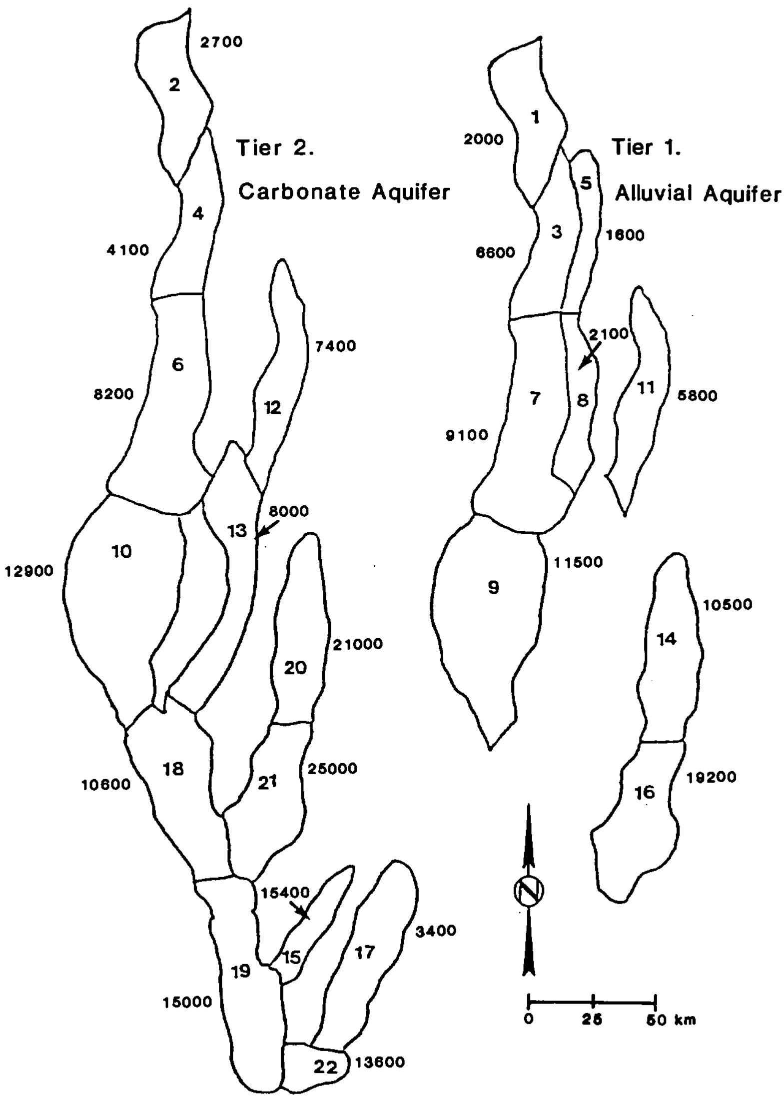

Fig. 4. Cell configuration for WRFS Scenario 1. Large numbers adjacent to cells are water mean ages (years).

volume of the alluvial aquifers compared with the carbonate aquifers in these basins and the lack of isotope data. Long Valley has been excluded and Lower Meadow Valley included in the WRFS based on potentiometric mapping by Thomas et al. (1985) and a reconnaissance report by Rush (1964). The areal extent of each cell coincided with exposed alluvium in each of the hydrographic basins, based upon available geological maps.

Scenario 2 divides the WRFS into 20 cells (Fig. 5). Preston Springs in

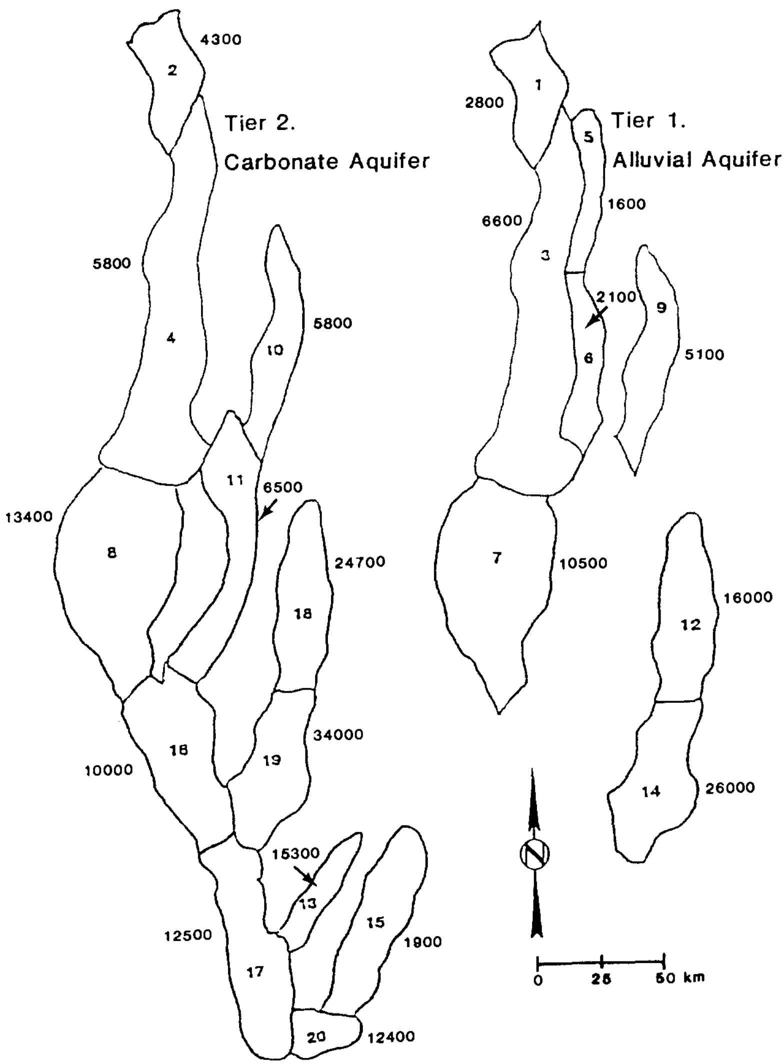

Fig. 5. Cell configuration for WRFS Scenario 2. Large numbers adjacent to cells are water mean ages (years).

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northwestern White River Valley is included in carbonate Cell 2 (Jakes Valley) with the remainder of White River Valley composed of four cells, as opposed to six cells in scenario 1. In addition, Scenario 2 adopts different intercellular flow paths and SBRV and SBRC values.

Scenario 3 introduces underflow from the Long Valley carbonate aquifer into the carbonate aquifer of Jakes Valley (Fig. 6). The amount of underflow is

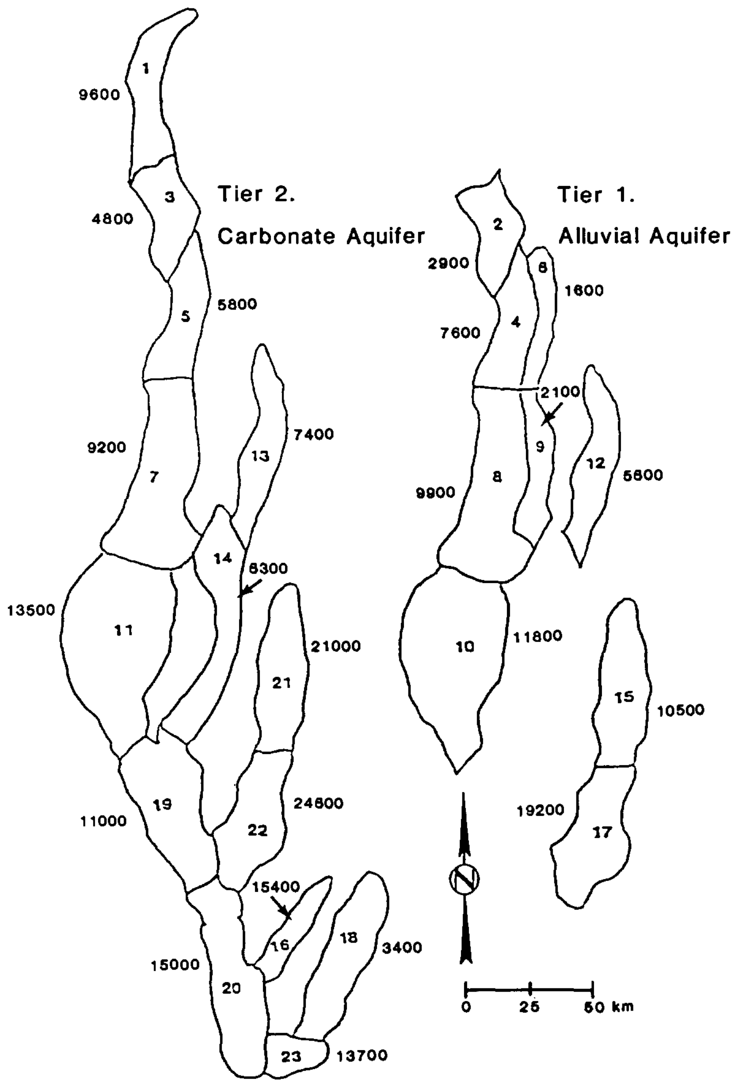

Fig. 6. Cell configuration for WRFS Scenario 3. Large numbers adjacent to cells are water mean ages (years).

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small (20%) relative to the total volume of recharge estimated for Long Valley. Eakin's (1966) original model of the WRFS included Long Valley in the system. Although recent potentiometric mapping in the alluvial aquifer by Thomas et al. (1985) concluded that Long Valley is not part of the system, this does not preclude the possibility that the carbonate aquifer of Long Valley contributes to regional flow in the WRFS. Other than inclusion of Long Valley, scenario 3 is similar to scenario 1.

Cell volumes

Thicknesses of the Paleozoic carbonates exceed 9000 m locally in the WRFS. Estimates of the thicknesses of the carbonate and alluvial aquifers are difficult because of lack of deep borehole data, although some geophysical data were available. We assumed thicknesses of 3050 m for the carbonate cells and 610 m for the alluvial cells. Effective porosities for the carbonate and alluvial aquifers were assumed to be 3 and 15%, respectively. These cell volumes (area × thickness × porosity) for all scenarios are listed in Table 1; carbonate

TABLE 1

Cell volumes for Scenarios 1, 2 and 3

Cell no.	Scenario 1 ($10^9 m^3$)	Scenario 2 ($10^9 m^3$)	Scenario 3 ($10^9 m^3$)
1	38.297	38.297	58.839*
2	38.297*	38.297*	38.297
3	63.931*	136.468	38.297*
4	63.931*	136.468*	63.931
5	19.198	19.198	63.931*
6	72.550*	24.044	19.198
7	72.550	107.912	72.550*
8	24.044	107.912*	72.550
9	107.912	49.937	24.044
10	107.912*	49.937*	107.912
11	49.937	52.452*	107.912*
12	49.937*	97.160	49.937
13	52.452*	18.865*	49.937*
14	97.160	47.421	52.452*
15	18.865*	18.865*	97.160
16	47.421	54.807*	18.865*
17	18.865*	66.261*	47.421
18	54.807*	97.160*	18.865*
19	66.261*	47.421*	54.807*
20	97.160*	0.543*	66.261*
21	47.421*		97.160*
22	0.543*		47.421*
23			0.543*
Totals	1209.451	1209.302	1268.288

* Carbonate cell.

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cells are designated by an asterisk, a convention that will be used throughout this paper. We feel that these cell volumes are reasonable given the few data, and represent 'average' values. Should more detailed information become available, it can be easily incorporated into the model. It should be noted that the cell volume equals the volume of water in a given cell.

System boundary recharge volumes

The SBRV estimate for each boundary cell was based initially on recharge estimates calculated by the Maxey–Eakin method of recharge estimation. Table 2 shows the calibrated SBRV for each cell used in the three scenarios; Table 3 shows the recharge estimates on a hydrographic basin basis for each scenario and the corresponding estimate from Eakin (1966). The amount of recharge assigned to the carbonate cells is speculative, as virtually no quantitative estimates of mountain block recharge have been reported in the literature.

System boundary recharge concentrations

Each SBRV in the model is assigned a characteristic isotopic signature or system boundary recharge concentration. Table 4 shows the estimated SBRC

TABLE 2

Calibrated system boundary recharge volumes for Scenarios 1, 2 and 3

Cell no.	Scenario 1 ($m^3 s^{-1}$)	Scenario 2 ($m^3 s^{-1}$)	Scenario 3 ($m^3 s^{-1}$)
1	0.626	0.430	0.196*
2	0.274*	0.391*	0.430
3	0.196	0.235	0.274*
4	0.196*	0.430*	0.196
5	0.391	0.391	0.196*
6	0.156*	0.313	0.391
7	0.117	0.274	0.156*
8	0.313	0.156*	0.117
9	0.274	0.313	0.313
10	0.156*	0.235*	0.274
11	0.274	0.078*	0.156*
12	0.156*	0.196	0.274
13	0.078*	0.039*	0.156*
14	0.293	0.059	0.078*
15	0.039*	0.313*	0.293
16	0.078	0.059*	0.039*
17	0.176*	0.235*	0.078
18	0.059*	—	0.176*
19	0.196*	—	0.059*
20	—	—	0.196*

* Carbonate cell.

TABLE 3

Recharge to WRFS hydrographic basins

Hydrographic basin	Eakin (1966) ($m^3 s^{-1}$)	Scenario 1 ($m^3 s^{-1}$)	Scenario 2 ($m^3 s^{-1}$)	Scenario 3 ($m^3 s^{-1}$)
Long Valley	0.391	—	—	0.196
Jakes Valley	0.665	0.900	0.822	0.704
White River Valley	1.448	1.369	1.369	1.369
Coal/Garden Valleys	0.391	0.430	0.430	0.430
Cave Valley	0.548	0.430	0.548	0.430
Pahroc Valley	0.086	0.078	0.078	0.078
Dry Lake Valley	0.196	0.293	0.196	0.293
Kane Springs Valley	—	0.039	0.039	0.039
Delamar Valley	0.039	0.078	0.059	0.078
Pahranagat Valley	0.078	0.059	0.059	0.059
Coyote Spring Valley	0.102	0.196	0.235	0.196
Lower Meadow Valley	0.313*	0.176	0.313	0.176
Totals	4.257	4.049	4.147	4.049

* From Rush (1964).

TABLE 4

System boundary recharge concentrations

Cell	Scenario 1 (‰ δD)	Scenario 2 (‰ δD)	Scenario 3 (‰ δD)
1	−124.0	−124.0	−126.0*
2	−124.0*	−124.0*	−124.0
3	−113.0	−112.0	−124.0*
4	−113.0*	−112.0*	−113.0
5	−113.0	−113.0	−113.0*
6	−110.5*	−104.0	−113.0
7	−110.5	−104.0	−110.5*
8	−104.0	−104.0*	−110.5
9	−103.0	−102.0	−104.0
10	−103.0*	−102.0*	−103.0
11	−102.0	−100.0*	−103.0*
12	−102.0*	−97.0	−102.0
13	−100.0*	−87.0*	−97.0*
14	−96.0	−87.0	−100.0*
15	−87.0*	−89.0*	−97.0
16	−87.0	−89.0*	−87.0*
17	−89.0*	−93.0*	−87.0
18	−89.0*	—	−89.0*
19	−93.0*	—	−89.0*
20	—	—	−93.0*

* Carbonate cell.

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inputs for all cells in the three scenarios. The SBRC for each cell receiving recharge was based on deuterium samples from high-altitude springs. We assumed that averaging deuterium values from high-altitude springs of a given mountain range yielded an average deuterium signature of recharge waters. In the case of Lower Meadow Valley, an average deuterium value based upon isotope data from wells in the valley was used for the SBRC. The average value ($-89.0‰$ δD) was assumed to represent the isotopic signature of underflow from Lower Meadow Valley into Upper Moapa Valley.

Flow distributions

During calibration, flow distributions among cells were adjusted to obtain agreement with observed δD values. Intercellular flow paths are shown in Figs. 7–9.

We assumed that virtually all groundwater in the alluvial aquifer flows into the underlying carbonate aquifer in Jakes, Cave, Coal/Garden, Dry Lake, and Delamar Valleys. Scenario 1 assumes downward flow in the southern portion of the White River Valley, whereas Scenario 2 assumes a net upward flow from the carbonates to the alluvium. These assumptions depend on whether we divide the western half of White River Valley into four cells (Scenario 1) or two cells (Scenario 2).

System boundary discharge volumes

System boundary discharge volumes (SBDV) in the form of springflow, ET, or underflow out of the system for Scenarios 1, 2 and 3 are listed in Table 5. Underflow out of the system, which is determined by calibration, is included in the SBDV. Underflow out of the system occurs only in Pahranagat and Upper Moapa Valleys. Springflow from the carbonate aquifers is relatively constant. The system is in steady state, i.e. total recharge = total discharge.

Eakin (1966) estimated $0.078\,m^3\,s^{-1}$ of ET in Garden Valley (Cell 9, Scenario 1) and assumed that in valleys where regional springs discharge, nearly all discharged water is subsequently consumed by ET; Eakin considered ET to be minor in all other valleys. This assumption may be in error, but is adopted for this regional analysis. In lieu of phreatophyte mapping in the study area, Eakin's (1966) estimates were used. Discharge from the system because of pumping was not considered, owing to the relatively short duration of pumping (40 years) compared with the age of the water in the flow system.

RESULTS AND DISCUSSION

Calibration

Calibration was accomplished by trial and error. The intercellular flow distributions and recharge rates were adjusted to achieve calibration, with the

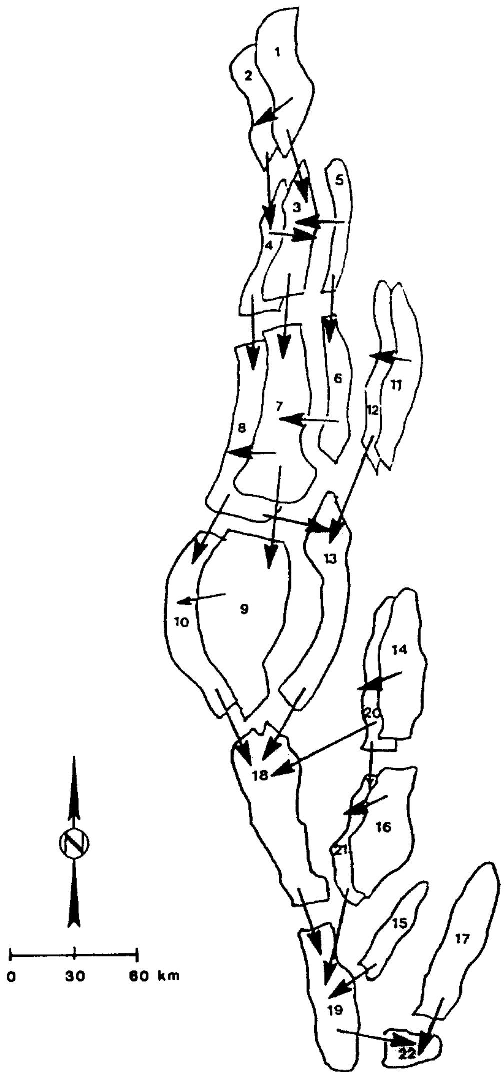

Fig. 7. Flow distributions for WRFS Scenario 1.

former subject to more adjustment than the latter. The model was run until calculated deuterium values did not change to the first decimal place. Both the real-world system and its model representation are assumed to be in steady state with respect to deuterium values. Calibration was achieved when the model-derived deuterium value agreed to within 2‰ with the observed deuterium value which had been assigned to a given cell. In some instances there was a trade-off and calibration within 2.5‰ was the best fit attained.

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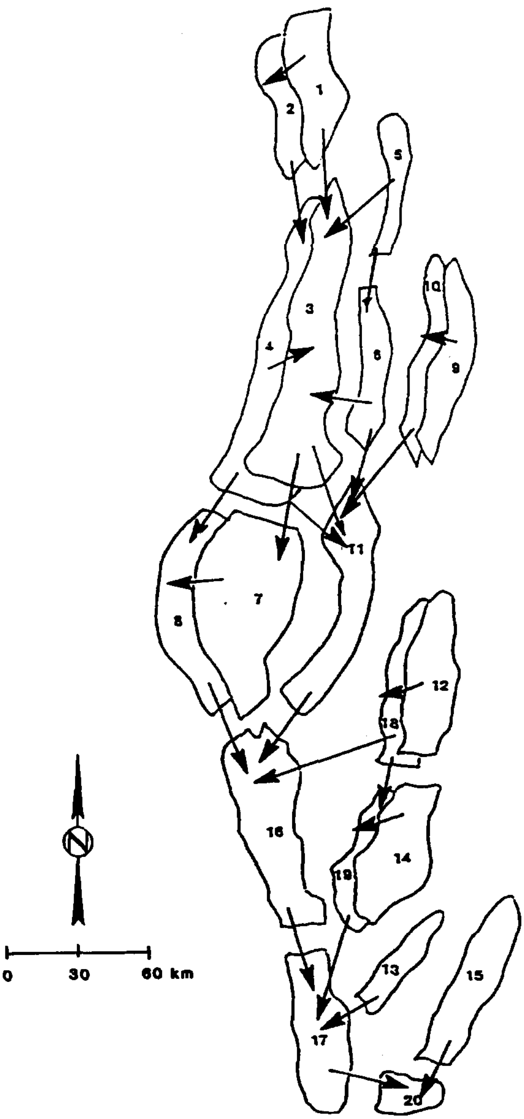

Fig. 8. Flow distributions for WRFS Scenario 2.

Calibration results were previously given in Tables 2 (SBRV or recharge rates to the model boundaries), 3 (recharge rates to hydrographic basins) and 5 (SBDV or discharge rates across the model boundaries). Table 6 shows the observed and calculated deuterium values, and Tables 7 and 8 show parameter ranges for the carbonate and alluvial systems, respectively.

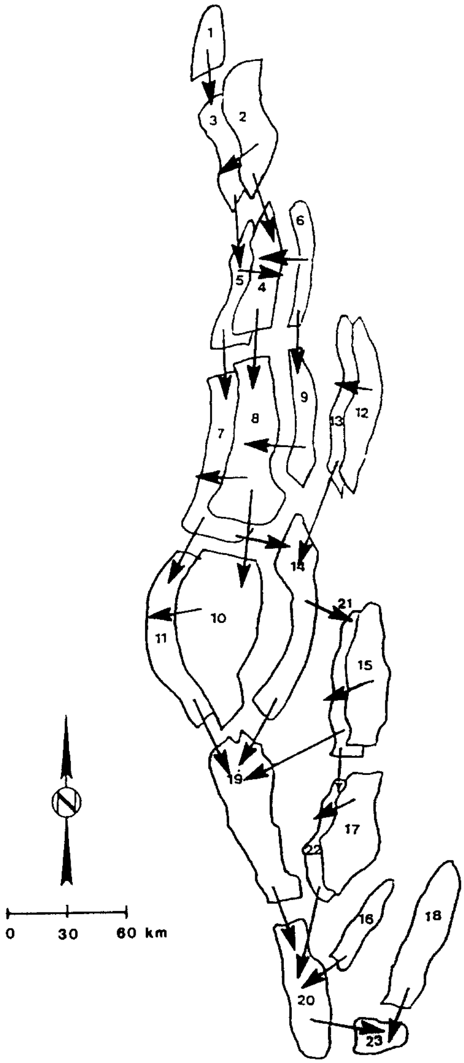

Fig. 9. Flow distributions for WRFS Scenario 3.

Differences among Scenarios 1, 2 and 3

Scenario 1 was calibrated by: (1) diverting 0.172 $m^3 s^{-1}$ from the system (west from Cell 18*) along the Pahranagat Shear Zone; (2) specifying 0.196 $m^3 s^{-1}$ of recharge from the Sheep Range to Coyote Spring Valley (Cell 19*); (3) including 0.176 $m^3 s^{-1}$ of underflow from Lower Meadow Valley (Cell 17*) into Upper Moapa Valley (Cell 22*); (4) increasing recharge to Dry Lake Valley to

TABLE 5

Calibrated system boundary discharge volumes

Cell no.	Scenario 1 ($m^3 s^{-1}$)	Scenario 2 ($m^3 s^{-1}$)	Scenario 3 ($m^3 s^{-1}$)
4	0.446*	0.863*	—
5	0.200	0.198	0.448*
6	0.436*	0.335	0.200
7	—	0.052	0.437*
8	0.340	—	—
9	0.077	—	0.340
10	—	—	0.077
16	—	1.065*	—
18	1.148*	—	—
19	—	—	1.131*
20	—	1.634*	—
22	1.401*	—	—
23	—	—	1.420*

* Carbonate cell.

$0.293\,m^3 s^{-1}$, 50% more than the Maxey–Eakin estimate; (5) increasing the recharge to Delamar Valley from 0.039 to $0.078\,m^3 s^{-1}$; (6) allowing most ($0.345\,m^3 s^{-1}$) of the combined groundwater flow from Dry Lake and Delamar Valleys to discharge at Coyote Spring (Cell 19*).

The following were required to calibrate Scenario 2: (1) dividing the western half of White River Valley into two cells, 3 and 4*, with upward vertical hydraulic gradients from Cell 4* to Cell 3; (2) allowing discharge from alluvial Cell 3 to the carbonate cell of Pahroc Valley (13*); (3) specifying that underflow from Cell 4* to Cell 8* of Coal/Garden Valleys is ~24% of the corresponding flow distribution in Scenario 1 (0.047 and $0.192\,m^3 s^{-1}$, respectively); (4) discharging $0.145\,m^3 s^{-1}$ from the system along the Pahranagat Shear Zone; (5) permitting groundwater flow of $0.188\,m^3 s^{-1}$ from Delamar Valley to Coyote Spring Valley (as opposed to the $0.345\,m^3 s^{-1}$ adopted in Scenario 1); (6) specifying $0.235\,m^3 s^{-1}$ of recharge from the Sheep Range to Coyote Spring Valley (Cell 17*); (7) allowing $0.313\,m^3 s^{-1}$ of groundwater to flow from Lower Meadow Valley (Cell 15*) into Upper Moapa Valley (Cell 20*); (8) diverting ~$0.117\,m^3 s^{-1}$ from the system as underflow from Upper Moapa Valley into Moapa Valley. Scenario 2 represents the maximum amounts of recharge from the Sheep Range and underflow from Lower Meadow Valley.

Scenario 3 used the calibrated inputs of Scenario 1, together with the introduction of $0.196\,m^3 s^{-1}$ of underflow from Long Valley (Cell 1*) and a corresponding decrease in recharge assigned to Jakes Valley (Cell 3*). Calibration was achieved by decreasing the SBRC of Cell 15 (Dry Lake Valley) by 2‰ and permitting flow from Cell 7* (White River Valley) to Cell 14* (Pahroc Valley).

Despite the differences among the scenarios, certain similarities exist.

TABLE 6

Observed and calculated deuterium values

Cell no.	Scenario 1			Scenario 2			Scenario 3		
	Observed (‰ δD)	Calculated (‰ δD)	Difference (‰ δD)	Observed (‰ δD)	Calculated (‰ δD)	Difference (‰ δD)	Observed (‰ δD)	Calculated (‰ δD)	Difference (‰ δD)
1		−124.0			−124.0			−126.0	
2		−124.0			−124.0			−124.0	
3	−119.0	−118.3	0.7	−119.0	−116.8	2.2		−124.4	
4	−124.5	−122.0	2.5	−120.0	−119.6	0.4	−119.0	−118.5	0.5
5	−113.0	−113.0	0.0	−113.0	−113.6	0.6	−124.5	−122.4	2.1
6	−119.0	−117.7	1.3	−106.0	−107.9	−1.9	−113.0	−113.0	0.0
7	−118.3	−116.7	1.6	−107.5	−109.0	−1.5	−119.0	−117.8	1.2
8	−106.0	−107.4	−1.4	−110.0	−108.6	1.4	−118.3	−116.8	1.5
9	−107.5	−107.0	0.5	−100.0	−102.0	−2.0	−106.0	−107.4	−1.4
10	−110.0	−109.2	0.8		−102.0		−107.0	−107.1	−0.1
11	−100.0	−102.0	−2.0	−108.0	−107.0	1.0	−110.0	−109.3	−0.7
12		−102.0		−95.0	−97.1	−2.1	−100.0	−102.0	−2.0
13	−108.0	−107.6	0.4	−88.0	−87.0	1.0		−102.0	
14	−95.0	−96.0	−1.0	−88.0	−88.8	−0.8	−108.0	−107.7	0.7
15		−87.1			−89.0		−95.0	−97.0	−2.0
16	−87.0	−87.6	−0.6	−108.0	−106.5	1.5		−87.0	
17		−89.0		−100.5	−101.8	−1.3	−87.0	−87.2	−0.2
18	−108.0	−107.4	0.6		−97.1			−89.0	
19	−100.5	−100.8	−0.3		−95.3		−108.0	−107.5	0.5
20		−97.0		−98.0	−98.8	−0.8	−100.5	−100.9	0.4
21		−95.1						−97.0	
22	−98.0	−99.3	−1.3					−95.0	
23							−98.0	−99.4	−1.4

Difference = calculated − observed.

TABLE 7

Parameter ranges for the carbonate system

Parameter	Scenario 1	Scenario 2	Scenario 3
Recharge rates ($m^3 s^{-1}$)	1.487	1.937	1.682
Storage volumes ($10^9 m^3$)	690.5	690.5	752.1
Mean ages (years)	2700–25 000	4300–34 000	4800–24 800

TABLE 8

Parameter ranges for the alluvial system

Parameter	Scenario 1	Scenario 2	Scenario 3
Recharge rates ($m^3 s^{-1}$)	2.563	2.210	2.367
Storage volumes ($10^9 m^3$)	517.9	517.9	517.9
Mean ages (years)	1600–19 200	1600–26 000	1600–19 200

Regardless of the scenario, calibration required: (1) the diversion of ground water outside the WRFS from Pahranagat Valley; (2) an increase in recharge from the Sheep Range; (3) the introduction of underflow from Lower Meadow Valley into Upper Moapa Valley. The greatly increased recharge from the Sheep Range, just west of Coyote Spring Valley, is supported by a water budget of Las Vegas Valley by Harrill (1979), who estimated that $0.078 m^3 s^{-1}$ of recharge from the Sheep Range flows to Las Vegas Valley, leaving the remaining estimated $0.364 m^3 s^{-1}$ of recharge available to Coyote Spring Valley and Desert Valley, which is just west of the Sheep Range. The attribution of underflow from Lower Meadow Valley into Upper Moapa Valley is based upon reconnaissance work by Rush (1964), who estimated that $0.313 m^3 s^{-1}$ is discharged from Lower Meadow Valley as underflow. Finally, it is feasible that a certain percentage of ground water entering Upper Moapa Valley is not discharged at Muddy River Springs but subsequently flows into Moapa Valley.

Recharge rates

System boundary recharge volumes (recharge rates) on a cell-by-cell basis were given in Table 2. Table 3 listed recharge rates on a valley-by-valley (hydrographic basin) basis and Tables 7 and 8 summarized recharge rates to the carbonate and alluvial aquifers, respectively.

The data in Table 3 indicate that whereas the valley-by-valley recharge rates may differ greatly, the total recharge rates are virtually the same. This holds regardless of whether comparisons are made among the various DSC model scenarios or between the DSC model estimates and the water-budget approaches of Eakin (1966) and Rush (1964). Among the scenarios, significant differences can be found in Dry Lake and Lower Meadow Valleys. Scenarios 1 and 3, virtually identical except for the inclusion of Long Valley in Scenario 3, yield identical recharge rates to the aforementioned valleys; the Scenario 2 recharge rate is 33% lower in Dry Lake Valley and ~78% greater in Lower Meadow Valley. When compared with the water-budget figures, the DSC model estimates are > 90% greater in Coyote Spring Valley; this increase is the result of increased recharge from the Sheep Range. Scenario 1 and 3 recharge estimates for Lower Meadow Valley are also significantly lower than either the Rush (1964) or the Scenario 2 estimate, which were identical.

Unlike the water-budget approach of Eakin and Rush, the DSC model is capable of distinguishing between recharge to the alluvial system and that to the carbonate system. The disadvantage to this is that, given the current state of knowledge, it is virtually impossible to verify these numbers, especially carbonate system recharge. However, these estimates should be viewed as first approximations, which can serve as starting points for more sophisticated models or planning purposes.

Pahranagat Shear Zone underflow

Eakin's (1966) original conceptual model of the WRFS did not allow for subsurface flow outside the flow system boundaries. However, to achieve calibration, each scenario required the diversion of flow west from Pahranagat Valley along the Pahranagat Shear Zone. Scenarios 1 and 3 diverted $0.172\,m^3\,s^{-1}$ in this manner, whereas Scenario 2 diverted $0.145\,m^3\,s^{-1}$ along this zone. Winograd and Friedman (1972) hypothesized that ~35% of the discharge at Ash Meadows, or $\sim 0.235\,m^3\,s^{-1}$, originated in Pahranagat Valley. Ash Meadows is a groundwater discharge area outside the WRFS located near the Nevada–California border ~160 km west of the WRFS terminus. It is the major discharge area for another regional carbonate flow system underlying and extending beyond the Nevada Test Site. Although the DSC underflow estimates are lower than that of Winograd and Friedman, they nevertheless provide additional evidence that the WRFS is not completely closed in the subsurface and is undoubtedly linked to at least one other regional carbonate flow system.

Storage estimates

The cell volume is the volume of water contained within the boundaries of that cell. Individual cell volumes were shown in Table 1, and estimates of the total amount of water in storage can be obtained by simply summing cell volumes. Tables 1, 7 and 8 showed these totals. The water storage figures for the carbonate system are the only known estimates for the WRFS and cannot be verified at this juncture. However, they do represent starting points for water resource planners who, before this, had little notion of the amount of water stored in the carbonate portion of the White River system.

Mean ages and age distributions

One of the advantages of using DSC models with tracer data is that once calibrated, the models will yield the mean ages of the water in the various regions (cells) of the system. This feature allows us to obtain water ages using stable tracers. Mean ages for Scenarios 1, 2 and 3 were previously shown in Figs. 4, 5, and 6, respectively; mean age ranges were given in Tables 7 and 8.

The groundwater mean ages shown in Figs. 4, 5 and 6 and Tables 7 and 8 are more useful than the decay ages that we might obtain from an environmental radioisotope such as ^{14}C, but they provide incomplete information in that nothing is learned about the median ages or the age distributions from which the means are derived. Some knowledge of the median ages, which are not necessarily equal to the corresponding mean ages, and the entire distribution of ages would be preferable to information on the mean ages alone. The entire age distribution could provide information on mixing and some indication of the age of the 'oldest' waters in a particular cell or aquifer region. Fortunately, DSC models can be used to produce age distributions and cumulative age distributions (Campana, 1987), so that we do not have to rely upon mean or median ages alone. If we had to rely on a single 'age', the median age is arguably more appropriate than the mean age, as, by definition, half the water in a given region is older than the median and half is younger. The mean age alone cannot provide such a breakdown.

As an illustrative example, the DSC cumulative age distribution function $F(N)$ was calculated for selected cells of Scenario 1. Three carbonate cells (2*, 10*, and 21*, representing Jakes, Coal/Garden, and Delamar Valleys, respectively) and three alluvial cells (1, 7, and 16, representing Jakes, a portion of White River, and Delamar Valleys, respectively) were selected as they represent cells in the upper (1 and 2*), middle (7 and 10*), and lower portions (16 and 21*) of the WRFS. Figures 10–15 show the cumulative age distribution function $F(N)$ for each cell. The mean age and median age, the age of the water at $F(N) = 0.5$, are shown on each graph. The striking differences between the mean and median ages are readily apparent. Groundwaters in excess of 100 000 years old are indicated in some of the regions, mainly the alluvial (Cell 16) and carbonate aquifers (Cell 21*) beneath Delamar Valley. Even in Cell 10*, the carbonate aquifer beneath Coal/Garden Valleys, the oldest ground water approaches 100 000 years old, although a higher percentage of the Delamar Valley ground waters are older than 100 000 years old. Jakes Valley (Cells 1 and 2*), at the very top of the flow system, naturally possesses the youngest waters, although a small percentage of the waters approach 15 000 years old in each cell. This detailed age information could not have been obtained from the mean or the median, either alone or together.

The shape of the $F(N)$ curve gives a qualitative indication of mixing in a

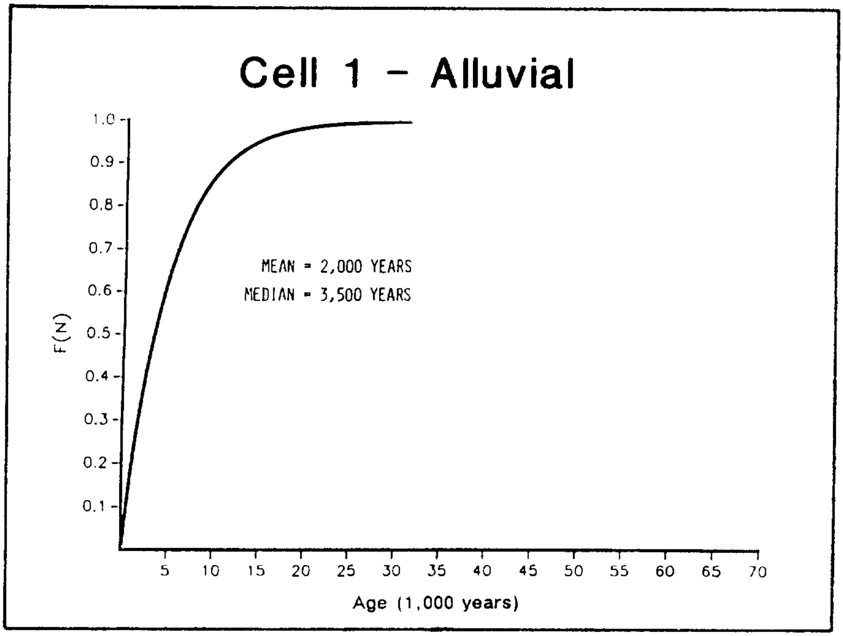

Fig. 10. Cumulative age distribution for Cell 1, Scenario 1.

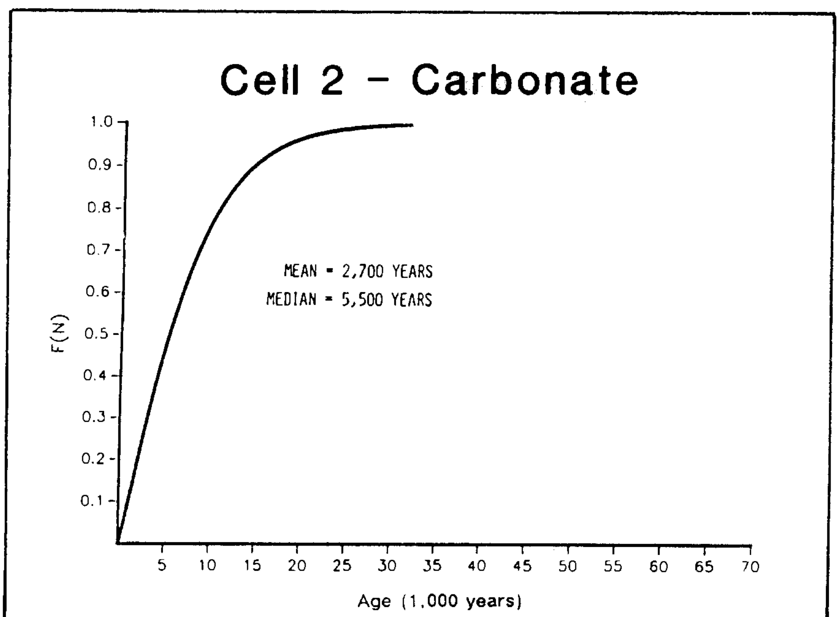

Fig. 11. Cumulative age distribution for Cell 2, Scenario 1.

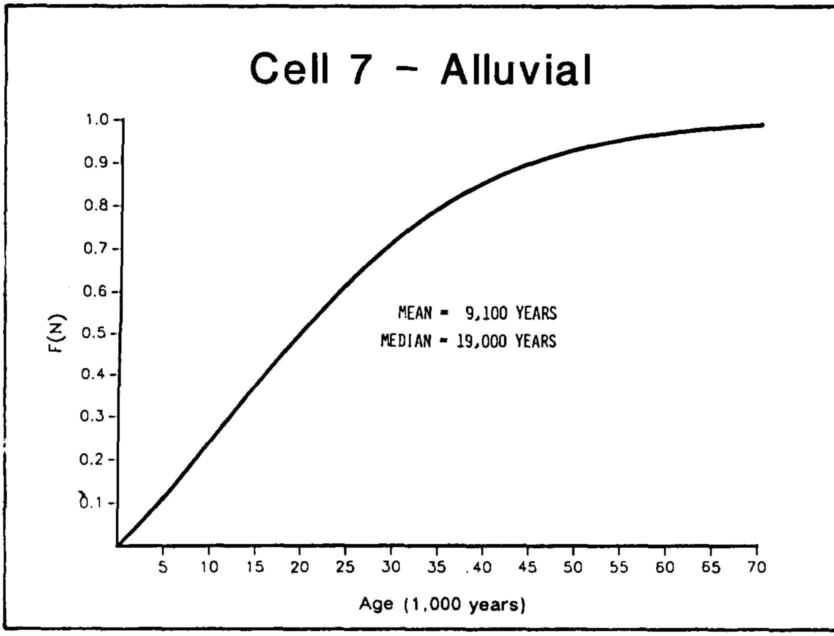

Fig. 12. Cumulative age distribution for Cell 7, Scenario 1.

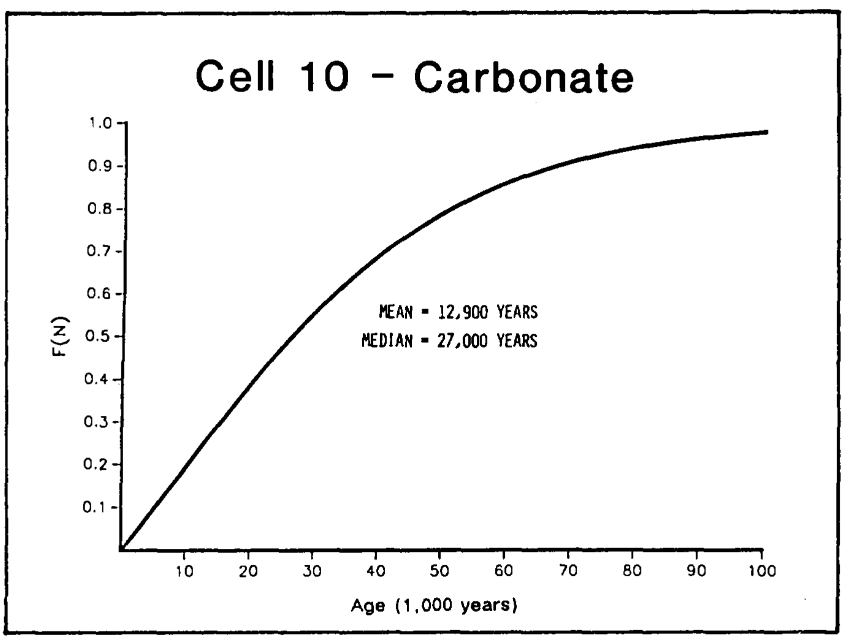

Fig. 13. Cumulative age distribution for Cell 10, Scenario 1.

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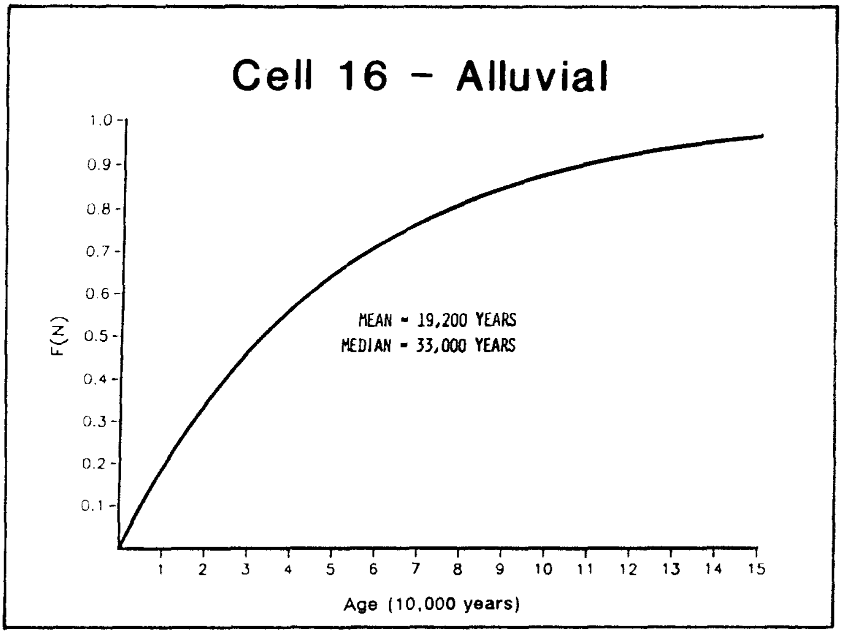

Fig. 14. Cumulative age distribution for Cell 16, Scenario 1.

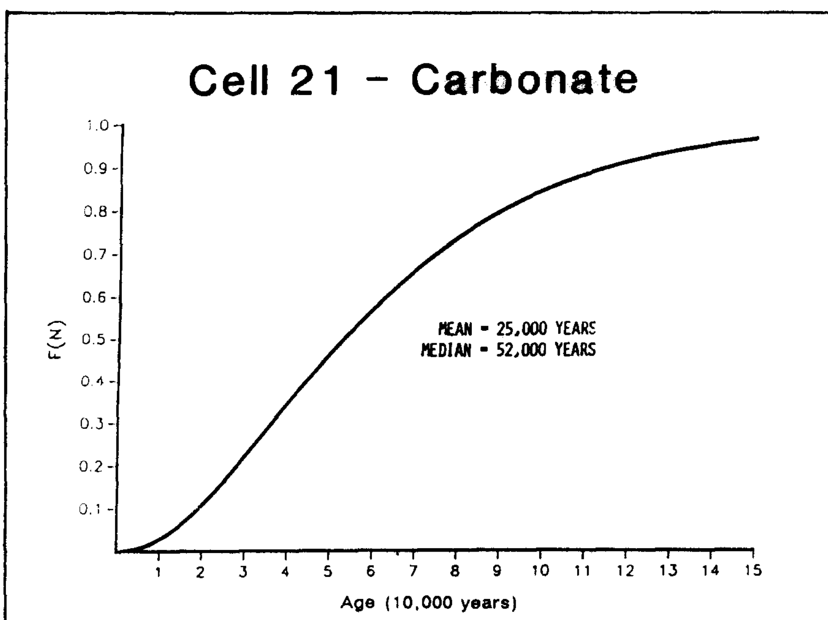

Fig. 15. Cumulative age distribution for Cell 21, Scenario 1.

given cell. A curve with a greater 'spread' about the median age indicates a higher degree of mixing than does one without as much 'spread'. The ground waters of Jakes Valley, at the top of the flow system, are the least well-mixed of the examples given, as they have had no opportunity to mix with other waters. As we move down the system, the ground waters in a given cell become better mixed as waters from different sources and of diverse ages commingle.

The ages alluded to above do not indicate the 'age' of the system; when we determine that a few per cent of the ground water beneath Delamar Valley are $> 100\,000$ years old, we simply mean that this percentage of the water was recharged $\sim 100\,000$ years ago. The flow system may have been 'operating' for millions of years. These age calculations, determined under steady conditions, might lead one to assume that the system has been in a steady-state mode for 100 000 years or so, an assumption that is very probably untrue. Climatic changes have occurred in the past 100 000 years in eastern Nevada, no doubt affecting recharge rates/areas and effecting storage changes in the ground-water reservoir—changes that have not been considered thus far. Although the DSC model age distribution functions are not well defined for transient conditions, we can nevertheless attempt to construct a model of the WRFS, using transient inputs in an attempt to see if we can discern what recharge rates existed tens of thousands of years ago. Such attempts are now being considered.

CONCLUSIONS

Three DSC models, each addressing slightly different conceptual models of the WRFS, were constructed and calibrated. Although differences exist among the three scenarios, their gross characteristics are similar. The major inconsistency is Long Valley and whether or not it belongs in the flow system. The model can be calibrated with it (Scenario 3) or without it (Scenarios 1 and 2), so the Long Valley dilemma is unresolved. Certain consistencies exist, and an examination of these results in the following conclusions:

(1) with the exception of the White River Valley itself, flow is generally downward from the alluvial aquifer to the underlying carbonate aquifer;

(2) underflow with an average value of $0.163\,m^3\,s^{-1}$ flows west from the Pahranagat Valley along the Pahranagat Shear Zone;

(3) Lower Meadow Valley is part of the WRFS and contributes underflow to Upper Moapa Valley;

(4) recharge from the Sheep Range to Coyote Spring Valley is at least 90% greater than that specified by Eakin (1966);

(5) recharge to the alluvial system is greater than that to the carbonate system;

(6) more water is stored in the carbonate system ($690.5 \times 10^9\,m^3$–$752.1 \times 10^9\,m^3$) than in the alluvial system ($517.9 \times 10^9\,m^3$);

(7) groundwater mean ages range from 1600 to 26 000 years in the alluvial system and from 2700 to 34 000 years in the carbonate system;

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(8) the oldest ground waters in each system are older than 100 000 years;

(9) the stable isotope deuterium can be used to calibrate simple groundwater flow models and provide groundwater ages;

(10) DSC models are capable of providing more detailed groundwater age information (means, medians and the entire age distribution) than other models.

Drawbacks do exist. For example, as none of the scenarios account for transience in either recharge rates or their deuterium signatures, these quantities represent long-term averages. Both long-term and short-term variations in each of these quantities have occurred. The effects of these variations on model calibration and results are now under investigation. Another questionable aspect involves the use of high-elevation springs to determine the deuterium signatures of recharge. Ideally, these signatures should be determined with time series data on deuterium but expense and site access difficulty precluded this. The problem of recharge deuterium signatures may be surmounted by sampling trees at suspected high-elevation recharge sites.

Despite the uncertainties inherent in a model of this type, the DSC model does provide first approximations to information that would be difficult or impossible to obtain otherwise. Some caution must be exercised in using this information, because as for other numerical models, the answers are non-unique. Discrete-state compartment models are perhaps more unconstrained than are other numerical models, so even greater caution must be exercised in using DSC model results. However, their greatest use perhaps lies in their application to sparse-data systems and their ability to test a number of different hypotheses, provide ranges in parameter estimates, guide the collection of additional data and serve as precursors for the development of more sophisticated models.

ACKNOWLEDGEMENTS

A number of individuals and organizations contributed to this research effort and deserve the authors' thanks. The State of Nevada, through its Carbonate Aquifer Studies Program, provided most of the funding. Additional support was provided by the Water Resources Center, Desert Research Institute. The senior author wishes to thank Marcia Olson Kirk for her advice, encouragement and patience. Deborah Wilson, Barbara Nauroth and Jan Walker were instrumental in producing this manuscript and Karla Cosens adroitly supervised its production. John W. Hess, Brad F. Lyles and W. Alan McKay unselfishly contributed their time to review the authors' efforts. The junior author wishes to thank Shirley Dreiss and James Gill of the Earth Sciences Board, University of California, Santa Cruz, for their hospitality during his sabbatical leave from the Desert Research Institute, when much of this paper was written. Finally, both authors extend a heartfelt thanks to John W. Hess, who served as Project Manager of the Institute's portion of the carbonate program.

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CENTER FOR WATER RESOURCES RESEARCH
DESERT RESEARCH INSTITUTE
UNIVERSITY OF NEVADA

GROUND WATER IN UPPER MUDDY RIVER BASIN

By

G. B. Maxey
A. L. Mindling
P. A. Domenico

Reno, Nevada
25 June 1966

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GROUND WATER IN UPPER MUDDY RIVER BASIN

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Introduction

For the past few years the staff of the Desert Research Institute have been making hydrologic and hydrogeologic observations in the Moapa Valley in order to determine the possibility of placing more water to beneficial use and thus more efficiently utilize the water resource in that area. As in many desert areas of the West it is obvious that although a large fraction of the resource is appropriated and is being beneficially used, appreciable quantities of water are lost to non-beneficial plants by evapotranspiration or are otherwise wasted. The studies in Moapa Valley are far from complete chiefly because adequate financial support has not been forthcoming for a regional study and because the Institute has been waiting for the results of regional hydrologic studies that have been currently carried on by the staff of the U. S. Geological Survey. The most recent report of the Survey's studies (Eakin, 1966) only reached the authors of this report during the second week of June, 1966.

Since most of the financial support of the work of the Institute has been afforded by the Nevada Power Company, the staff has concentrated on problems in the area above the headwater springs of the Muddy River and in the Meadow Valley Wash. Only the former area is of interest in this report which outlines the facts regarding possibilities of developing more water without interfering with pre-existing water rights in the Muddy River drainage basin.

The area under discussion includes most of Section 8 and adjacent parts of Sections 5, 6, 7, 9, 15, 16, and 17 in T. 14 S., R. 65 E., Mt. Diablo Base and Meridian. The greater part of the area, especially the valley bottom, has been subjected to intensive agricultural development for many years. Irrigation water has always come chiefly from the springs, but since World War II several wells have been drilled and supply appreciable amounts of water for domestic and stock use and some irrigation.

The first intensive use of water for industrial purposes in the valley occurred in 1965 with the completion of the Reed Gardner Generation Plant of the Nevada Power Company. Although some rights to surface water were acquired by the Company, it is planned that the greater part of the needed water is to be pumped from wells in the area described by this report, provided this can be accomplished without affecting pre-existing water rights. It is important to point out that the required amount of water can be obtained from water rights owned by the Company in Meadow Valley Wash in conjunction with presently owned water rights in the area of this report. However, this would require construction of a pumping plant and pipeline from the Meadow

Valley Wash site to the plant resulting in a considerable expense which, of course, would be reflected in the power rates in the area. Since the pipeline (Figures 1 and 2) from the present well field can accomodate the required water supply, essentially no additional expense, and therefore no increase in power rates would result if the required water can be acquired from the existing well field.

At the request of the Company and of the Moapa Valley Irrigation District, this report has been prepared to review the present status of knowledge regarding the potential availability of this amount of water.

The Regional Ground-Water System

The upper part of Moapa Valley contains two more or less separate ground-water systems which must be recognized in order to understand the occurrence, motion, and availability of water. These are a deep-seated regional system and a local, very shallow system of limited and sporadic occurrence.

The regional ground-water system has been described by Eakin in two reports (Eakin, 1964 and Eakin, 1966). The summary description given below is drawn from these reports with greatest reliance being placed on the 1966 report which is the latest and, therefore, presumably the most accurate and complete. According to these reports, Muddy River and related springs constitute a discharge area within a regional ground-water system of large dimension encompassing a series of more or less hydraulically inter-connected valleys and mountain ranges underlain by varying thicknesses of limestone. The system is bounded either by relatively impermeable clastic and volcanic rocks or by hydrologic boundaries formed under ranges such as the Sheep Range where ground-water ridges form ground-water divides. This system is portrayed by Figure 3. Also given on the figure are estimated amounts of annual recharge and discharge within the system. The estimated amount of discharge from Coyote Springs Valley, about 37,000 acre-feet a year, represents the amount of water available to the springs at the head of Muddy River. As Eakin points out, this is essentially all of the water available to those springs.

Much of the water in this system moves deeply as is indicated by the temperature and quality of the water. Also, the water moves upward from depth to discharge from the springs. As Eakin states, appreciable local recharge to the system does not occur since little water for recharge is available in Moapa Valley and even if it were, it could not move downward against the higher head in the deep system. Therefore, in the valley area adjacent to the springs water from local recharge, if any, must move laterally down gradient subject to local variations in hydrological, geological and other factors.

The mean annual discharge from the regional system is grossly represented by the flow of Muddy River, the greater part of the evapotranspiration from the valley lowlands, and some underflow (probably negligible) below Glendale. Eakin's budget essentially shows that the river discharge is by far the greater factor and roughly balances the estimated recharge of 37,000 acre-feet a year. As Eakin has pointed out and as all experts in the field recognize, these estimates are based on approximative methods and therefore must be applied with some question of quantitative accuracy. Indeed, we do not presume to

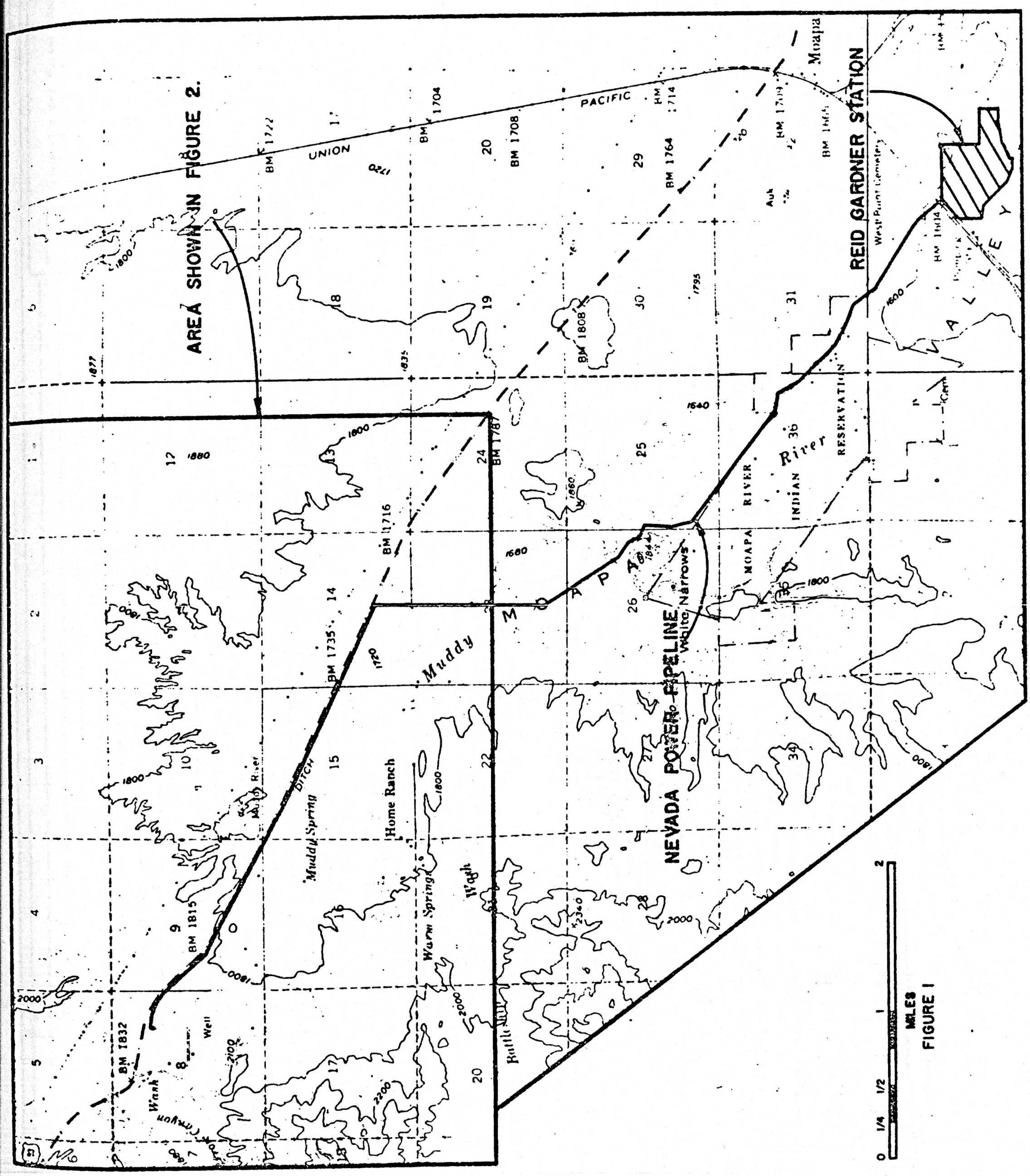
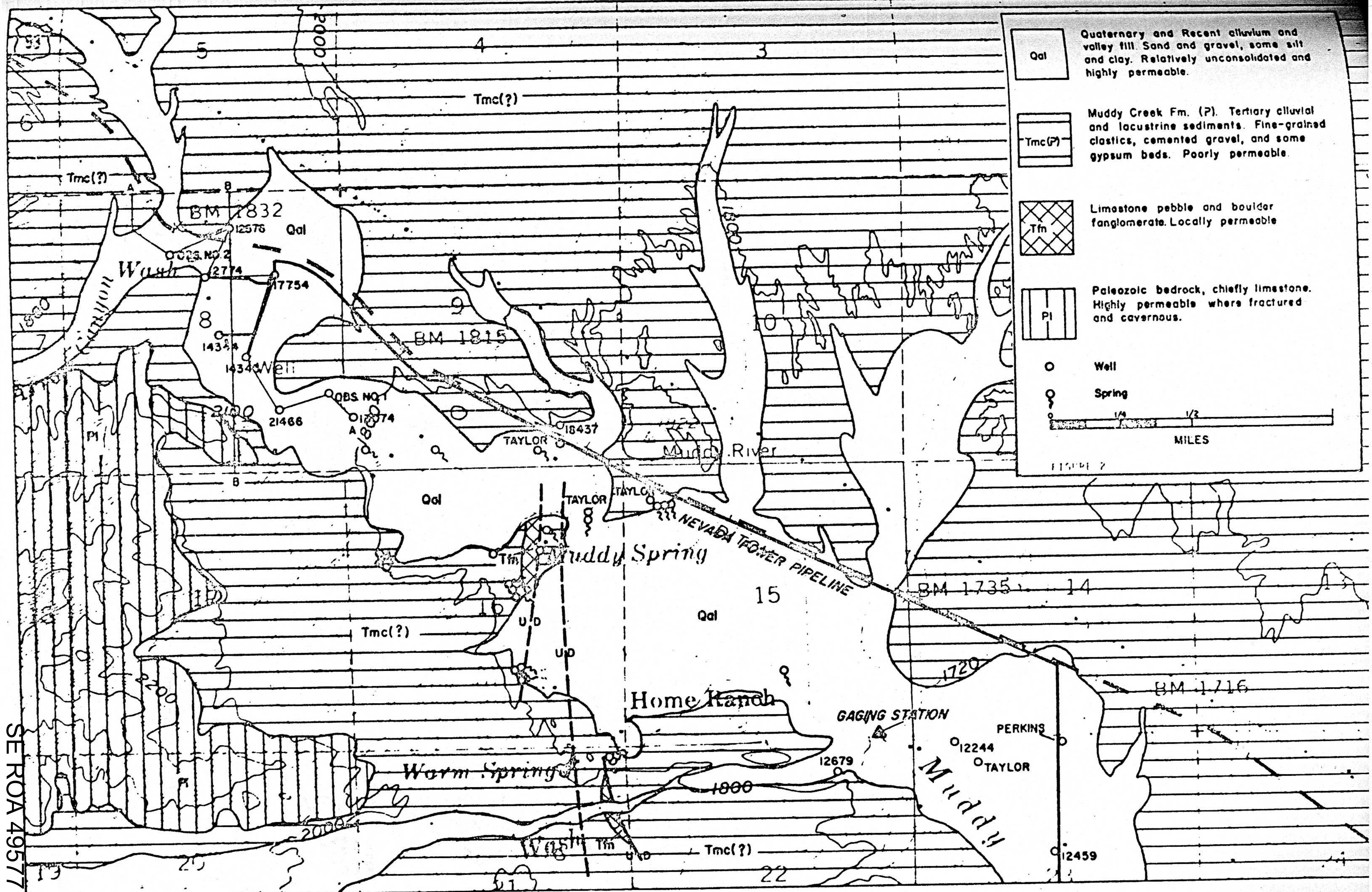

AREA SHOWN IN FIGURE 2.
REID GARDNER STATION
NEVADA POWER PIPELINE
UNION PACIFIC
MOAPA
MOAPA RIVER INDIAN RESERVATION
Muddy River
Muddy Spring
Home Ranch
Warm Springs
White Narrows
VALLEY
MILES
0 1/4 1/2 1 2

FIGURE I


Qal
Quaternary and Recent alluvium and valley fill. Sand and gravel, some silt and clay. Relatively unconsolidated and highly permeable.
Tmc(P)
Muddy Creek Fm. (P). Tertiary alluvial and lacustrine sediments. Fine-grained clastics, cemented gravel, and some gypsum beds. Poorly permeable.
Tfn
Limestone pebble and boulder fanglomerate. Locally permeable
Pl
Paleozoic bedrock, chiefly limestone. Highly permeable where fractured and cavernous.
Well
Spring
0
1/4
1/2
MILES
Tmc(?)
BM 1832
12576
Qal
OBS. NO. 2
Wash
2774
17754
8
14344
Well
21466
OBS. NO. 1
17774
A
B
BM 1815
9
TAYLOR
18437
Muddy River
10
TAYLOR
Muddy Spring
NEVADA POWER PIPELINE
15
BM 1735
14
16
U D
Home Ranch
Tfn
GAGING STATION
PERKINS
12244
TAYLOR
12679
1800
Muddy
Warm Springs
2000
22
12459
BM 1716
1720
Pl
5
4
3
6
7
19

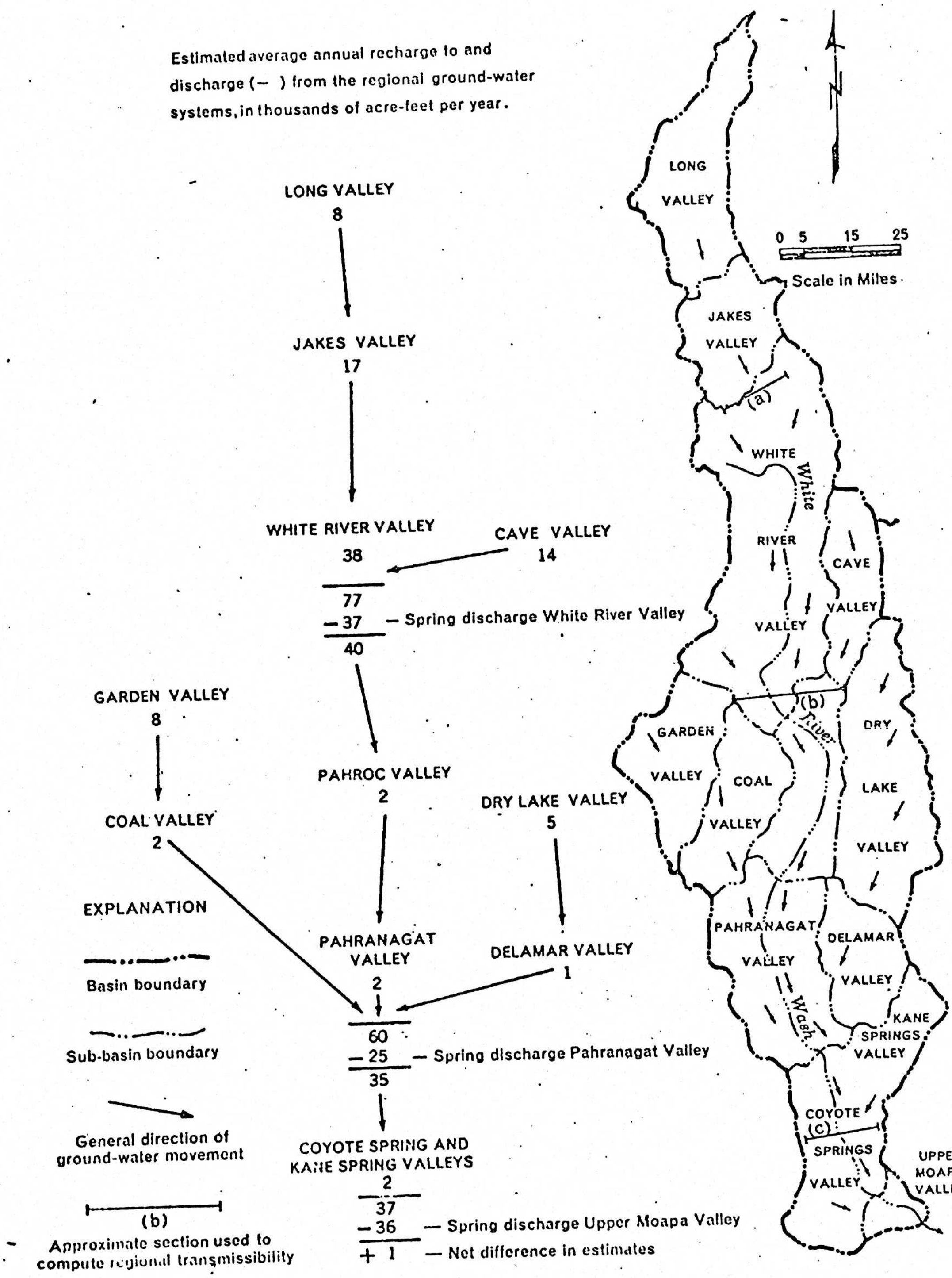


Figure 3. Regional ground-water system (from Eakin, 1966).

estimate accurately this accuracy and it probably ranges from the order of ten percent to over thirty percent. However, we do know that our measurements of spring and stream discharge are within an accuracy of ten percent. Thus, the example showing Muddy River discharge at the gage near Moapa in Figure 4 and the cumulative departure from average flow in Figure 5 are accurate representations. These illustrations are prepared to demonstrate the steady flow of the river and the approximate departure from average flow that might be expected on both a long-term basis (Figure 5) and on a short-term (Figure 4) primarily as a result of local storms.

The quality of the water discharged from the regional system is shown in the analyses given in Table 3. The concentrations of the various constituents and the total dissolved solids are roughly twice that of the springs in Pahranagat Valley which forms a discharge area much closer to the source of maximum recharge. This degradation is to be expected since the waters discharged farther from the point of recharge are longer in contact with rocks and may also have circulated to greater depths and reached higher temperatures. The temperature of the Moapa Valley springs is somewhat higher than that of springs farther north.

As the discharged water moves through the shallow sediments and the river course in Moapa Valley it is further degraded in part as a result of concentration of minerals by evapotranspiration and in part by further solution of minerals from the soil. Thus, the total solids at the springs is a little over 600 parts per million, at the gaging station in Section 15 over 700 parts per million, and below the gaging station south of Glendale total solids range from slightly over 1000 parts per million to more than 1500 parts per million.

In summary, the regional system supplies a relatively steady flow of good quality water that originates far away from the area of discharge and that supplies essentially all of the water flowing from the large springs which, in turn, are the source of the Muddy River. Below the spring areas and along the river probably most of the shallow ground water and underflow is also derived from this system, either directly or as return flow from irrigation. Movement of this water through the highly mineralized soils, concentration of the minerals in it as a result of evapotranspiration, and return of the water to the river above the Narrows probably results in most of the degradation of river water quality in the Narrows and southward.

THE LOCAL GROUND-WATER SYSTEM

The staff of the Desert Research Institute has made a careful study of the area including most of Section 8 and contiguous parts of Sections 5, 6, 7, 9, 15, 16, and 17 in T. 14 S., R. 65 E. This area includes the Nevada Power Company property and parts of contiguous properties owned by other interests. It will be referred to as the "Upper Muddy Basin" in subsequent sections of this report. This upper basin lies wholly up-gradient from the outcrop of the large springs (Figure 2) and constitutes a more or less geologically distinct basin through which Arrow Canyon Wash drains into Muddy River. All of the wells owned by the Nevada Power Company except Observation Well No. 1 (14S/65-8dal) are within this basin. The latter and one of the Taylor wells (14S/65-9ccl) are just outside the basin to the south.

MUDDY RIVER NEAR MOAPA, NEVADA

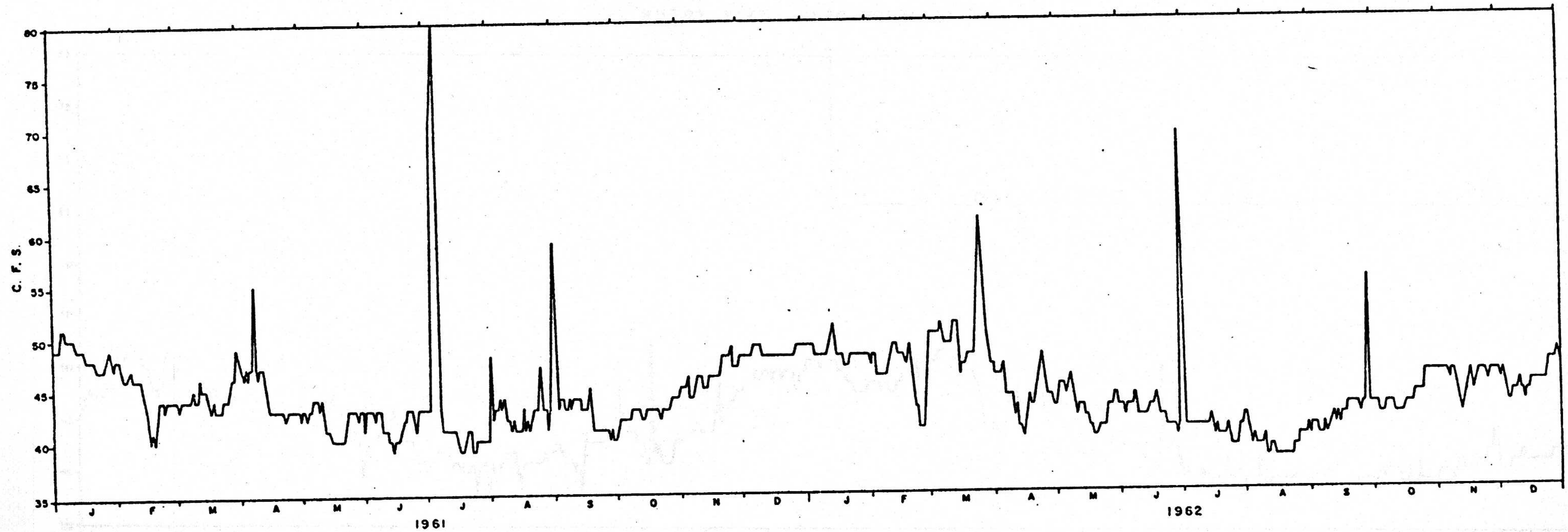
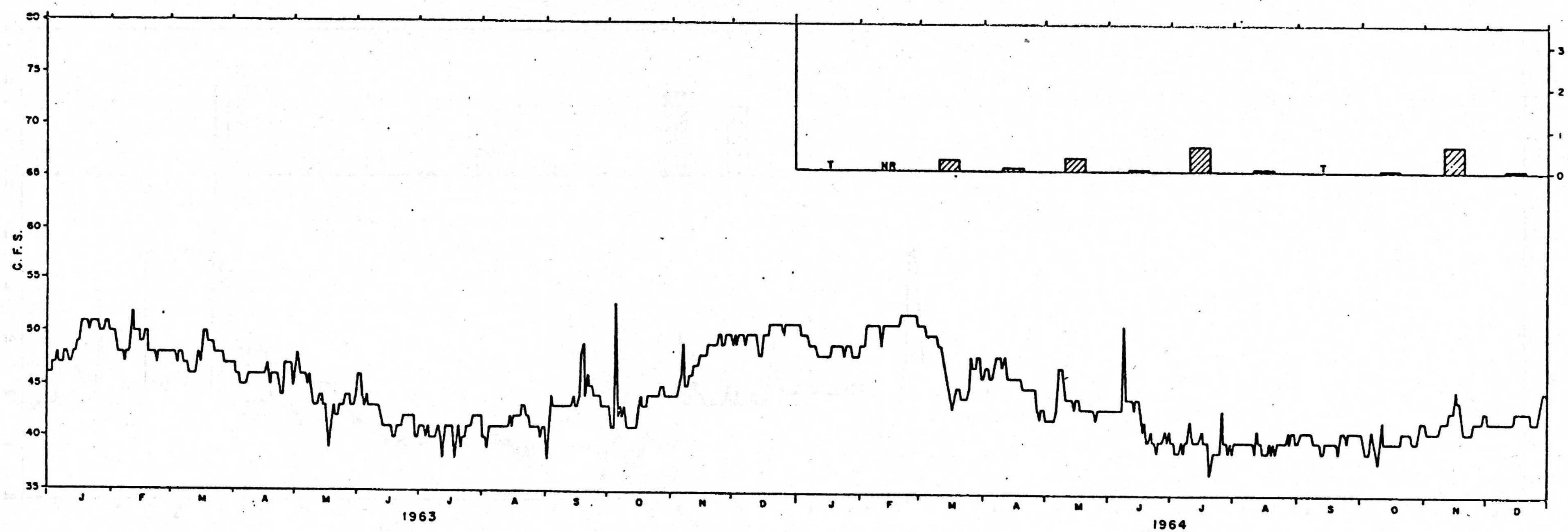
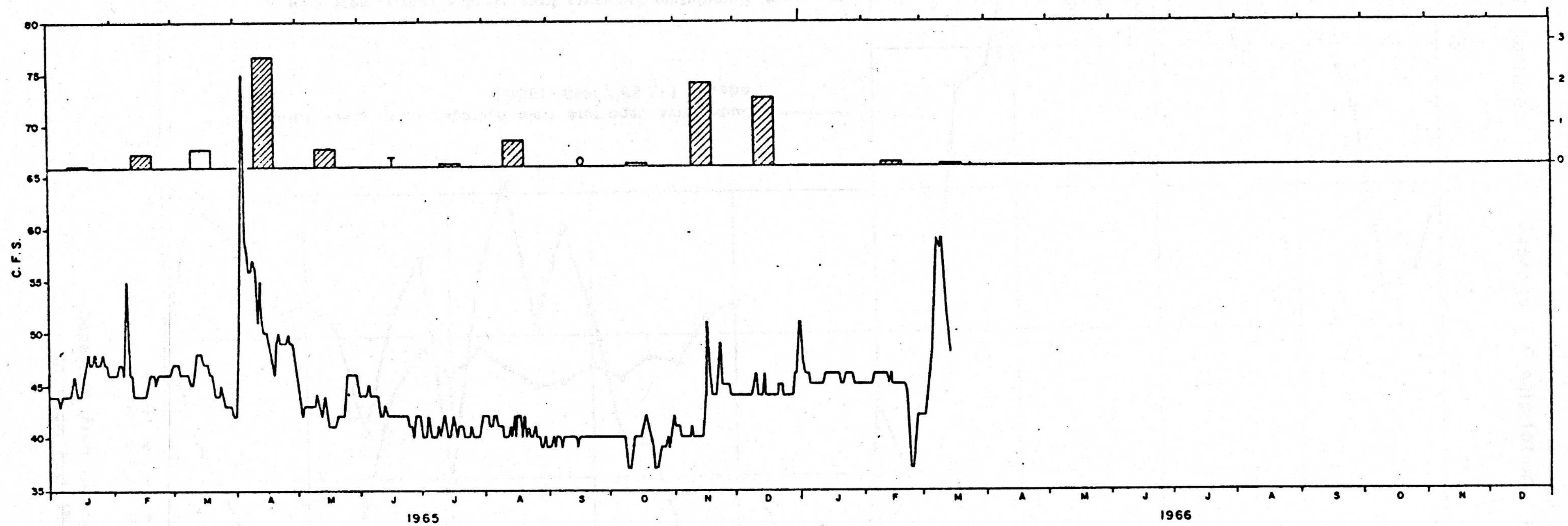


FIGURE 4

MUDDY RIVER NEAR MOAPA, NEVADA



MUDDY RIVER NEAR MOAPA, NEVADA



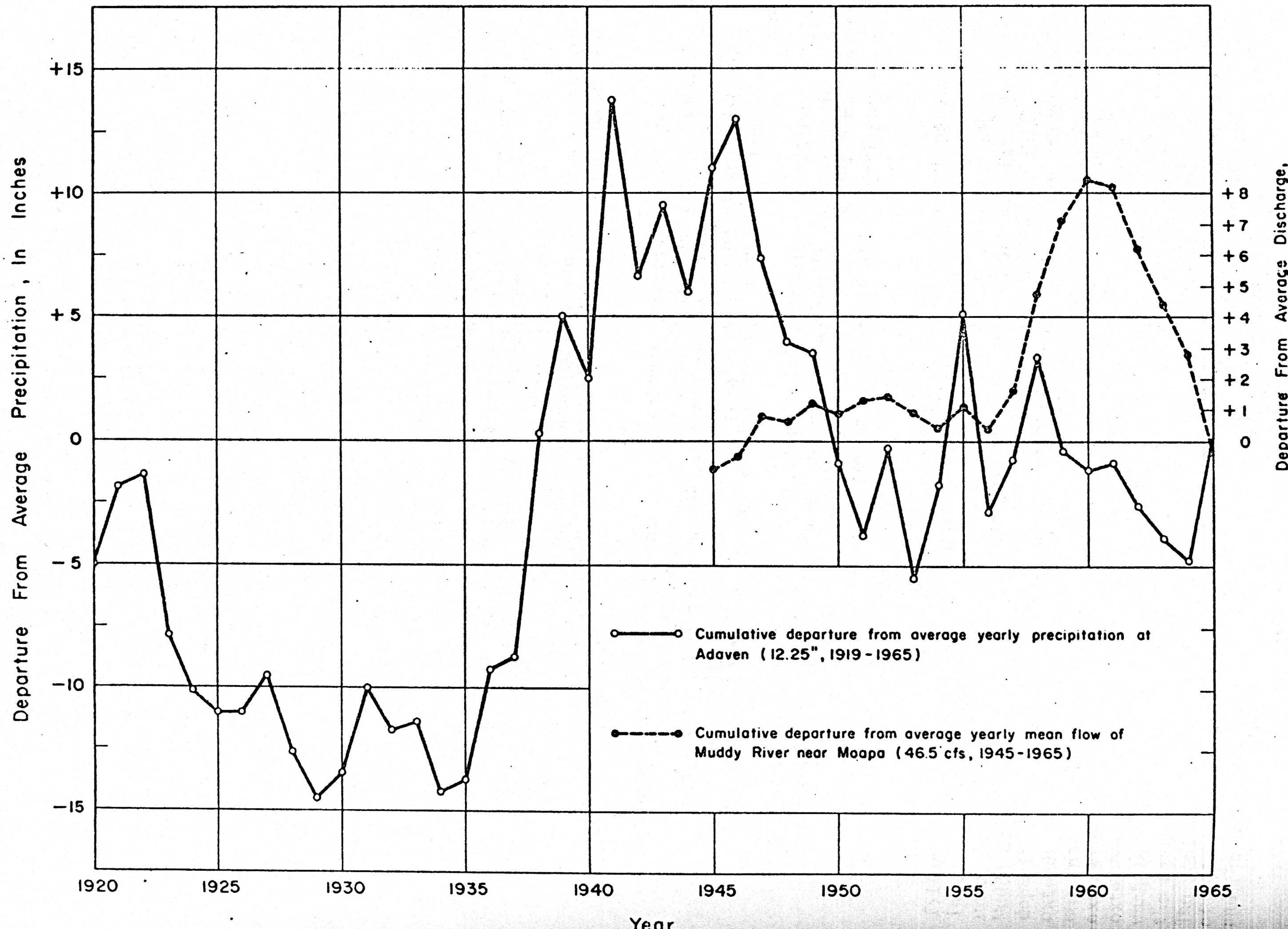

Departure From Average Precipitation, In Inches
+15
+10
+5
0
-5
-10
-15
Departure From Average Discharge, In Cubic Feet Per Second
+8
+7
+6
+5
+4
+3
+2
+1
0
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
Year
Cumulative departure from average yearly precipitation at Adaven (12.25", 1919-1965)
Cumulative departure from average yearly mean flow of Muddy River near Moapa (46.5 cfs, 1945-1965)

FIGURE 5

Geology

A preliminary geological map is shown on Figure 2. This map indicates that four geologically distinct formations can be recognized in the basin and in vicinity of the springs to the south. These include (from youngest to oldest):

1) Quaternary and Recent alluvium and valley fill. This formation is made up of sand and gravel with some silt and clay all relatively unconsolidated. It ranges in thickness from a featheredge to over 100 feet but in the upper basin is generally about 50 to 60 feet thick. It forms the chief aquifer in the upper basin where wells encounter water in it at about 20'.

2) Tertiary alluvial and lacustrine (?) sediments. Commonly called the Muddy Creek Formation, these are made up of fine-grained clastics and cemented gravels with some limestone and gypsum beds. This formation ranges considerably in thickness and is a valley fill. Its maximum thickness exceeds 1000 feet in many areas but is unknown in Moapa Valley. It contains several distinctive members, one of which is a massive limestone pebble fanglomerate here mapped as a separate unit (see Item 3 below). In general, the Muddy Creek Formation is poorly permeable to impermeable and acts as an aquitard or confining bed. Water from the Muddy Creek Formation is usually of poor quality.

3) Limestone pebble and boulder fanglomerate (described above as a member of the Muddy Creek). This fanglomerate when cut by faults and joints (some enlarged by solution) may be a highly permeable though areally restricted aquifer. It seems to be closely related to the occurrence of many of the big springs in Moapa Valley.

4) Paleozoic bedrock (chiefly limestone). This carbonate formation is a good aquifer when fractured and cavernous and is the medium in which the regional ground-water system occurs. It forms the mountains on the west side of Moapa Valley and presumably also underlies the Valley in most places.

The general geologic picture is one of large basins in bedrock partly filled with the Muddy Creek Formation which was dissected by valleys which in turn were partly filled with the Quaternary and Recent alluvium. The upper basin clearly illustrates this picture. It is a valley cut into the Muddy Creek Formation, which almost completely surrounds a 60-foot thick deposit of Quaternary sand and gravel. A thin narrow neck of the gravel extends southward in the center of the southeast quarter of Section 8, widening out into a lower basin in which Taylor's Ranch is situated. Also, a thin extension of the Quaternary gravel lies in the bottom of Arrow Canyon Wash extending from the west side of Section 8 westward and northward. A third wash in the northwest part of Section 8 also extends out of the basin to the north and west. This wash is also floored with Quaternary sand and gravel. The geologic map and profiles (Figures 2 and 6) illustrate the size and shape of this basin, the thickness and distribution of the valley-fill sediments, and the distribution of the Muddy Creek sediments in which the basin is formed.

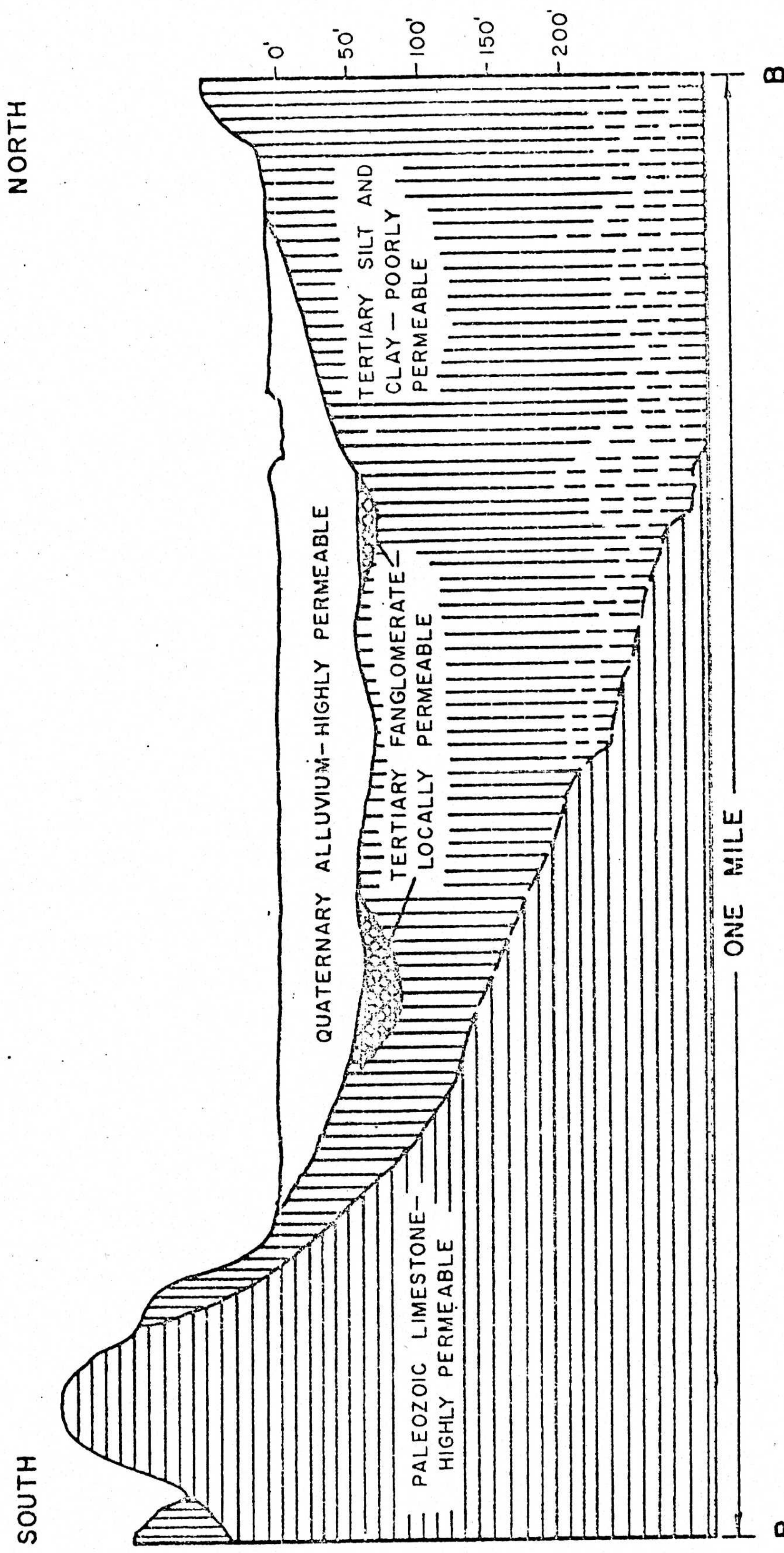


FIGURE 6 Generalized Cross Section B-B

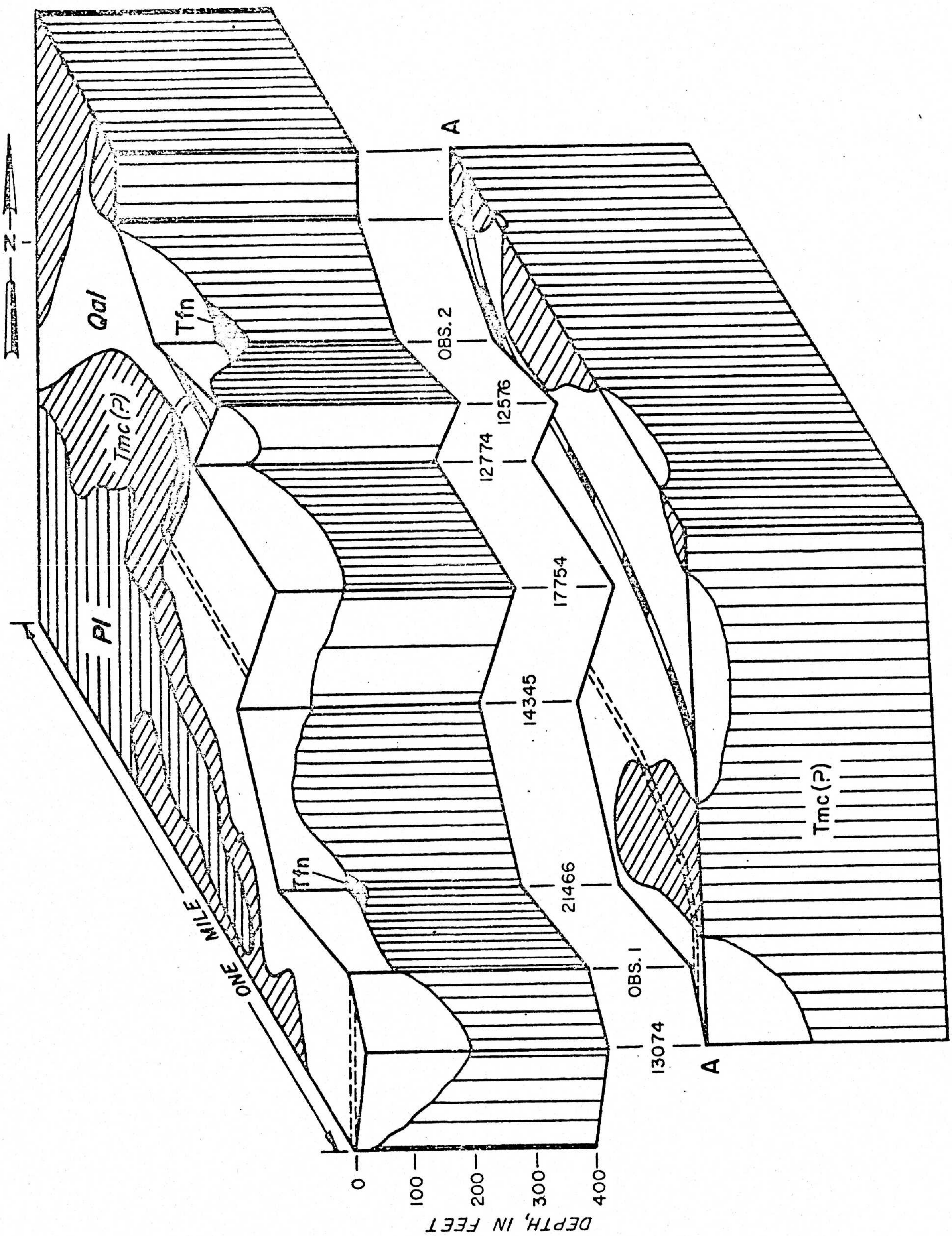


Figure 6a. Block diagram of section 8, T14S R65E, showing cross section A-A.

Hydrology

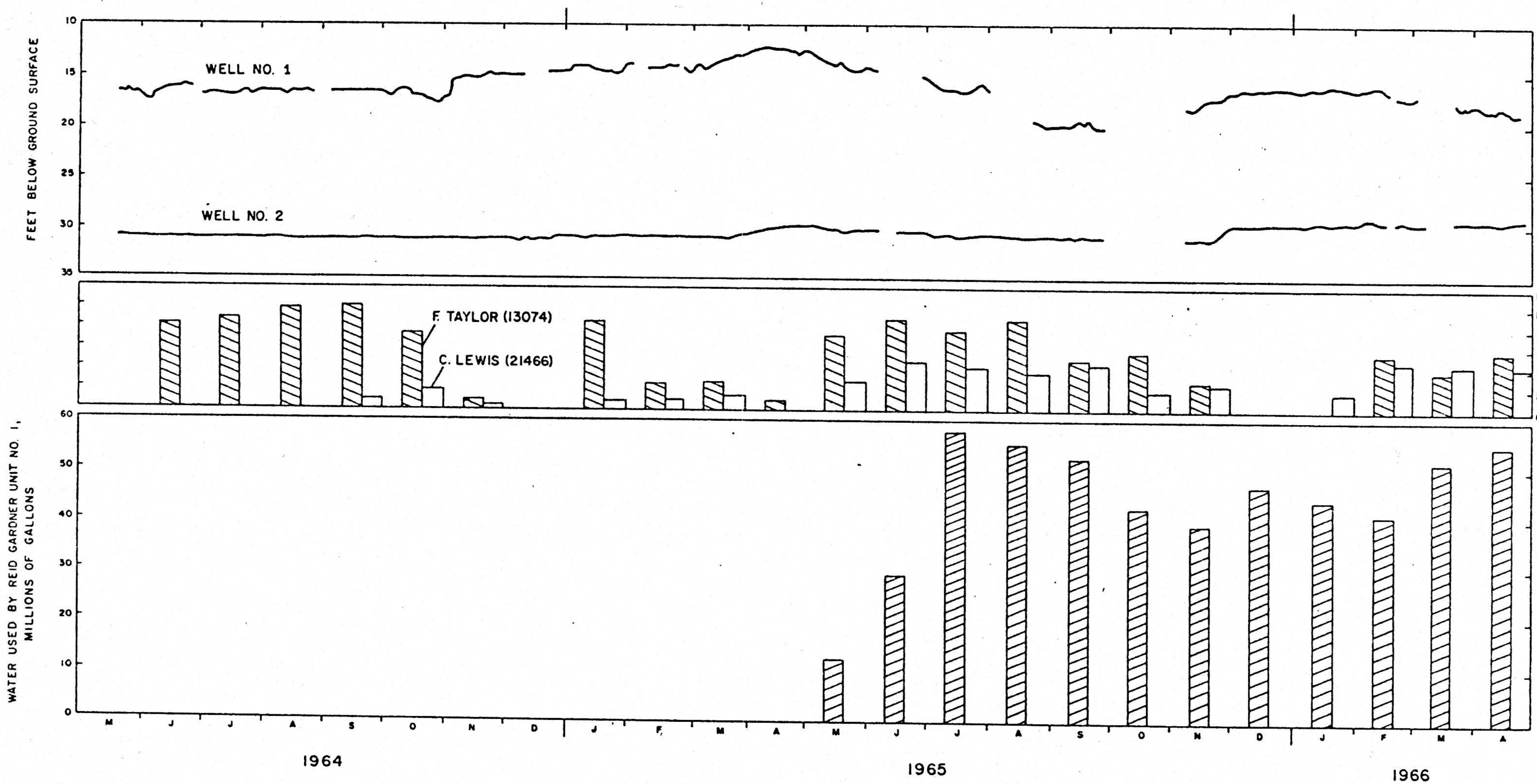
Our knowledge of ground water in the Upper Muddy Basin is limited to data collected from well-drilling, pumping, and observational operations since 1948. As far as is known 25 wells have been drilled in or closely adjacent to the basin. Most of the records on these wells are given in Figure 7 and in Tables 1, 2, 3, 4, and 5.

Continuous water-level records collected since May, 1964, in observation wells number 1 (14S/65-8da1) and 2 (14S/65-8ba1) (see Figure 7) demonstrate the influence of local pumping on water levels. Observation well number 2 (14S/65-8ba1) is in the close proximity of the Nevada Power well field and is not influenced by the pumping (Figure 7). As care was taken to complete this well in aquifers supplying water to the pumping wells, it is apparent that the "cone of influence" of Nevada Power Company pumping has little or no affect beyond the immediate well field, at least in the direction of this observation well. On the other hand, the water level in this well does show a sizable positive response to local storms and runoff. This suggests a source of recharge to the subbasin that, in effect, could provide some water to the well field. It is emphasized that this recharge, if allowed to follow natural paths instead of being subject to capture by Nevada Power wells, would be lost to evapotranspiration; thus, this recharge does not contribute appreciably to runoff in Muddy Creek.

Observation well number 1 (14S/65-8da1), on the other hand, is influenced by local pumping (Figure 7). This well is about 500 feet from the Taylor well and 1100 feet from the Lewis well, and 1800 feet from the closest Nevada Power well. Water levels in this well respond rather rapidly to changes in pumping schedules employed by Taylor and Lewis. Note the recovery of the water level in response to a cessation in pumping at the end of October, 1964, in March, 1965, and in November, 1965. Note further a decline of this level in response to an increase in pumping in May, 1965, and February, 1966. It is recognized that Nevada Power pumping also affects water levels in the vicinity of this observation well. However, the amount of water Nevada Power wells can divert from this area is limited owing to transmissivity restrictions of Muddy Creek sediments at the neck of the re-entrant, or subbasin.

If any significant conclusions can be made from these records, it is that the effect on water levels at the fringes of the Power Company well field and the Lewis-Taylor field are minor and temporary, with a maximum 8-foot decline. It is inconceivable that the natural cone of influence of this combined local pumping,which is of minor depth and laterally restricted, could in any way effect either the springs feeding Muddy River or the river itself.

The shallow ground water in this basin forms a local system bounded by the relatively impermeable Muddy Creek sediments which form a partial hydraulic boundary at the bottom and sides of the Quaternary sediments. Water moves into this basin primarily from the two large washes to the northwest especially during periods of storm (compare hydrographs in Figure 7, Figure 4, and precipitation chart, Figure 8). Some water may move upward through the Muddy Creek sediments from the regional system but it is believed that only a small quantity may do this. The quality of the water in the Quaternary beds is



WELL NO. 1
WELL NO. 2
FEET BELOW GROUND SURFACE
10
15
20
25
30
35
F. TAYLOR (13074)
C. LEWIS (21466)
12
10
8
6
4
2
0
WATER USED BY REID GARDNER UNIT NO. 1, MILLIONS OF GALLONS
60
50
40
30
20
10
0
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
1964
1965
1966

FIGURE 7

reported to be much better than that in the Muddy Creek Formation whereas large quantities of water moving through the Muddy Creek into the Quaternary gravel would quickly degrade the quality of the water in the Quaternary beds. Also, the low permeability of the Muddy Creek beds is an obstacle to movement of large quantities of water.

Before pumping was initiated in the basin the gradient of the shallow water was probably from northwesterly to southwesterly with a small amount of discharge from the basin occurring as underflow through the narrow neck in the southeast quarter of Section 8 and, to a lesser degree through the much less permeable Muddy Creek beds on the southeast side of the basin. Other discharge and probably the greater fraction occurred as a result of evapotranspiration since the water table is close to the land surface. The effect of evapotranspiration is clearly recorded on the well hydrographs in Figure 7. It appears that this is still the prevailing pattern and that the only modification of it is that pumping by Lewis and later by Nevada Power Company has formed a small cone of pumping depression in the basin. As mentioned previously, the pumping cone is temporary and vanishes when pumping ceases, thus there has been no net change in storage and well discharge is balanced by recharge. That the cone is small is indicated by the fact that the water level in Observation Well #2 (14S/65-8bal; see Figure 7) within a few hundred feet of the nearest pumping well, has not yet been discernibly affected by the pumping.

With these facts in mind, it is apparent that increased pumpage in the basin will result in a spread of the cone of depression to some unknown distance depending upon the amount of the pumpage increase. There are, as yet, no data available to allow a quantitative evaluation since values for the aquifer characteristics are unknown. However, a qualitative analysis shows that the cone will reach the impermeable sediments surrounding the basin long before it reaches the large springs on the Taylor Ranch and below. Since the elevation of the large springs is near or at the elevation of the bottom of the aquifer in the Upper Basin, a cone of depression cannot physically be developed that would intercept them. Also, it is quite apparent that, while small declines may result in the water level in the nearest Taylor well (14S/65-9ccl) the other wells farther south and east in the valley will be essentially unaffected. With only about 30 feet of allowable drawdown in the aquifer the maximum possible spread of a cone of depression is severely limited and this, combined with the effect of the geological barriers described, seems to assure that the cone will be essentially contained within the upper basin regardless of the amount of water that might be pumped from the Nevada Power Company well field. Obviously, this amount is severely limited by the geologic characteristics of the basin.

Essential data on the wells in the area are given in Tables 1 through 5. It is of interest to note that although considerable pumping has occurred in the past in the basin previous to the initiation of pumping by the Power Company, (maximum recorded annual discharge was in 1962, about 1900 acre-feet as shown in Table 5) no discernible adverse effect has been reported on the springs, on wells in the valley outside the basin, or on the flow of Muddy River as recorded on the gage in Section 15. Further, the recovery of the water level in the Nevada Power Company wells is rapid and complete when the pumps are turned off and no relict water-level decline has been recorded. These facts suggest that the well field is not being pumped to its maximum capacity and that further pumpage can be accomplished without adverse effects on existing water rights. Without accurate values of the aquifer characteristics, evapotranspiration rates, and other hydrologic factors, it is not possible to estimate quantitatively how much additional water may be pumped from the well field. However, proper monitoring of the well field and vicinity can provide a safeguard as far as pre-existing rights are concerned.

Properly installed and observed observation wells, such as Observation Well Number 1 (14S/65-3Ja1) will indicate the extent of spread of the cone of depression in a southerly direction, and therefore potential interference or diversion of water from the large springs south and east of the well field. Such wells will also indicate the amount of interference with the Taylor well (14S/65-9cc1).

The length of record of flow of Muddy River at the gaging station in Section 15 is over 30 years. Any appreciable diversion from the springs or the river as a result of further pumping in the valley upstream must be recorded on this gage. As long as the discharge retains its pattern of flow in relation to other climatic effects it can safely be said that the pumping is not appreciably affecting existing water rights.

Thus, an efficient and dependable mechanism for monitoring the effect of additional pumpage is available and can be used to safeguard pre-existing water rights.

CONCLUSIONS

1) The source of water for the springs that feed Muddy River is not indiginous to Moapa Valley but lies far north in interconnected watersheds extending at least as far north as White Pine County. All evidence developed in available studies shows that the flow of Muddy River depends on hydrologic conditions and events far north of Moapa Valley, with the exception of local high intensity storms of short duration.

2) Ground water contributes to Muddy River only in the area below which the river is perennial. Above this area which is about one mile south of the south boundary of the Nevada Power Company property, essentially all ground water is discharged by evapotranspiration or by withdrawal from wells and does not materially contribute to the flow of the river. Therefore, withdrawals from the Upper Basin alluvium will not materially affect the flow of the river.

3) Presently available evidence indicates that most of the water available to wells in the Upper Muddy Basin must come from local recharge or is diverted from natural discharge. The record indicates no permanent change in storage or any diversion from seeps or springs.

4) The elevation of the major springs feeding Muddy River is at about the same elevation or below the effective bottom of the chief water-yielding sediments in the Nevada Power Company well field, therefore a cone of depression cannot be created by pumping wells that will intercept the springs. Further water-level data collected since May, 1964 suggests that the cone of influence of the combined pumping in the Upper Muddy Basin is shallow and extends barely

beyond the boundaries of the Upper Basin, an area of about one square mile.

5) The record indicates that a greater but unknown quantity of water can be pumped from the Upper Basin without diverting water from present rights. In view of the lack of knowledge of aquifer characterisites and evapotranspiration rates and quantities, among other factors, it would appear rational to proceed to increase the pumpage until the desired amount of water is aquired or until water from pre-existing rights is diverted at which time pumping could be cut back.

6) A monitoring system which will indicate the vertical extent of water-level decline and the lateral spread of the cone of depression resulting from increased pumping is available and can be utilized to determine the effect on pre-existing water rights on Muddy River and springs and wells in the area. Monitoring this system consists of observing the two existing observation wells now maintained by the Nevada Power Company and the U. S. Geological Survey Gaging Station in the southeast quarter of Section 15, T. 14 S., R. 65 E.

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LOCATION	OWNER	PERMIT	COMPLETED	DEPTH	DIAM.	DEPTH TO WATER	USE	REMARKS	SOURCE OF DATA: DR. LOG	SOURCE OF DATA: HEARING 1964
14S/65-8[illegible]	Nevada Power Co.		4/29/64	70'	8-5/8"	28'	Obs.	N. P. Obs. No. 2	X	
14S/65-8cb1	C. A. Lewis	12576	5/16/49	57.5'	12"	23'	Comm.	N. P. No. 1	X	X
14S/65-8ac1	C. A. Lewis	12774	5/15/62	65'	14"	18'	Comm.	N. P. No. 3	X	X
14S/65-8cd1	C. A. Lewis	17754	7/15/59	66'	16"	16'	Comm.	N. P. No. 2	X	
14S/65-8db1	C. A. Lewis	14344					Comm.	N. P. No. 4		
14S/65-8db2	C. A. Lewis	14345	2/16/54	52'	14"	21'	Comm.	N. P. No. 5	X	
14S/65-8da1	Nevada Power Co.		4/22/64	115'	8-5/8"	17'	Obs.	N. P. Obs. No. 1	X	
14S/65-8dd1	C. A. Lewis	21466	9/9/64	65'	16"	28'	Irr.		X	
14S/65-9cc1	F. Taylor	13074	1/17/58	60'	12"	14.5'	Irr.		X	X
14S/65-9dd1	F. H. Godfrey	18437	8/20/59	65'	12"	10'	Irr.		X	X
14S/65-9dd2	F. Taylor		6/10/57	60'	12"	14'	Irr.			X
14S/65-16ac1	F. Taylor			80'	14"		Irr.	Flowing 75 gpm, 9/65		X
14S/65-18bb1	F. Taylor		1948	80'	20"		Irr.	19' to water, 6/8/65		X
14S/65-22ab1	U. V. Perkins	12679	12/21/48	150'	10"	21'	Irr.		X	
14S/65-23bb1	D.B. & G.M. Perkins		1948	60'	10"		Obs.	14' to water, 6/65		
14S/65-23bb2	D. and L. Perkins						Dom. Irr.			X
14S/65-23bb3	R. Beamer	12244	1/22/58	80'	10"	8'2"	Irr.		X	
14S/65-23bb4	F. Taylor		1965							
14S/65-23ab1	L. W. Perkins			50'	6"		Obs.	2.48' to water, 3/61		X
14S/65-23ac1	L. W. Perkins	12459	2/13/48	82'	16"	3'	Irr.		X	X

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. TABLE 2. NEVADA POWER COMPANY WELLS

...DA ...ER ...PANY ...LL NU... ...BER	ORIGINAL PERMIT NUMBER	CHANGE OF USE NUMBER	INCREASE AMOUNT NUMBER	ORIGINAL AMOUNT AC.FT.	GPM	PROPOSED INCREASE AC.FT.	GPM	TOTAL AMOUNT AC.FT.	GPM	WELL TESTS PUMPING RATE GPM	DISCHARGE PRESSURE	STATIC HEAD	PUMPING LEVEL	DRAWDOWN (FEET)	SPECIFIC CAPACITY GPM/FT
1	12576	22634	22948	510	193	390	242	700	435			NO TESTS RUN			
2	17734	22635	22949	185	115	515	320	700	435	645	0.1 lb.	26.33	33.67	7.33	89.0
3	12774	22633	22950	297.5	185	402.5	250	700	435	550.5	20.4in/wtr.	24.67	30.67	6.00	92.0
4	14344	22636	29951	260	162	440	273	703	435	540.6 555.6 631.55 652.16	1.0 lb. 1.0 lb. -3.7in/wtr. -5.7in/wtr.	26.16	30.67 31.75 32.24 32.46	4.51 5.50 6.08 6.30	120.0 100.0 105.5 104.4
	14345	22632	22952	315.5	196	384.5	239	700	435	540.6 540.6	2.1 lb. 2.2 lb.	24.67	30.33 30.67	5.66 6.00	96 90
						TOTAL		3500	2170						

TABLE 3. ANALYSES OF WATER FROM MUDDY RIVER AND TWO SPRINGS IN MOAPA VALLEY (FROM EAKIN, 1966)

	1. WARM SPRING	2. IVERSON'S SPRING	3. MUDDY RIVER (SE 1/4 Sec. 15, T. 14 S. R. 65 E.)
Date of Collection	4/15/63	9/12/63	3/9/62
Temperature ^{o}F	90	89	71
SiO_2	31	29	32
Fe	0.00	0.00	--
Ca	65	70	71
Mg	28	26	33
Na	99	101	125
K	10	11	14
*HCO_3	288	274	303
SO_4	174	179	216
Cl	60	64	75
F	2.4	2.3	2.4
NO_3	2.3	2.2	1.5
B	0.3	0.3	0.4
TDS	614	620	719
Hardness			
Ca and Mg	279	280	313
Non-Carbonate	43	55	65
Specific Conductance at 25^{o}C	985	964	1,090
pH	7.7	7.5	8.2

*CO_3 Reported as 0 in all analyses.

TABLE 4. PUMPAGE FROM NEVADA POWER COMPANY WELLS, MAY, 1965 TO APRIL, 1966

	ACRE-FEET	GALLONS
1965		
May	38.9	12,662,000
June	89.7	29,237,000
July	178.7	58,225,000
August	170.5	55,554,000
September	160.5	52,297,000
October	131.2	42,743,000
November	121.4	39,548,000
December	144.1	46,955,000
1966		
January	136.4	44,431,000
February	127.3	41,470,000
March	158.6	51,666,000
April	168.9	55,021,000
TOTAL	1,626.2	

TABLE [illegible]. [illegible]
[illegible] WELLS ([illegible] NEVADA [illegible] CO. WELLS)
FROM NOVEMBER, 1961 TO OCTOBER, 1963

	WELL NO. 1 (12376)	WELL NO. 2 (17754)	WELL NO. 3 (12774)	WELL NO. 4. (14344)	WELL NO. [illegible] (14[illegible])	[illegible]
1961						
November	32.22	10.48	35.57	14.41	21.67	
December	22.26	0	13.09	18.62	11.27	
1962						
January	34.71	5.66	24.68	24.41	0.72	
February	26.40	5.27	7.36	17.58	30.15	
March	30.58	9.32	45.71	23.10	25.93	
April	31.76	0.76	21.81	17.02	15.57	
May	44.58	18.12	40.31	59.89	55.99	
June	50.52	24.58	59.28	57.19	58.18	
July	38.48	13.11	58.69	55.47	59.49	
August	36.43	27.05	59.02	60.26	56.29	
September	49.51	16.69	69.69	61.98	43.06	
October	31.81	14.97	22.08	63.80	45.27	
November	0.24	4.65	18.05	56.38	11.82	1931.[illegible]
[illegible]	12.30	17.83	23.31	17.03	0	

TABLE 5. CONT.

	WELL NO. 1 (12576)	WELL NO. 2 (17754)	WELL NO. 3 (12774)	WELL NO. 4 (14344)	WELL NO. 5 (14345)	TOTAL
1963						
January	0.35	.03	14.04	19.71	15.37	
February	1.25	36.51	21.78	5.68	20.84	
March	26.66	10.63	19.73	36.51	36.25	
April	19.66	17.08	15.23	17.42	21.71	
May	13.73	19.13	46.17	32.19	51.37	
June	26.77	28.21	61.99	47.35	59.81	
July	45.99	50.59	69.34	46.89	60.97	
August	36.24	40.67	59.45	47.14	60.59	
September	15.76	23.85	12.82	55.66	24.53	
October	14.44	12.14	25.74	17.64	55.12	1689.6

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Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems, Nevada, Utah, and Arizona

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

Open-File Report 2006–1040

U.S. Department of the Interior
U.S. Geological Survey

SE ROA 49598

JA_15452

U.S. Department of the Interior
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U.S. Geological Survey
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Suggested citation:
Page, W.R., Scheirer, D.S., and Langenheim, V.E., 2006, Geologic cross sections of parts of the Colorado, White River, and Death Valley regional ground-water flow systems, Nevada, Utah, and Arizona: U.S. Geological Survey Open-File Report 2006-1040, Denver, CO, 80225.

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Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Ground-Water Flow Systems, Nevada, Utah, and Arizona

By William R. Page[1], Daniel S. Scheirer[2], Victoria E. Langenheim[2]

Abstract

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

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

Tertiary volcanic and plutonic rocks are exposed in the northern and southern parts of the study area. In the Clover and Delamar Mountains, these rocks are highly deformed by north- and northwest-striking normal and strike-slip faults that are probably important conduits in transmitting ground water from the basins in the northern Colorado and White River flow systems to basins in the southern part of the flow systems.

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

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

Introduction

The 10 geologic cross sections (plate 1) were constructed to better understand the hydrogeologic framework for parts of the Colorado, White River, and Death Valley regional

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ground-water flow systems in southern Nevada, southwestern Utah, and northwestern Arizona. The main purpose of the cross sections is to provide the National Park Service with geologic framework data for input into a numerical ground-water model. Rapid urbanization and commercial development in the region has increased demand for water from surface-water sources and from local and regional aquifers in these flow systems. As a result, the geology in the area needs to be defined to assist in understanding the complex hydrologic processes that govern ground-water recharge, movement, storage, and discharge.

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

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

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

Methods

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

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

The cross sections integrate data from existing maps and reports, geophysical investigations, and well data, and are progressively more interpretive with depth because of the lack of data at deeper levels. Page and others (2005a) provided a comprehensive list of geologic map sources and reports used in their compilation and in this study, and they presented detailed lithologic description and thickness of individual units in the map and cross section region. Data from several deep petroleum exploration wells were used to constrain thickness of basin-fill sediments and bedrock geology along several cross sections. These wells were tied into the cross section lines (fig. 3) and include the Texaco Federal #1 well (C-C'), Mobil Virgin River # 1-A well (D-D'), and the Grace Petroleum Arrow Canyon #1 well (G-G'). Stratigraphic and structural data from these wells were from well logs and from Garside and others (1988).

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

Stratigraphy

Proterozoic and Paleozoic Rocks

Early Proterozoic metamorphic and intrusive rocks consist of gneiss, granite, and schist that are about 1.7 Ga (Quigley and others, 2002). These crystalline rocks form both geologic and hydrologic basement and are considered barriers to ground-water flow because of their low permeability. The crystalline rocks may be locally permeable where highly fractured, but fractures in these rocks are generally poorly connected (D'Agnese and others, 1997). Early Proterozoic rocks exposed in the Beaver Dam and Virgin Mountains form the eastern boundary of the flow systems (A-A', B-B', C-C', D-D' and E-E'). Early Proterozoic rocks also form the core of the Mormon Mountains where they act as a local barrier to ground-water flow (Burbey, 1997) (B-B', and C-C'), although through-going, north-striking faults along the western and eastern Mormon Mountains may provide conduits for some southward ground-water flow through the mountain range.

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

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

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

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

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

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

Late Proterozoic-Paleozoic Facies Belts

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

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

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

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

Mesozoic Rocks

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

Tertiary-Quaternary Rocks

Tertiary and Quaternary rocks in the cross sections were grouped into three map units, QTu, Tv, and Ti. Unit QTu represents basin-fill deposits, which consist of alluvium and colluvium, playa deposits, eolian deposits, spring discharge deposits, and landslide breccias of Miocene to Holocene age. Unit QTu also consists of older sedimentary rocks including the Miocene and Pliocene Muddy Creek Formation and equivalent units in the Lake Mead area, and the Oligocene and Miocene Horse Spring Formation and equivalent units. The Muddy Creek Formation is mostly lacustrine and fluvial mudstone, tuffaceous sandstone, gypsum, halite, and conglomerate. The Horse Spring Formation consists of fluvial and lacustrine rocks, comprised of tuffaceous sandstone, tuff, conglomerate, siltstone, mudstone, limestone, and gypsum.

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

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

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

Structural Geology

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

Mesozoic Thrust Faults

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

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

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

Duplex zones in the Paleozoic carbonate rocks are interpreted along the Dry Lake and Muddy Mountain thrusts (F-F' and G-G'). These duplex zones define areas of maximum thickness for the Paleozoic carbonate rocks in the region because the Paleozoic section is essentially repeated along the thrusts. In cross section G-G', these rocks are interpreted to be greater than 7 km thick based on logs from the Grace Petroleum Arrow Canyon # 1 well. In this well an upper thrust fault is interpreted at about 2,288 m where rocks of the Cambrian Carrara Formation are in the upper plate above rocks of the Cambrian Bonanza King Formation in the lower plate. A lower thrust fault occurs at about 2,800 m depth where rocks of the Bonanza King Formation in the upper plate are above rocks of the Mississippian-Permian Bird Spring Formation in the lower plate, thus repeating the Paleozoic section from the Bird Spring Formation downward. We interpret the upper fault as the Dry Lake thrust and the lower fault as the Muddy Mountain thrust (G-G'). The zone between the two faults is characterized by complexly repeated Cambrian units indicating horse blocks and (or) imbrication structures, features commonly associated with thrust fault zones.

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

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

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

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

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

Magmatism

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

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

Strike-slip Faults, Normal Faults, and Basin Development

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

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

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

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

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

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

Strike-slip faults are reported in the Tule Springs Hills and East Mormon Mountains (Anderson and Barnhard, 1993; Hintze and Axen, 2001; Axen and others, 1990). The East Tule Desert fault (fig. 5) is a left-lateral, strike-slip fault that bounds the west flank of the Tule Springs Hills. In cross section A-A' Paleozoic and Mesozoic rocks of the Tule Spring autochthon are offset along the fault, and the downthrown side forms Tule Desert, a shallow basin with less than 500 m of Cenozoic basin-fill deposits (Scheirer and others, in press). The Sams Camp and Carp Road faults (fig. 5) are probably equivalent to the East Tule Desert fault, and extend farther south along the East Mormon Mountains. These faults juxtapose Paleozoic rocks in the hanging wall against a footwall horst cored by Proterozoic crystalline rocks (B-B'). At the south end of the East Mormon Mountains, the Carp Road fault bends southwestward where it merges with the Davidson Peak fault, an east-striking transverse zone composed of highly folded Paleozoic and Mesozoic rocks (fig. 5), and then bends south to bound the west flank of the southern Mormon Mountains (along Candy Peak; D-D'; fig. 2). Anderson and Barnhard (1993) interpreted that the large sinistral displacements along these strike-slip faults are kinematically linked to major uplifts and depressions in the Mormon Mountain area that formed during Miocene extension. Alternatively, Axen and others (1990) interpreted that these faults are kinematically linked to the large-magnitude Cenozoic extension on the Tule Spring and Mormon Peak detachment faults (see below).

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

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

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

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

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

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

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

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

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

Virgin Valley is segmented into two deep northeast-trending basins (fig. 4), the Mormon basin to the southwest and the Mesquite basin to the northeast (Bohannon and others, 1993; Langenheim and others, 2000, 2001a). The basins formed by subsidence caused by Miocene extension mainly along the Piedmont fault. Cenozoic basin-fill deposits in the Mesquite basin are estimated to have maximum thicknesses of about 8 to 10 km, with the deepest part of the basin beneath the Littlefield, Ariz., area (Langenheim and others, 2000, 2001a) (fig. 2). Cross sections B-B' and C-C' extend across the Mesquite basin and show an east-dipping sequence of deformed Paleozoic and Mesozoic rocks overlain by moderately deformed Cenozoic basin-fill rocks. The subsurface stratigraphy and structure portrayed in the cross sections are derived mostly from seismic-reflection data from Bohannon and others (1993) and Carpenter and Carpenter (1994), and gravity data from Langenheim and others (2000, 2001a). Cross sections D-D' and E-E' extend across the Mormon basin where Cenozoic basin-fill deposits reach maximum thicknesses of 5 to 6 km. The subsurface stratigraphy and structure portrayed in the cross sections in the Mormon basin is mostly from seismic-reflection data from Bohannon and others (1993), gravity data from Langenheim and others (2000, 2001a), and the Mobil Virgin River # 1-A deep petroleum test well on Mormon Mesa. The Mobil well encountered the base of Cenozoic basin fill at about 2 km and the well bottomed out in Proterozoic crystalline rocks at about 5.9 km depth (Bohannon and others, 1993).

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

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

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

Summary

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

Above the Late Proterozoic to Lower Cambrian clastic rocks are Middle Cambrian to Lower Permian units that are predominantly carbonate rocks, and they form the main aquifer in the regional ground-water flow systems. The Paleozoic carbonate rocks thin from west to east in the study area, from as much as 7 km in the western part to less than 2 km in the eastern part. Much of the thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton.

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

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

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

Acknowledgments

We thank the National Park Service, Water Resources Division, Fort Collins, Colo., for funding this work. Mary Berger and Kenzie J. Turner designed the cross section plate layout and prepared the report figures. Robert G. Bohannon and Robert B. Scott provided comprehensive technical reviews which greatly improved the report.

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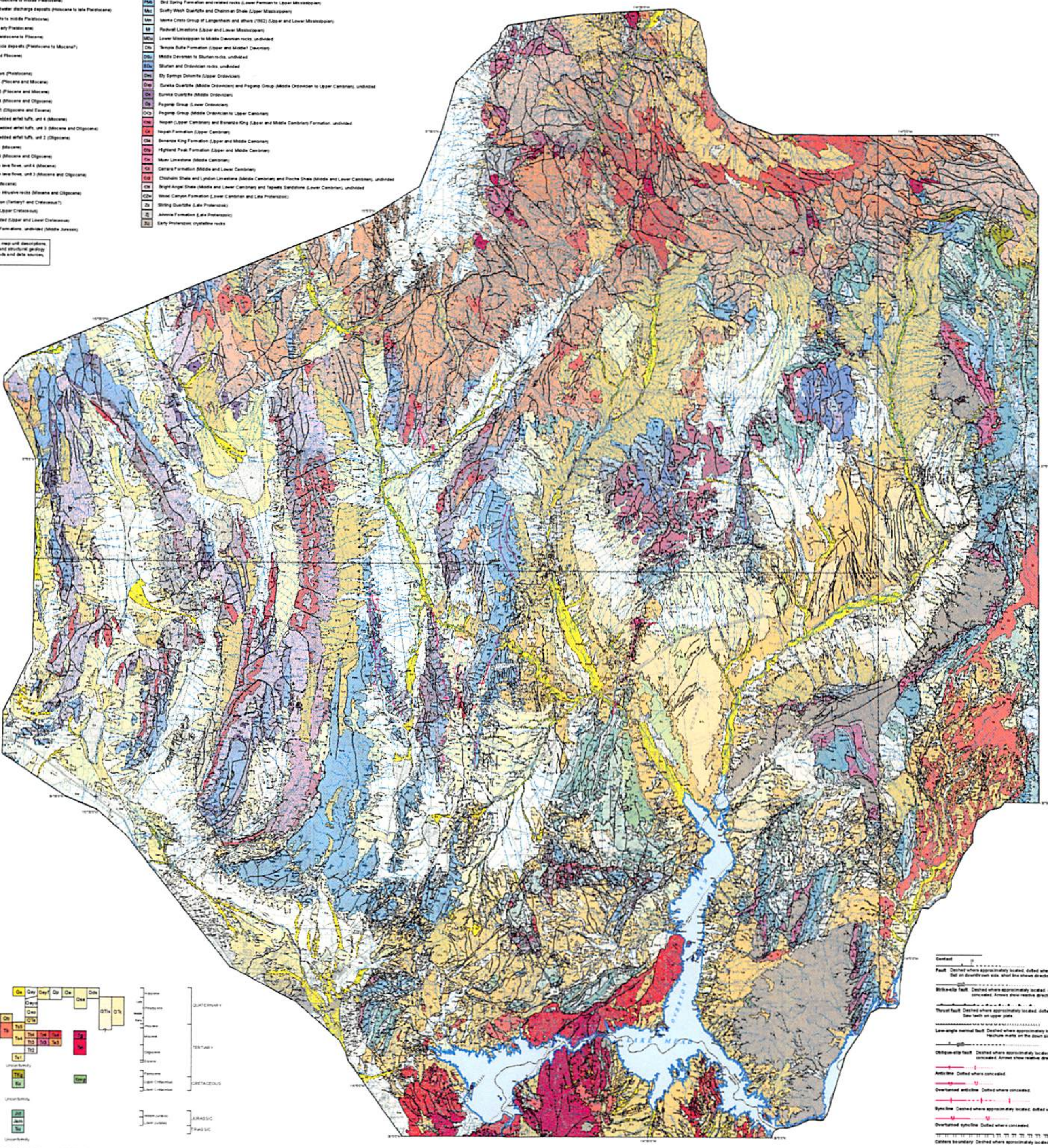
NEVADA BUREAU OF MINES AND GEOLOGY

MAP 150 GEOLOGIC MAP OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY GROUNDWATER FLOW SYSTEMS, NEVADA, UTAH, AND ARIZONA



GEOLOGIC MAP OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY GROUNDWATER FLOW SYSTEMS, NEVADA, UTAH, AND ARIZONA

William R. Page[1], Gary L. Dixon[2], Peter D. Rowley[3], and David W. Brickey[4]

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October 29, 2008
File Nos. 84320-2008-F-0007 and
84320-2008-I-0216

Memorandum

To: Field Manager, Ely Field Office, Bureau of Land Management, Ely, Nevada

From: Field Supervisor, Nevada Fish and Wildlife Office, Reno, Nevada

Subject: Request for Formal and Informal Consultation on the Kane Springs Valley Groundwater Development Project in Lincoln County, Nevada

This document transmits the U.S. Fish and Wildlife Service's (Service) biological opinion based on our review of the proposed Kane Springs Valley Groundwater Development Project and its possible adverse effects on the desert tortoise (*Gopherus agassizii*) (Mojave population), listed as threatened under the Endangered Species Act of 1973, as amended (Act) (16 U.S.C. 1531 *et seq*.), and its designated critical habitat, and the Moapa dace (*Moapa coriacea*), listed as endangered under the Act. No critical habitat has been designated for the Moapa dace. Further, the Bureau of Land Management (BLM) requests concurrence that the proposed project *may affect, but is not likely to adversely affect* the southwestern willow flycatcher (*Empidonax traillii extimus*), listed as endangered under the Act. No designated critical habitat for the southwestern willow flycatcher occurs in the project area. The Lincoln County Water District (LCWD) has applied for a BLM right-of-way to construct and operate a system of water facilities on BLM-managed land in southern Lincoln County.

This biological opinion is issued in accordance with section 7 of the Act and based on information provided in BLM's memorandum dated September 27, 2007, to the Service (received on September 28, 2007), and revised biological assessment (BA), dated December 2007 (ARCADIS 2007); Amended Stipulation for Withdrawal of Protests (Stipulated Agreement) dated August 8, 2006; discussions between the Service and BLM; and our files. A complete administrative record of this consultation is on file in the Service's Nevada Fish and Wildlife Office in Las Vegas.

This biological opinion does not rely on the regulatory definition of "destruction or adverse modification" of critical habitat at 50 CFR 402.02. Instead, we have relied upon the statutory provisions of the Act to complete the following analysis with respect to critical habitat.

INFORMAL CONSULTATION

Southwestern willow flycatcher

No habitat is present for the southwestern willow flycatcher within the project area. The closest breeding populations occur at Pahranagat National Wildlife Refuge (NWR) approximately 23 miles northwest and in the Warm Springs Area, approximately 25 miles southeast. Since the springs in the Warms Springs Area are supplied by water from the deep carbonate aquifer, groundwater pumping in the Kane Springs Valley Hydrographic Basin could affect water levels in the Muddy River System. These effects to riparian vegetation will be minimized by actions contained in the Stipulated Agreement among the Service, LCWD and Vidler Water Company, Inc (VWC), which are designed to maintain minimum in-stream flows in the Warm Springs Area of the Muddy River system in order to protect and recover the Moapa dace. (See section below entitled "Proposed Minimization Measures for Moapa Dace"). The project is anticipated to have insignificant effects to the southwestern willow flycatcher since any decreases in groundwater flow to the Muddy River system will be minimized by the Stipulated Agreement.

In consideration of the proposed action, potential effects of the proposed action, and measures proposed by BLM, the Service concurs with BLM's determination that the proposed action *may affect, but is not likely to adversely affect* the southwestern willow flycatcher. This response constitutes informal consultation under regulations promulgated in 50 CFR§402.14, which establishes procedures governing interagency consultation under section 7 of the Act. This informal consultation does not authorize take of any listed species.

CONSULTATION HISTORY

The following chronology documents the consultation process that culminated in the following biological opinion for the desert tortoise and its designated critical habitat and for the Moapa dace:

On May 8, 2006, the Service sent BLM a memorandum containing a species list of endangered, threatened, and candidate species that may occur in or near the proposed Kane Springs Valley Groundwater Development Project (Service File No. 1-5-06-SP-499).

On July 12, 2007, BLM sent the Service a memorandum requesting formal consultation on the Kane Springs Valley Groundwater Development Project for potential adverse effects to the desert tortoise and its designated critical habitat. A BA accompanied the memorandum.

On September 4, 2007, the Service sent BLM a memorandum recommending formal consultation for the Moapa dace and requesting additional information necessary to initiate formal consultation for the desert tortoise (Service File No. 1-5-07-F-558).

On September 27, 2007, BLM sent the Service a memorandum requesting formal consultation on the project for potential adverse effects to the desert tortoise and its designated critical habitat and the Moapa dace. A revised BA accompanied the memorandum.

On October 19, 2007, the Service sent BLM a memorandum that initiated formal consultation on September 28, 2007, since the revised BA contained sufficient information (Service File No. 84320-2008-F-0007).

On December 4, 2007, BLM, the Service, and the project proponent participated in a conference call to discuss several topics including the monitoring wells that are required by the stipulated agreement among LCWD, VWC, and the Service for withdrawal of the Service's protests of water rights applications in Kane Springs Valley. It was decided that the BA would include acreages and potential effects associated with the two new monitoring wells.

On December 6, 2007, ARCADIS, the project consultant, sent the Service a revised BA on behalf of BLM, which included acreages associated with the two new monitoring wells.

On January 28, 2008, the Service sent BLM a memorandum extending the consultation period for this project by 60 days due to a substantial consultation workload.

On June 17, 2008, VWC sent the Service comments on the terms and conditions of the draft biological opinion.

On June 18, 2008, the Service provided BLM a copy of a draft biological opinion via email.

On June 30, 2008, a Memorandum of Understanding (MOU) among LCWD, VWC, and the Service was signed. Pursuant to the MOU, the Service will issue a biological opinion for the project which will include an incidental take statement authorizing such take of Moapa dace as may occur in connection with the pumping and transfer of 1,000 acre-feet of groundwater under Phase I of the Project and implementation of the Monitoring, Management and Mitigation Plan. Upon receiving authorization from the Nevada State Engineer to appropriate more than 1,000 and up to 5,000 acre-feet per year of groundwater from the Kane Springs Valley for use in the Coyote Springs Valley, the Service will reinitiate consultation for the project pursuant to section 7 of the Act.

On July 15, 2008, the Service received a copy of BLM's comments on the draft biological opinion via email.

On July 28, 2008, the Service and BLM met to discuss the draft biological opinion.

On August 18, 2008, BLM sent the Service proposed language for term and condition 4.d. and 5. of the biological opinion via email.

On October 1, 2008, BLM sent the Service updated proposed language for term and condition 4.d. of the biological opinion via email.

On October 1, 2008, the Service and BLM met to discuss deposition of remuneration fees for offsetting desert tortoise habitat loss.

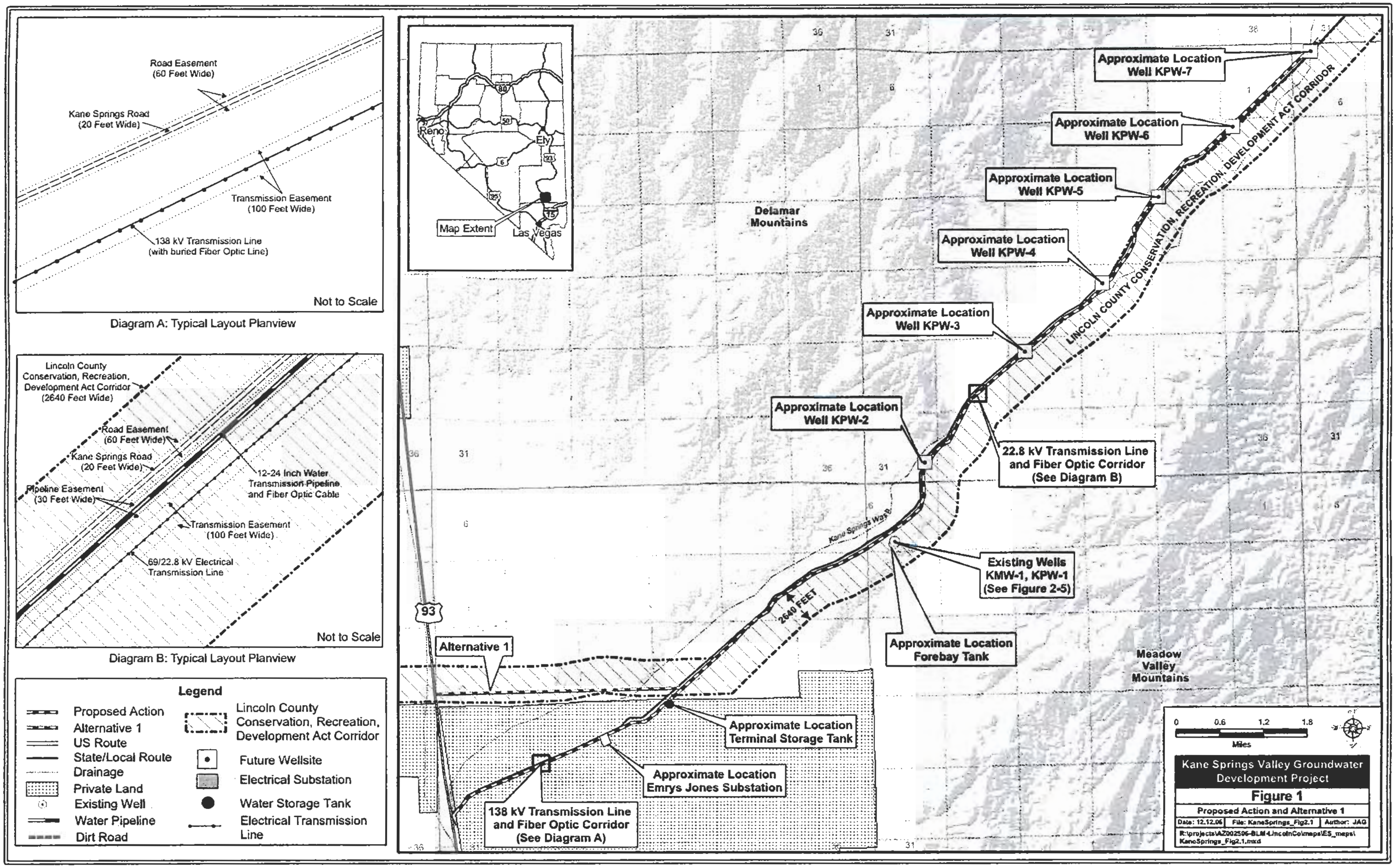
BIOLOGICAL OPINION

A. Description of the Proposed Action

The purpose of the proposed action is to develop a system for tapping groundwater resources in the Kane Springs Valley Hydrographic Basin for municipal water purposes within the Coyote Spring Valley Hydrographic Basin. The project proponents applied to the Nevada State Engineer's Office for 17,375 acre-feet per year (afy), but to date have been granted 1,000 afy under Ruling # 5712. The proposed pipeline would have capacity to transport up to 5,000 afy. Construction and operation of the proposed action would supply a small, but initially substantial portion of the total water requirements for the Coyote Springs Investment (CSI) development projects in southern Lincoln County. The majority of the proposed facilities would be located along or near the Kane Springs Road, within the 2,640-foot wide Lincoln County Conservation, Recreation, and Development Act (LCCRDA) utility corridor on public land, or on private land owned by CSI. The project area extends approximately 16.6 miles along Kane Springs Road from the intersection with US 93 (US 93).

The proposed action consists of several components including, groundwater production wells, monitoring wells, water pipelines, storage tanks, power transmission lines and substations, access roads and a fiber optic line. Figure 1 shows the approximate location of the project components in the lower Kane Springs Valley. LCWD is developing this project in cooperation with Lincoln County Power District (LCPD) Number 1 and Lincoln County Telephone Company. Each utility agency is responsible for the construction, operation, and rehabilitation of disturbed land associated with their utility. Each utility agency may be required to apply for a separate right-of-way with BLM.

Although the BA included the construction of the Emrys Jones Substation and power line west of the Substation, LCPD is constructing these facilities under another project, the Coyote Springs Transmission Line Project. Therefore, these facilities are not considered to be part of the proposed action for this consultation.



Road Easement (60 Feet Wide)
Kane Springs Road (20 Feet Wide)
Transmission Easement (100 Feet Wide)
138 kV Transmission Line (with buried Fiber Optic Line)
Not to Scale
Diagram A: Typical Layout Planview
Lincoln County Conservation, Recreation, Development Act Corridor (2640 Feet Wide)
Road Easement (60 Feet Wide)
Kane Springs Road (20 Feet Wide)
Pipeline Easement (30 Feet Wide)
12-24 Inch Water Transmission Pipeline and Fiber Optic Cable
Transmission Easement (100 Feet Wide)
69/22.8 kV Electrical Transmission Line
Not to Scale
Diagram B: Typical Layout Planview
Legend
Proposed Action
Alternative 1
US Route
State/Local Route
Drainage
Private Land
Existing Well
Water Pipeline
Dirt Road
Lincoln County Conservation, Recreation, Development Act Corridor
Future Wellsite
Electrical Substation
Water Storage Tank
Electrical Transmission Line
Reno
Ely
Las Vegas
Map Extent
Delamar Mountains
Meadow Valley Mountains
Approximate Location Well KPW-7
Approximate Location Well KPW-6
Approximate Location Well KPW-5
Approximate Location Well KPW-4
Approximate Location Well KPW-3
Approximate Location Well KPW-2
LINCOLN COUNTY CONSERVATION, RECREATION, DEVELOPMENT ACT CORRIDOR
22.8 kV Transmission Line and Fiber Optic Corridor (See Diagram B)
Existing Wells KMW-1, KPW-1 (See Figure 2-5)
Approximate Location Forebay Tank
Kane Springs Wash
2640 FEET
93
Alternative 1
Approximate Location Terminal Storage Tank
Approximate Location Emrys Jones Substation
138 kV Transmission Line and Fiber Optic Corridor (See Diagram A)
0 0.6 1.2 1.8
Miles
Kane Springs Valley Groundwater Development Project
Figure 1
Proposed Action and Alternative 1
Date: 12.12.06 File: KaneSprings_Fig2.1 Author: JAG

1. Project Features

a. Wells

Groundwater from the Kane Springs Valley Hydrographic Basin would be supplied to the Coyote Spring Valley area from up to seven groundwater production wells. All production wells would be located within the LCCRDA corridor on public land, spaced approximately 1.3 to 1.8 miles apart. The first well (KPW-1), approved under BLM Serial Number NVN-079630, was drilled in 2005. Each wellhead would be enclosed in a masonry block structure, which would also contain all aboveground piping, shutoff valve, check valve, flow meter, air release valve, and electrical equipment. The size of each fenced well yard would be approximately 150 feet by 150 feet. Production wells would be equipped with an electric pump.

An existing monitoring well, KMW-1, is located adjacent to KPW-1 (Figure 1). The monitoring well was installed in 2005 to assist in assessing the hydrogeology of the Kane Springs Valley Hydrographic Basin. Two new monitoring wells may also be installed per the stipulated agreement for withdrawal of the Service's protests of LCWD and VWC's water rights applications in Kane Springs Valley. The wells would be placed on CSI land and would each have a footprint of less than 1 acre in size. The final location would be coordinated through the Technical Review Team (TRT) established under the stipulated agreement. Should the TRT decide that these monitoring wells are not necessary, funds for the material and construction of the monitoring would be used instead for Moapa dace conservation.

b. Pipelines

There are two types of pipelines associated with the proposed action: the well field pipeline collection system and the main transmission pipeline. Ancillary pipeline components include isolation valves, cathodic protection, control valves, air release/vacuum valves, blow-off valves, access manways, fiber optic splice vaults, and pipe alignment markers.

The well field pipeline collection system would consist of individual branch pipelines from each well to a single main collection pipeline terminating at the forebay storage tank. The total pipeline collection system would extend approximately 9.4 miles. The pipeline, to be constructed of ductile iron, would vary in size (telescope) from 12 inches to 24 inches in diameter, with the largest diameters located closest to the forebay storage tank. The pipeline would be buried to a minimum depth of three feet below grade, or three times scour depth in washes in accordance with engineering requirements. In general, the pipeline would parallel the Kane Springs Road to the south, with a 60-foot wide construction easement and a 30-foot wide permanent easement. If cross-country construction is required, the temporary construction easement would be 75 feet wide, with a permanent easement of 60 feet.

Approximately 3.8 miles of buried 24-inch diameter transmission pipeline would be constructed adjacent to the Kane Springs Road between the forebay storage tank and the terminal storage tank. Appurtenant groundwater facilities (e.g., isolation valves, control valves) would occur, on average, every mile along the alignment. These facilities would be located predominantly below existing grades in traffic-rated, lockable, concrete vaults that would vary in dimension. Typically, these vaults would be located outside of traffic areas and may require small location markers extending several feet above the surface of the ground.

c. Storage Tanks

A 50,000-gallon forebay storage tank would be installed adjacent to the existing production well (KPW-1) and would initially serve as the termination point for the groundwater collection system. This tank would be used to normalize flow pressures in the system and provide storage for secondary lifting to the terminal storage tank, if required. The water level in the forebay storage tank would control the operation of the well field via telemetry. Either wireless telemetry or direct-burial fiber optic telemetry cable located in pipeline trenches would enable communication between the collection system, forebay storage tank, and the terminal storage tank.

A terminal water storage tank would ultimately be located at the southern end of the water transmission pipeline to receive the imported water and to serve as a water distribution source for the northern Coyote Spring Valley area. The storage tank would be constructed with a maximum capacity of 700,000 gallons, subject to final design requirements.

d. Power Distribution

In order to provide reliable electric service to the well fields, LCPD would construct and operate transmission lines and substations. Power facilities built for this project would connect to the Emrys Jones Substation, part of the Coyote Springs Transmission Line Project.

Under the proposed project, LCPD would construct an overhead transmission line with a 69 kV/22.8 kV distribution circuit from the Emrys Jones Substation to the proposed well fields along the Kane Springs Road, parallel to the pipeline. A total of 14 miles of transmission line would be installed. The 69 kV/22.8 kV transmission line would be a single-circuit line supported by wood pole structures. The 69 kV/22.8 kV transmission line would primarily be located on public lands managed by BLM, with a short section near the Emrys Jones Substation located on private property. Each wood pole structure would require a temporary construction easement of 0.07 acre and after construction, each structure would occupy 0.02 acre. The transmission line would have a 100-foot permanent easement.

At each well location, a fenced power substation (approximately 155 feet by 95 feet) would be constructed to serve the well pump motor and ancillary equipment. The substation yards would consist of a 69 kV/22.8 kV to 4.16 kV pad-mounted step-down transformer, primary metering, switch cabinet, capacitor bank, and a station service transformer.

e. Fiber Optic

The Lincoln County Telephone Company is proposing to install fiber optic cables within the proposed project right-of-way. The fiber optic line would be buried in the same trench as the pipeline and adjacent to the 138 kV transmission line on private lands proposed under the Coyote Springs Transmission Line Project. The fiber optic cables would be used for communication to manage the pipeline operation. The fiber optic cables would tie into an existing fiber optic line located on the east side of US 93.

f. Additional Project Components

Approximately 50 acres may be used for temporary extra work spaces. These areas would be spaced approximately 0.5 mile apart and would cover approximately 2 acres. Some larger staging areas may be sited in suitable areas near steeply incised drainages, above and below slopes where construction is expected to be difficult, and at pipe laydown areas. All extra work spaces on Federal lands would be located within the project right-of-way. Staging areas on private lands would be used during construction for storage of materials and equipment, construction office trailers, fuel storage, equipment maintenance, stockpiling and handling of excavated material, and other construction-related activities. Following construction, the staging areas would be restored as described in the Kane Springs Valley Groundwater Development Project Environmental Impact Statement (EIS).

g. Road Access and Transportation

US 93 and the Kane Springs Road would provide primary access into the project area. Spur roads would be constructed from the Kane Springs Road to temporary and permanent facilities sites, such as contractors' yards, well fields, and power pole locations, within the project right-of-way corridor. The number of new spur roads would be held to a minimum, consistent with their intended use (e.g., facility construction, conductor stringing and tensioning). It is estimated that seven new minor access roads would be required to access the proposed well houses. Each of these roads would be approximately 100 feet long and 12 feet wide. Access roads not required after construction would be removed and restored to their approximate original contour and dimensions and made to discourage vehicular traffic. All temporary road surfaces would be ripped or harrowed to establish conditions appropriate for reseeding, drainage, and erosion prevention.

Table 1 lists the estimated temporary and permanent disturbance acreage required for construction and operation of the proposed project. The estimated disturbance acreage is based on preliminary engineering plans and therefore may change slightly.

Table 1 Estimated Surface Disturbance by Land Ownership (at full buildout of the proposed project)		
	Temporary (acres)*	Permanent (acres)*
Federal (BLM)		
Well House and Well Substation	3.2	3.0
KPW-1 Well, Forebay Tank, KMW-1 Well	0.3	1.0
Pipeline Construction right-of-way	148.7	0.0
Terminal Storage Tank	0.0	0.0
Electrical Substation	0.0	0.0
Electrical Transmission Line	14.8	5.0
Electrical Transmission Line Access Roads	0.0	8.0
Fiber Optics Line	0.0	0.0
Subtotal	**167.0**	**17.0**
Private		
Well House and Well Substation	0.0	0.0
KPW-1 Well, Forebay Tank, KMW-1 Well	0.0	0.0
Pipeline Construction right-of-way	0.0	0.0
Terminal Storage Tank	0.7	0.3
Electrical Substation	0.0	0.0
Electrical Transmission Line	2.4	1.1
Electrical Transmission Line Access Roads	0.0	0.7
Fiber Optics Line	14.2	0.0
Two Groundwater Monitoring Wells	4.0	2.0
Subtotal	**21.3**	**4.1**
Total	**188.3**	**21.1**

h. Construction Procedures

Each utility agency would conduct all activities associated with the construction, operation, and rehabilitation of temporarily disturbed areas within the authorized limits of their BLM right-of-way. To supply electrical power to the well fields, it is anticipated that LCPD would be the first utility agency to begin construction after all approvals have been acquired. During construction activities, water would be used to suppress dust in the construction area.

Construction of the electric transmission lines and substation would involve the following general sequence: engineering surveys and staking, clearing and grading, material storage and handling, creation of structure holes or foundations, structure assembly and erection, installation of security fencing around substation, post construction cleanup and reclamation, and construction monitoring. Construction of the overhead lines would be completed in two phases: setting the pole structures and installing the cable. The setting of the pole structures is accomplished with a single multi-purpose truck. The truck has a small crane suitable for lifting and placing poles. A pole trailer is towed behind the crane truck to transport the poles to the installation site. Affixed to the crane is an auger for boring the holes for the pole structures. Soil excavated during construction would be used for backfill and for restoration of disturbed areas. The cable would be installed using two vehicles: a cable truck and a truck with a power lift. The cable would be strung out along the installation route and the man lift would be used to place the cable on the pole structure.

Construction of the groundwater facilities and fiber optic line would involve the following sequence: engineering surveys and staking, topsoil salvage and storage, clearing and grading (including access road construction), trenching and blasting, pipeline stringing/installation, installation of fiber optic line in common pipeline trench, backfilling, hydrostatic testing, re-grading, post-construction cleanup, and reclamation, and construction monitoring. Trenching would consist of excavating the trench using either a trenching machine or track-mounted excavator. In general the bottom of the trench would be five feet wide and up to six feet deep to provide the required cover over the top of the installed pipe. In areas of weathered rock, track-mounted excavators may be preceded by a bulldozer equipped with a single-shank ripper. Limited blasting may be required in areas where shallow or exposed bedrock is present. This project would be constructed utilizing a "Dig and Lay" procedure. In other words, a portion of trench would be dug, the pipe would be laid, welded, and back filled and another segment would begin. There would be minimal (less than 500 feet) open trench at any one time and the backfill would occur almost immediately following pipe installation.

i. Operation and Maintenance

The electrical facilities would be in continuous operation and water facilities would be operated and maintained to ensure safe operation and integrity of the pipeline. Periodic inspection and maintenance of power and water facilities would be required. If a pipeline break were to occur, immediate steps would be taken to isolate the break, the break would be repaired, and the trench backfilled. Areas would be contoured and revegetated after these types of repairs. Emergency maintenance of power lines, such are repairing downed wires and correcting unexpected outages would be performed by LCPD.

j. Project Phases

Construction of the project would occur in three phases, with one to three years between phases. Phases would correspond to demand for water and issuance of permits for additional water rights. Eventually LCWD would like to harvest 5,000 afy from the carbonate aquifer within the Kane Springs Valley Hydrographic Basin but so far has been granted an appropriation of 1,000 afy by the Nevada State Engineer. This appropriation granted four points of diversion, which constitutes the initial production under Phase 1 of the project. If additional appropriations are granted, production from Phase 1 wells could be increased, and Phase 2 and Phase 3 wells could be developed.

- Construction of Phase 1 would occur over a 90- to 180-day period and would begin upon completion of environmental reviews and the acquisition of necessary permits and approvals. Phase 1 water facilities would include the transmission pipeline (main water line) and approximately 9.4 miles of well field collection pipelines for up to four wells (main collection plus laterals to wells), up to four production wells, the storage tanks, and up to two monitoring wells. Power facilities would include 14 miles of 69 kV/22.8 kV overhead power lines and up to four smaller substations to serve each well.

- Construction of Phase 2 would occur over a 30- to 60-day period. Phase 2 water facilities would include one to two production wells and lateral pipelines from these wells to the main collection pipeline (combined length of the two lateral pipelines is expected to be less than 1 mile). Power facilities would include 22.8 kV underground power lines from the main transmission line to the substation(s) and one to two smaller substations to serve the new well(s).
- Phase 3 construction would only occur if production from Phase 1 and Phase 2 were insufficient to meet anticipated demand or if production from previous wells were lower than estimated or designed. Phase 3 facilities and construction times are similar to Phase 2.

2. State Engineer Ruling

On February 2, 2007, the Nevada State Engineer issued Ruling 5712, which granted 1,000 afy of groundwater from the Kane Springs Valley Hydrographic Basin to LCWD and VWC for municipal purposes within the Coyote Spring Valley Hydrographic Basin. Specifically 500 afy was granted under Application 72220 and applications 72218, 72219, and 72221, were granted for a total combined duty of 500 afy.

The State Engineer concluded that to permit the appropriation of water in an amount greater than permitted under this ruling would conflict with existing rights and threaten to prove detrimental to the public interest. After reviewing the existing information, the State Engineer concluded that a small amount of water can be developed in the Kane Springs Valley and not unreasonably impact existing rights in the discharge areas of the White River carbonate-rock aquifer system, which are already fully appropriated. The State Engineer found that no water has been previously appropriated in the Kane Springs Valley Hydrographic Basin and by limiting the quantity of water authorized for appropriation the potential impacts to existing waster rights in down-gradient hydrographic basins would be minimized.

3. Proposed Minimization Measures for Desert Tortoise (Mojave population)

a. The applicant will implement an Environmental Training Program. Prior to beginning work, all contractor personnel assigned to the field for construction-related activity will attend a mandatory one-time Worker Environmental Training Program presented by the project developer's Environmental Compliance Team. The presentation will review topsoil salvage, access restrictions, general site restrictions, and other environmental requirements regarding the project. Participants will sign a statement declaring that they understand and will abide by any guidelines set forth in the material presented.

b. All areas around structures will be backfilled, compacted, and returned as close as possible to the original condition and grade.

c. Signs will be placed along the access roads to discourage off-highway vehicle use of adjacent areas.

d. Clearance surveys will be performed prior to any construction activities within the right-of-ways. Any tortoises located will be handled and relocated by a qualified tortoise biologist in accordance with Service-approved protocol (Desert Tortoise Council 1994, revised 1999). Burrows containing tortoises or nests will be excavated by hand, with hand tools, to allow removal of the tortoise or eggs. Desert tortoises moved during the tortoise inactive season or those in hibernation, regardless of date, must be placed into an adequate burrow; if one is not available, one will be constructed in accordance with Desert Tortoise Council (1994, revised 1999) criteria. During mild temperature periods in the spring and early fall, tortoises removed from the site will not necessarily be placed in a burrow. Tortoises and burrows will only be relocated to federally managed lands. If the responsible Federal agency is not BLM, verbal permission, followed by written concurrence, will be obtained from BLM and the Service before relocating the tortoise or eggs to lands not managed by BLM.

e. Construction monitoring will employ a field contact representative, authorized biologist(s), and qualified biologist(s) during construction activities except in those areas with high disturbance. The Service employs a specific set of guidelines for such monitoring.

f. Tortoises requiring moving will only be handled by the authorized and qualified tortoise biologist or other trained personnel approved by the Service and the Nevada Department of Wildlife (NDOW).

g. A 25 mile per hour (mph) project access road speed limit will be enforced for all project vehicles and personnel.

h. The area limits of project construction and survey activities would be predetermined based on the temporary and permanent disturbance areas noted on the final design engineering drawings to minimize environmental effects arising from the project, with construction activities and traffic restricted to and confined within those limits.

i. Littering is not allowed. Project personnel would not deposit or leave any food or waste in the project area, and no biodegradable or non-biodegradable debris would remain in the right-of-way following completion of construction.

j. No wildlife, including rattlesnakes, may be harmed except to protect life and limb.

k. Project personnel are not allowed to bring pets to any project area in order to minimize harassment or killing of wildlife and to prevent the introduction of destructive animal diseases to native wildlife populations.

l. Wildlife species may not be collected for pets or any other reason.

m. Project supplies or equipment where wildlife could hide will be inspected prior to moving or working on them, to reduce the potential for injury to wildlife. Supplies or equipment that cannot be inspected or from which wildlife cannot escape or be removed, will be covered or otherwise made secure from wildlife intrusion or entrapment at the end of each work day.

n. All steep-walled trenches or excavations used during construction will be inspected twice daily (early morning and evening) to protect against wildlife entrapment.

o. All new access roads constructed as part of the project that are not required as permanent access for future project maintenance and operation would be permanently closed to minimize impacts from increased public access.

p. To minimize perching opportunities for raptors near habitats supporting sensitive prey species, structures incorporating a design to discourage raptor perching will be selected.

q. Only the minimum amount of vegetation necessary for the construction of structures and facilities will be removed. Topsoil will be conserved during excavation and reused as cover on disturbed areas to facilitate re-growth of vegetation.

r. Construction holes left open overnight will be covered. Covers will be secured in place nightly, prior to workers leaving the site, and will be strong enough to prevent livestock or wildlife from falling through and into a hole.

s. Holes and/or trenches will be inspected prior to filling to ensure absence of mammals and reptiles.

t. Where necessary, a biological resource monitor shall be present during the construction to ensure resources are protected in the construction area.

u. Excavations will be sloped on one end to provide an escape route for small mammals and reptiles.

v. A revegetation plan will be developed and implemented for the project which describes procedures the LCWD and its contractors would use to conduct revegetation of the disturbed areas. The Plan describes seedbed preparation; seed mixtures; seeding, salvaging, and transplanting methods; revegetation schedule; post-construction monitoring; evaluation of revegetation success; remediation; and reporting.

w. A noxious weed management plan will be developed and implemented for the project which includes site-specific measures that LCWD and its contractors would implement to control noxious weeds including, but not limited to, the use of cleaned, weed-free equipment, pressure washing of all vehicles and equipment prior to arrival at the work site, and the use of certified weed-free straw/hay bales to control erosion. A key element of the noxious weed management plan is to identify and treat existing weed infestations prior to construction.

x. A fire mitigation plan will be developed and implemented for the project which identifies measures to be taken during construction, operation, and maintenance of the project facilities to prevent and suppress fires. The purpose is to establish standards and practices to minimize the risk of fire or, in the event of fire, to implement immediate suppression procedures.

4. Proposed Minimization Measures for Moapa Dace

On August 8, 2006, the Service entered into a stipulated agreement with LCWD and VWC for water rights applications in the Kane Springs Valley Hydrographic Basin, then under review by the Nevada State Engineer's Office. The Service agreed to withdraw its protests for the granting of these water rights in exchange for the parties agreeing to implement the Monitoring, Management, and Mitigation Plan which would help protect senior Federal water rights in the Muddy River Springs/Warm Springs Area from unreasonable adverse impacts from groundwater pumping. The common goal of the parties is to manage the development of the LCWD and VWC water rights in their entirety from the Kane Springs Valley Hydrographic Basin, without resulting in any losses to senior water rights or unreasonable adverse impacts to Federal water resources.

The Monitoring, Management, and Mitigation Plan lists monitoring requirements in relation to the production wells, two new monitoring wells, elevation control and springflow, water quality, data quality, and reporting. The management requirements include action criteria to help to maintain minimum in-stream flows in the Warm Springs Area in order to protect and recover the Moapa dace. The parties agreed to the following, summarized from the Plan:

a. The Average Flow Level shall be determined by flow measurements at Warm Springs West flume. See the Plan for the definition of Average Flow Level.

b. If the Average Flow Level decreases to an amount within the Trigger Range of 3.2 cubic feet per second (cfs) or less, the parties agree to meet as soon as practically possible to discuss and interpret all available data and plan for mitigation measures in the event that flows continue to decline.

c. If the Average Flow Level is within the Trigger Range of 3.15 cfs or less but greater than 3.0 cfs, LWCD and VWC agree to reduce pumping from all wells in Kane Springs Valley by 50 percent or to a pumping level not greater than 2,500 afy, whichever results in the lesser amount of pumping, until the Average Flow Level exceeds 3.15 cfs. The subsequent State Engineer ruling limited pumping to 1,000 afy. Accordingly, under this scenario, LCWD and VWC would be required to reduce pumping by 50 percent.

d. If the Average Flow Level is within the Trigger Range of 3.0 cfs or less, LWCD and VWC agree to cease pumping from all wells in Kane Springs Valley until the Average Flow Level exceeds 3.0 cfs. However, if LWCD and VWC, together with CSI, effectuate a reduction in the quantity of water, CSI would have otherwise been entitled to pump in a given year from wells within the Coyote Spring Valley, then LWCD and VWC shall have the right to pump a like quantity of water from wells within Kane Springs Valley in that year.

The management requirements also include the establishment of a TRT with two representatives each from LCWD/VWC and the Service. The objectives of the TRT include reviewing existing data, making recommendations concerning the monitoring efforts required by this Plan, and determining whether other criteria, such as water levels in the monitoring wells, are a better indicator of potential effects of the pumping wells on the springs in the Muddy River Springs/ Warm Springs Area. As part of their commitment to the recovery of the Moapa Dace, LCWD and VWC will commit annual funds for a period of five years following the granting of the water rights applications, for the restoration of Moapa dace habitat outside the boundaries of the Moapa Valley National Wildlife Refuge (NWR).

B. Definition of the Action Area

The action area is defined as all areas to be affected directly or indirectly by the Federal action, including interrelated and interdependent actions, and not merely the immediate area involved in the action (50 CFR § 402.02). Subsequent analyses of the environmental baseline, effects of the action, cumulative effects, and levels of incidental take are based upon the action area as determined by the Service.

For the desert tortoise and its designated critical habitat, impacts will be tied to the project area and a zone-of-influence extending 0.5 miles (2,400 feet) beyond the project area to cover potential effects to desert tortoises that could move into construction areas or onto access roads.

For the Moapa dace, which depends on thermal springs in the Warm Springs Area for survival, the action area includes the Kane Springs Valley Hydrographic Basin and the hydrographic basins down gradient of this basin in the White River Groundwater Flow System that are hydrologically connected to the Muddy River ecosystem. These hydrographic basins are the Coyote Spring Valley (Basin 210) and Muddy River Springs Area (Basin 219). The Service acquired the Moapa Valley NWR to secure habitat and assist the recovery efforts for the endangered Moapa dace, a species restricted to the Warm Springs Area and the mainstem of the upper Muddy River. Springs in this area are considered regional discharge points for the carbonate aquifer of the White River Flow System.

C. Status of the Species- Rangewide

1. Desert Tortoise (Mojave population) and Designated Critical Habitat

The current rangewide status of the desert tortoise and its critical habitat consists of information on its listing history, species account, recovery plan, recovery units, distribution, reproduction, and numbers, and critical habitat units and their constituent elements. This information is provided on the Service's website at: http://www.fws.gov/nevada. If unavailable, contact the Nevada Fish and Wildlife Office in Las Vegas at (702) 515-5230 and provide File No. 84320-2008-F-0007.

2. Moapa Dace

See the description in the Intra-Service Programmatic Biological Opinion for the Proposed Muddy River Memorandum of Agreement Regarding the Groundwater Withdrawal of 16,100 afy From the Regional Carbonate Aquifer in the Coyote Spring Valley and California Wash Basins and Establishment of Conservation Measures for the Moapa Dace, Clark County, Nevada (Service 2006c) (File No. 1-5-05-FW-536). Updated information on the Moapa dace is provided below.

Warm Springs Natural Area

In September 2007, Southern Nevada Water Authority (SNWA) purchased 1,179 acres of private property that encompasses several springs in the Muddy River headwaters area, including the former Warm Springs Ranch. The property includes 3.8 miles of the mainstream Muddy River. The Warms Springs Natural Area is to be managed as a nature preserve for protection of Moapa dace; and restoration and management of the areas as an ecological reserve.

Current Distribution and Abundance

Moapa dace surveys have been conducted annually throughout the upper Muddy River system. Dace surveys conducted semi regularly between 1994 and 2006 indicate Moapa dace numbers range between 1,296 and 3,825 individuals. The 2007 survey data indicate that there were approximately 1,172 fish in the population that occurred throughout 5.6 miles of habitat in the upper Muddy River system. Approximately 97 percent of the total population occurred within one major tributary that included 1.78 miles of spring complexes that emanate from the Pedersen, Plummer, and Apcar spring complexes on the Moapa Valley NWR and their tributaries (upstream of the gabion barrier). Approximately 48 percent of the population was located on the Moapa Valley NWR and 48 percent occupied the Refuge Stream supplied by the Pederson-Plummer springs. The highest densities of Moapa dace occurred on the Moapa Valley NWR's Plummer and Pedersen units.

In 2008, there was an approximately 60 percent decrease in the number of Moapa dace, from 1,172 fish in 2007 to 460 in 2008. Most of this decline is due to large changes in the numbers of dace in the Pederson, Plummer, and Refuge Stream areas which supported more than 92 percent of the population in 2007. The cause of the population decline is currently unknown, although beavers have recently changed stream characteristics in the Refuge Stream and vegetation management occurred along the Pederson Unit. In addition, habitat restoration projects have been implemented over the past few years in the Pederson and Plummer units of the Moapa Valley NWR, restoring the streams to a more natural state to augment Moapa dace habitat and populations.

D. Environmental Baseline

1. Status of the Listed Species/Critical Habitat in the Action Area

a. *Desert Tortoise (Mojave Population) - Status within the Action Area*

The action area occurs in the Mojave Desert Scrub Biome (Turner 1982), along the Kane Springs Road located in the valley between the Meadow Valley Mountains to the south and the Delamar Mountains to the north. The project area crosses Kane Springs Wash, which flows southwest to its confluence with the Pahranagat Wash in the northern part of the Coyote Spring Valley, in several locations. The vegetation in the action area consists of creosote bush scrub and desert wash scrub along Kane Springs and Pahranagat washes. Elevations in the action area range from approximately 2,600 to 3,300 feet.

Between October 16 and 18, 2006, Greystone-ARCADIS biologists conducted desert tortoise presence-absence surveys in the project area for BLM (ARCADIS 2007). Evenly spaced along the project area were 18, 1.5 mile long by 10 yard wide triangular strip transects. Transects were surveyed for live or dead desert tortoise, and any tortoise sign including burrows, scat, tracks, and water scrapes. The total corrected sign method was used to estimate tortoise densities. Estimated tortoise densities ranged from 10 to 0 tortoises per square mile. No live tortoises were found and most of the tortoise sign was comprised of burrows and water scrapes. The highest tortoise densities were 10 per square mile at 3 transects, and 7 per square mile at 3 transects. The remainder of the transects had densities of 5 per square mile or less. No desert tortoise sign were found in the two transects that overlapped with a wildfire perimeter from 2005 at the northeast end of the project area. Over the project area, tortoise densities average 4 desert tortoises per square mile. Densities in the project area are therefore estimated to be very low.

Recent surveys have been conducted in the Coyote Spring Valley as part of the rangewide population monitoring program. Survey data from 2005 line-distance sampling in the Coyote Spring Valley, which includes transects in the CSI private and lease lands located in the Mormon Mesa Critical Habitat Unit (CHU), estimate the tortoise densities in the valley to be 8.3 tortoises per square mile (Service unpublished data). Over the first five years of line-distance sampling monitoring, tortoises were least abundant in the Northwest Mojave Recovery Unit (2 to 8 tortoises per square mile) as compared to other recovery units (Service 2006b). Tortoise densities in the Coyote Spring Valley are therefore among the highest in the recovery unit. These results are preliminary and additional analysis is needed, incorporating 2006 and 2007 survey results. Desert tortoise clearance surveys were conducted in 2006-2007 in the southern part of the Coyote Spring Valley. One hundred percent clearance surveys were conducted on 5,302 acres of CSI private lands in Clark County as of January 2008. Based on the total number of tortoises cleared during surveys (108 adults and juveniles), we estimate a density of around 13 tortoises per square mile on the CSI private lands in Clark County.

Older desert tortoise survey data exists for the action area including BLM strip triangle surveys and the Coyote Springs Permanent Study Plot (PSP). Prior to 1991, BLM surveyed for tortoises using the strip triangle method, recording all tortoise sign within approximately 5 meters (15 feet) of the transect and estimating species density based on methods described by Karl (1981) for southern Nevada. Densities within one half mile of Kane Springs Road ranged from high to very low. Densities averaged medium (45 - 90 tortoises per square mile) and low (10 - 45 tortoises per square mile) over the project area. Densities on the northeast part of the project area were very low (0 - 10 tortoises per square mile). It appears that densities have declined somewhat since 1991.

The closest 1-square-mile PSP to the project area is the Coyote Spring plot, which is located 1.9 miles east of US 93 and 1.9 miles north of Kane Springs Road. This plot was established in 1986 and resurveyed in 1992 and 1995. EnviroPlus Consulting (1995) characterized this site as having moderately high tortoise numbers, with a size distribution typical of that observed on other PSPs and a significantly skewed sex ratio with female tortoises comprising two-thirds of the observed sub-adult and adult population (however, this effect was not significant for tortoises >208 mm mid-carapace length). Over the three survey periods, total estimated population size on the plot ranged from 96 ± 31 to 116 ± 29 (Esque1986, Converse Environmental Consultants Southwest, Inc. 1992, EnviroPlus Consulting 1995). This is considerably higher than densities in the action area. The annual adult mortality rate for the Coyote Spring plot in 1995 was estimated at 4 percent, which is higher than the 2-3 percent rate that the Service believes necessary to sustain desert tortoise populations (Service 1994). However, the tortoise population at the Coyote Spring PSP was apparently stable over the 10 years that the surveys spanned (EnviroPlus Consulting 1995).

Tortoises with symptoms of cutaneous dyskeratosis and URTD were observed during plot surveys; however, comparisons across survey periods are unreliable due to differences in diagnosis/evaluation criteria used to evaluate health status. In 1995, approximately one-third of tortoises had trauma-related injuries, likely caused by a predator. Overall, mortality by predation was characterized as present, but not at a high rate. Human impacts on tortoise populations in this area were considered low and inconsequential (EnviroPlus Consulting 1995). The PSP is located in the northern part of the Coyote Spring Valley and BLM strip triangle survey data corroborates that this area north of the Kane Springs Road and east of US 93 has higher tortoise densities than the surrounding areas with several very high density (greater than 140 tortoises per square mile) and high density (90 -140 tortoises per square mile) survey triangles.

b. ***Desert Tortoise Critical Habitat - Status within the Action Area and the Mormon Mesa CHU***

The project area is located mostly within the 427,900 acre Mormon Mesa CHU of the Northeastern Mojave Recovery Unit for the desert tortoise. The primary vegetation community within the Mormon Mesa CHU is creosotebush-white bursage desert scrub, which in Nevada is found in broad valleys, lower bajadas, plains and low hills of the Mojave Desert. Shrub cover is sparse to moderately dense, consisting primarily of creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*) with a variety of different shrubs and cacti as co-dominants or understory species. Where poorly-drained soils with high salt and clay content are found on valley bottom floors, pockets of salt desert scrub community may be present, typified by one or more *Atriplex* species.

The CHU boundaries were based on proposed desert wildlife management areas (DWMAs) in the Draft Desert Tortoise Recovery Plan. The land management agencies have subsequently designated areas of critical environmental concern (ACECs) in each DWMA, where they are managing the land as reserves. In general, land management activities that may negatively affect the desert tortoise and its habitat such as domestic livestock grazing, grazing by wild burros and horses, commercial harvest of desert flora, and off-road vehicle use are mostly restricted or not allowed in these areas, as per Recovery Plan recommendations. The Mormon Mesa CHU contains the following ACECs: Kane Springs, Coyote Springs, and Mormon Mesa. The project area is in the Kane Springs ACEC.

CSI owns 29,055 acres of lands in Coyote Spring Valley, in Clark and Lincoln counties, Nevada, all of which is designated critical habitat for the desert tortoise. In addition CSI has a lease for approximately 13,767 acres of BLM-administered land in Coyote Spring Valley for 99 years. In Clark County, CSI is currently constructing a residential and golf community with associated commercial development on 6,881 acres of private land. Construction will occur over 25 years, with an eventual build out of 29,000 residential units, approximately 72,500 residents, and a visitor capacity equal to 14,500 residents (based on full-time equivalency). In Lincoln County, CSI proposes to develop 21,454 acres of private land over a 40 year period. It is estimated that there would be up to 111,000 residential units, resulting in an increase of population of 275,300 residents in Lincoln County. CSI plans to create a natural reserve on 13,767 acres of BLM leased land (approximately 7,548 acres in Lincoln County and 6,219 acres in Clark County).

EnviroPlus Consulting (1995) characterized the Coyote Spring PSP as having low historical and present-day human impact: Old Highway 93 was rarely used and had large shrubs growing through cracks in the pavement; little trash was observed on the plot; no power lines were present; no cattle or burros were observed; and while a few old two-track roads were discernible for short distances, none appeared to be recently made. Furthermore, this area was characterized as having somewhat variable but adequate tortoise habitat, with abundant forage and good soil for burrowing (EnviroPlus Consulting 1995).

The Mormon Mesa CHU is highly fragmented with an extensive network of primarily unimproved and two-track roads. The Desert Tortoise Recovery Plan (companion document for proposed DWMAs, Service 1994), describes this area as having the highest density of roads and trails (1.3 linear miles per square mile) of any desert tortoise *crucial* habitat in southern Nevada based on a 1984 status report [crucial habitat was defined by BLM in the California Desert Plan (1980) as "...Portions of the habitats of sensitive species that if destroyed or adversely modified could result in their being listed as threatened or endangered pursuant to section 4 of the Act or in some category implying endangerment by a State agency or legislature."]. US 93 runs along the western edge and bisects the southwestern tip of the unit, providing a substantial barrier between the unit and protected tortoise habitat in the Desert NWR to the west. State Route (SR) 168 also runs through the western part of the CHU, and I-15 traverses the southeastern edge of the unit. Other well-established roads include the Kane Springs Road and the Carp-Elgin Road which bisects the unit. Powerlines, pipelines, and access roads dissect much of the area.

The 2005 wildfire season in southern Nevada was severe due in large part to the high bio-mass of flammable non-native annual grasses after above-average moisture conditions the previous winter. Approximately eight acres in the northeast part of the project area burned in 2005 in the Meadow Valley Fire, which burned approximately 148,000 acres overall, including a small amount of the Mormon Mesa CHU. In total, over 56 fires of various sizes in southern Nevada, southwestern Utah, and northern Arizona burned roughly 964,806 acres in the Northeastern Mojave Recovery Unit in 2005 including 15,559 acres (4 percent) within the Mormon Mesa CHU. The wildfire hazard in the Mormon Mesa CHU remains significant although fire activity in 2006 and 2007 was lower due to dryer conditions over the winter and spring. Monitoring of the 2005 fires in critical habitat being conducted by the U.S. Geological Survey (USGS) shows that proportionally less tortoise activity occurred in burned areas (treatment plots and control plots) compared to unburned reference plots.

The Mormon Mesa CHU is primarily in Federal ownership, administered by BLM. In addition to CSI's private lands, there are several small privately-held parcels along the Meadow Valley Wash that are within or adjacent to the CHU. Other privately-held lands or Federal land slated for disposal adjacent or near the Mormon Mesa CHU have the potential for future development. Land near the extreme southwestern tip of the Mormon Mesa CHU and northeast of Las Vegas is also in private ownership. Future development of these private lands, as well as possible future disposals of Federal land to allow for expansion of existing cities will create additional challenges for the Service and Federal lands managers in terms of management of the Mormon Mesa DWMA/ACEC, and conservation and recovery of desert tortoises in the Mormon Mesa CHU.

c. ***Moapa Dace - Status within the Action Area***

The action area encompasses the entire range of the Moapa dace. Population numbers were discussed in detail in the section entitled "Status of the Species Rangewide, C. Moapa Dace;" thus, no further details are provided here. The relationship of the dace's habitat to groundwater is discussed in more detail below.

2. *Factors Affecting the Listed Species/Critical Habitat in the Action Area*

The action area is located primarily within the Kane Springs Valley, Coyote Spring Valley and Muddy River Springs Area hydrographic basins. These basins are part of the White River Groundwater Flow System, a regional groundwater flow system located in southern Nevada (Eakin 1966, Harrill *et al.* 1988, Prudic *et al.* 1993). The flow system consists of numerous local basin fill aquifers underlain by a large regional carbonate aquifer that transmits groundwater from basin to basin, beneath topographic divides. Groundwater inflow or recharge to the regional carbonate aquifer is primarily through precipitation. The terminal discharge of the White River Groundwater Flow System is most likely the Warm Springs in the Upper Moapa Valley, an area consisting of about twenty regional springs, with numerous seeps and wetlands. Since the Moapa dace is dependent upon these springs for survival it is important to discuss the hydrology of this area in more detail.

The source water supporting spring discharge in the Warm Springs Area is from the regional carbonate groundwater (62 percent) and from local recharge based on precipitation in the surrounding mountain ranges (BLM 2008). The production wells in the Kane Springs Valley that would be pumped under the proposed action are located about 20 miles northwest of the Warm Springs Area. The high permeability and transmissivity of the carbonate aquifer underlying the Kane Springs Valley and down-gradient Coyote Spring Valley could connect the proposed action to springs in the Warm Springs Area. Long-term effects from groundwater extraction could be propagated over great distances. Barriers to flow, such as faults or rock units with low permeability, also affect the extent of drawdown. There may be a break in the regional hydraulic gradient at the location of the Kane Springs Wash fault zone; however until additional long-term pumping data are obtained, the true relationship cannot be fully evaluated (BLM 2008).

a. *Existing Groundwater Rights and State Engineer Rulings in the Action Area:*

Groundwater wells within the Kane Springs Valley and Coyote Spring Valley Hydrographic Basins are associated with municipal, mining, industrial, commercial and irrigation use. Permitted diversion rates for existing wells vary from 145 to 7,242 afy. Within the Kane Springs Valley Hydrographic Basin, permitted water rights are limited to the LCWD/VWC applications recently approved by the State Engineer under Ruling 5712. The LCWD has an additional four groundwater applications pending before the Nevada State Engineer. Currently, in the Kane Springs Valley Hydrographic Basin permitted groundwater rights are 1,000 afy (BLM 2008).

In the Coyote Spring Valley Hydrographic Basin, groundwater rights filed with the Nevada State Engineer include 15 industrial use permits owned by SNWA, 4 municipal use permits owned by CSI, 1 industrial use permit owned by Nevada Power Company, and 4 permits owned by Bedrock Limited, LLC associated with sand and gravel mining operations. Bedrock Limited, LLC also has one vested application for irrigation use. Currently, in the Coyote Spring Valley Hydrographic Basin permitted groundwater rights are 16,304 afy (BLM 2008). There are 34 pending applications by Las Vegas Valley Water District (LVWD); CSI; Dry Lake Water, LLC;

and Bedrock Limited, LLC in the Coyote Spring Valley Hydrographic Basin. A list of surface water and groundwater rights in the Kane Springs Valley and Coyote Spring Valley hydrographic basins is provided in Appendix D of the Kane Springs Valley Groundwater Development EIS (BLM 2008).

There are three Nevada State Engineer rulings that affect the withdrawal of groundwater in the action area. In these rulings the Nevada State Engineer has required "staged development," an incremental approach for phasing in development of the carbonate aquifer with adequate monitoring in cooperation with other parties in order to assist in assessing effects. This approach was adopted by the Nevada State Engineer "...in order to predict, through the use of a calibrated model, the effects of continued or increased development with a higher degree of confidence." Ruling 5712, granting 1,000 afy of groundwater from the Kane Springs Valley to LCWD and VWC was summarized in the section entitled "Description of the Proposed Action." The other two rulings are summarized below.

In Order 1169 issued in 2002, the Nevada State Engineer held in abeyance applications for new groundwater rights in the Coyote Spring Valley, Black Mountains Area, Garnet Valley, Hidden Valley, Upper Moapa Valley, and Lower Moapa Valley groundwater basins until a pump test is completed. All major water right holders in these basins (SNWA, LVVWD, Moapa Valley Water District [MVWD], CSI, and Nevada Power Company) were required to conduct a regional groundwater study, including the pumping of at least 50 percent of the permitted water rights within the Coyote Spring Valley hydrographic basin for a period of at least two consecutive years. Order 1169 is designed to evaluate how groundwater pumping activities in Coyote Spring Valley will impact water rights and the environment within the Warm Springs Area, including the Muddy River ecosystem. Data obtained from the study will be used to evaluate groundwater development activities within the regional carbonate groundwater system.

To date, there has been limited pumping of the permitted groundwater rights in Coyote Spring Valley. In 2005, CSI drilled and pump tested two wells in Coyote Spring Valley under Nevada Division of Water Resources permit numbers 70429 and 70430. Currently, CSI is monitoring and pumping water as needed for their development activities in Clark County.

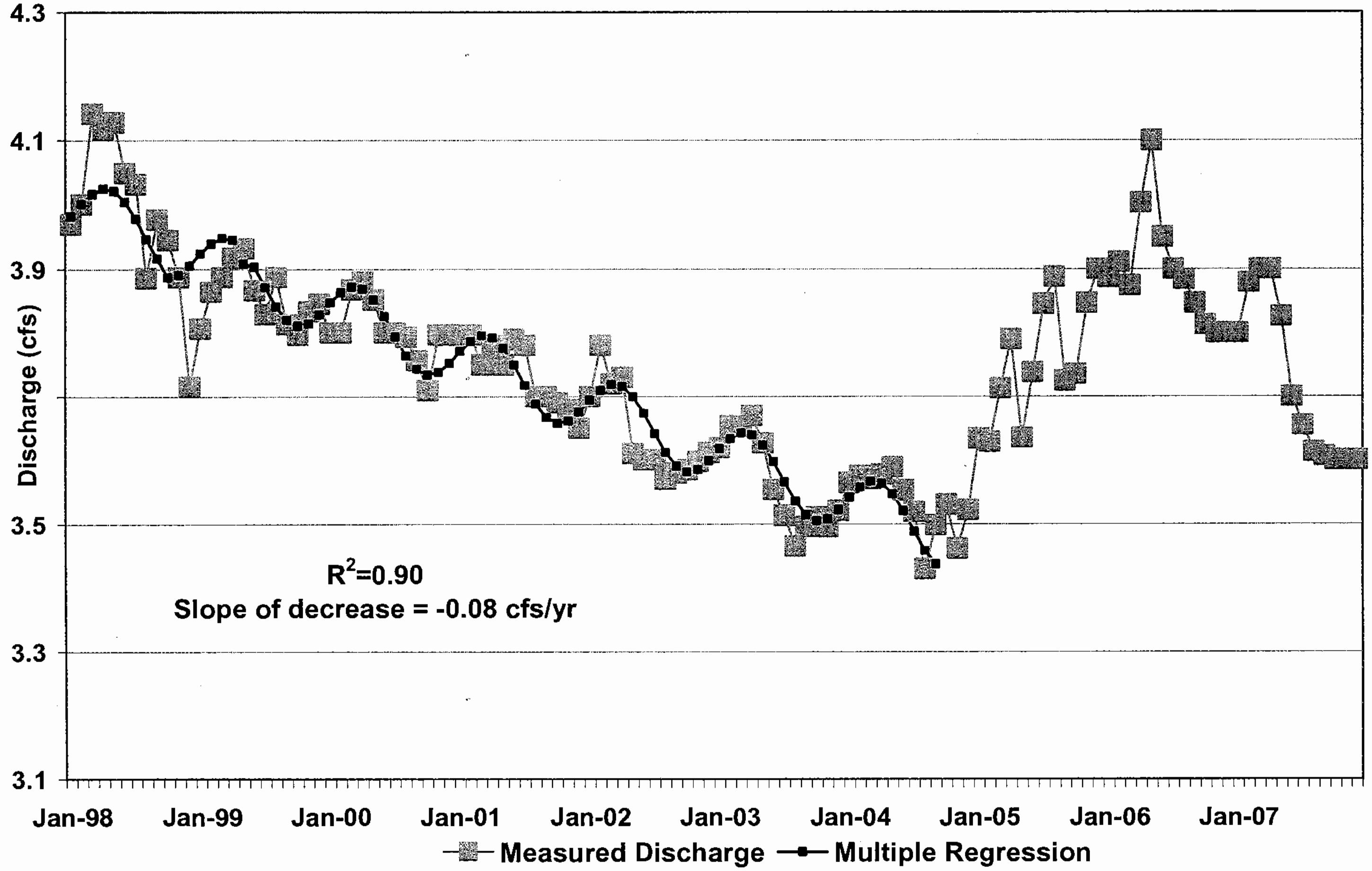
In Ruling 4243 in the Muddy River Springs Area Hydrographic Basin, the Nevada State Engineer granted permits to MVWD for 5,800 afy from Arrow Canyon Well, but with pumping phased in over a 10-year period while monitoring surface water flows and groundwater levels in order to assess potential effects to wells and springs. Annual volume pumped is limited to annual demand, up to the maximum permitted. Annual pumping has consistently been less than the amount allowed in the ruling.

As of 2002, the Nevada State Engineer had granted a total of approximately 14,800 afy of groundwater permits for the alluvial and carbonate aquifer in the Muddy River Springs Area Hydrographic Basin (Service 2006c). Included in these are MVWD permits for the Arrow Canyon Well totaling 7,240 afy (1,440 afy prior to Ruling 4243 plus 5,800 afy from Ruling 4243) from the carbonate aquifer. To date, the actual pumping from the Arrow Canyon Well has been far less than the permitted volume. Approximately 2,400 afy has been pumped on average since 1998.

Concurrent with groundwater pumping between 1998 and 2004, groundwater levels and spring discharge in the Warm Springs Area consistently declined (Service 2006c). Over the same period, the total spring discharge from the Pedersen Unit, as measured at Warm Springs West, decreased from 4.00 cfs to 3.55 cfs (Service 2006c) (Figure 2). The discussion in Mayer (2004) shows that the observed decreases in spring discharge are consistent with expected decreases based on the two-foot decline in groundwater levels observed in the carbonate monitoring wells in the Warm Springs Area. The extremely wet winter of 2005 appears to have recharged the springs with monthly discharge peaking at 4.1 cfs in May of 2006, and decreasing since that time (Mayer 2008). This is expected to be a transient response but the timing and level of a return to equilibrium conditions is not known for certain. Discharge has currently declined to 3.6 cfs (USGS 2008).

The exact timing of the groundwater level decline is important because if the actual decline precedes in time any action or event suspected of causing the decline (such as increased pumping or drought), then this is strong evidence that there are other factors causing the decline. The Service (2006c) analyzed the timing of the decline as it was concerned about the rate and magnitude of the 1998 to 2004 decrease. The start of the decline coincides with MVWD's increased pumping from the carbonate aquifer. In order to address the possibility that drought caused the groundwater level declines, the Service (2006c) compiled precipitation records from a number of stations in the southeastern Nevada area. Their analysis showed that the decline from 1998 to 2004 was not likely to be drought-related. These declines observed between 1998 and 2004 have occurred not only locally in the Warm Springs Area, but have also occurred in monitoring wells 12 miles upgradient in Coyote Spring Valley and 15 miles south in monitoring

Figure 3: Warm Springs West, Moapa Valley NWR - USGS Average Monthly Discharge, Apr 1998 to Dec 2007



wells in the California Wash Basin, based on USGS monitoring well data and monitoring well data shared with the Service in July 2004 (Service 2006c).

On July 14, 2005, a Memorandum of Agreement (MOA) was signed by the SNWA, MVWD, CSI, Moapa Band of Paiutes (Tribe), and the Service, regarding groundwater withdrawal of 16,100 afy from the regional carbonate aquifer in Coyote Spring Valley and California Wash Basins, and establishment of conservation measures for the Moapa dace. The MOA outlined specific conservation actions that each party would complete in order to minimize potential impacts to the Moapa dace should water levels decline in the Muddy River system as a result of the cumulative withdrawal of 16,100 afy of groundwater from two basins within the regional carbonate aquifer system.

To minimize effects to the Moapa dace, conservation actions were identified in the MOA. In order to be considered a benefit to the species, the proposed conservation measures will be initiated or fully implemented prior to the proposed groundwater withdrawal of 16,100 afy. Since development of these water rights requires the construction of facilities, as identified above, there would be a two to five year timeframe in which to implement many of these actions prior to the pumping of the full amount of water. CSI would utilize a small portion of their water right in Coyote Spring Valley prior to full implementation of all of the conservation measures. The action items identified in the MOA include development of a Recovery Implementation Program, restoration, ecological studies, construction of fish barriers, eradication of non-native fish, and dedication of water rights. Minimum in-stream flow levels were established in the MOA that trigger various conservation actions should those predetermined levels be reached. The flow levels will be measured at the Warm Springs West Flume located on the Moapa Valley NWR.

b. Section 7 Consultations Completed for Activities and Projects in the Action Area

1. **File Nos. 1-5-99-F-450 and 84320-2008-F-0078:** On March 3, 2000, the Service issued a programmatic biological opinion (File No. 1-5-99-F-450) to BLM's Ely District Office for implementation of actions in the Caliente Management Framework Plan Amendment (CMFPA). The planning area consisted of public lands in White Pine, Lincoln, and a portion of Nye counties in east-central Nevada. Cumulatively, 25,521 acres of desert tortoise habitat were projected to be affected by the proposed activities within the planning area over a 10-year period.

   On September 9, 2008, the Service issued a programmatic biological opinion (File No. 84320-2008-F-0078) to BLM for the Ely District Resource Management Plan (Ely RMP). This programmatic biological opinion superseded the March 3, 2000, programmatic biological opinion for the CMFPA. Programs in the 2008 programmatic biological opinion included: vegetation management; weed management; wild horse management; lands, realty, and renewable energy projects; travel and off-highway vehicle management;

recreation; livestock grazing management; geological and mineral extraction; and fire management.

Implementation of multiple-use activities (excluding vegetation and weed management) were projected to result in the disturbance of 22,624 acres of desert tortoise critical habitat and 37,311 acres of desert tortoise habitat. During the 10-year term of the programmatic biological opinion, the Service authorized the take of no more than 47 desert tortoises and estimated that 972 tortoises would be taken by non-lethal means (i.e. harassment).

2. **File Nos. 1-5-94-F-334, 335, 336, and 035:** On May 15, 1995, the Service issued a non-jeopardy biological opinion to BLM for the issuance of a right-of-way to install four proposed fiber-optic lines in Clark and Lincoln counties, Nevada. Four applicants comprising the Fiber Toll Joint Venture Project requested a 7.6-m-wide (25-foot-wide) right-of-way for construction of four buried fiber-optic lines. Segments of these lines would parallel SR 168 for approximately 23 miles, and for 43 miles along US 93 (File Nos. 1-5-94-F-334 and 336). Approximately 98 and 65 acres of long- and short-term habitat disturbance, respectively, was attributed to the two segments adjacent to US 93 and SR 168 described above, a majority of which runs through the action area for the CSI project. This included approximately 53 acres of long-term disturbance and 35 acres of short-term disturbance to designated critical habitat (Mormon Mesa CHU) for the desert tortoise. The Service anticipated that up to 34 tortoises would be incidentally taken, 8 through mortality and 26 through injury or harassment.

3. **File No. 1-5-98-F-053, as amended:** On June 18, 1998, the Service issued a programmatic biological opinion to BLM for implementation of the Las Vegas Resource Management Plan (RMP). The project area for this consultation covers all lands managed by BLM's Las Vegas Field Office, including desert tortoise critical habitat, desert tortoise ACECs, and BLM-withdrawn land. The Las Vegas Field Office designated approximately 648 square miles of tortoise habitat as desert tortoise ACEC in the Northeastern Mojave Recovery Unit, and approximately 514 square miles of tortoise habitat as desert tortoise ACEC in the East Mojave Recovery Unit, through the final RMP. As identified in the RMP, BLM manages 743,209 acres of desert tortoise habitat within four tortoise ACECs for desert tortoise recovery. To accomplish desert tortoise recovery in the Northeastern and Eastern Mojave Recovery Units, the Las Vegas Field Office implements appropriate management actions in desert tortoise ACECs.

4. **File No. 1-5-98-FW-177:** On November 2, 1998, the Service issued a non-jeopardy biological opinion to the Nevada Fish and Wildlife Office for the implementation of eradication of non-native fish activities and installation of fish barriers in the Apcar Stream in the Warm Springs Area of the Muddy River. The Service concluded that the project was not likely to jeopardize the continued existence of the Moapa dace.

Incidental take was authorized and Reasonable and Prudent Measures were identified to minimize take to the species.

5. **File No. 1-5-99-F-411:** On December 8, 1999, the Service issued a non-jeopardy biological opinion to BLM for issuance of a right-of-way permit for the Nevada segment of the Las Vegas to Salt Lake City Long-haul Fiber-Optic Project. This consultation evaluated impacts to the desert tortoise and designated critical habitat from the construction, operation, and maintenance of a buried fiber-optic cable and related structures over an 180-mile linear stretch from the Utah-Nevada border to its terminus north of Nellis Air Force Base in Las Vegas. The section of the fiber-optic cable that runs through the Mormon Mesa CHU and CSI lands was located in NDOT's right-of-way east of US 93. The final area of disturbance was calculated at approximately 270 acres, including 158 acres of permanent impacts. The Service estimated that 4 desert tortoises may be incidentally injured or killed and 200 tortoises could potentially be affected by project activities.

6. **File No. 1-5-01-F-463:** On December 26, 2001, the Service issued a non-jeopardy biological opinion to the Bureau of Indian Affairs for approval of a lease for lands on the Reservation for construction and operation of the Moapa Paiute Energy Center. The proposed project would disturb up to 7 percent of the total available spawning habitat for the Moapa dace. As of the date of this biological opinion, the proposed project has not moved forward and the Service is not aware of any plans in the near future to construct the project.

7. **File No. 1-5-02-FW-463:** On March 13, 2002, the Service issued a non-jeopardy biological opinion to the Desert NWR Complex, Las Vegas, Nevada for the implementation of riparian and aquatic habitat restoration activities in the Pedersen Unit of the Moapa Valley NWR. The Service concluded that the incidental take of less than 10 percent of the 180-200 individuals (18-20 individuals) that may be present in the project area, would not likely jeopardize the continued existence of the Moapa dace. Reasonable and Prudent Measures were identified and implemented to minimize take of the species.

8. **File No. 84320-2008-F-0066 and 1-5-94-F-28R:** On December 20, 2007, the Service issued a biological opinion to BLM-Las Vegas for their proposal to amend an existing right-of-way for construction, operation, and maintenance of a single-circuit, overhead 500 kV transmission line (Southwest Intertie Project). The southern portion of the project begins at the Harry Allen Substation in Clark County, Nevada, crossing through the planning area, and ending approximately 34 miles north of Ely in White Pine County, Nevada. The project would disturb 231 acres of non-critical and 365 acres of critical desert tortoise habitat.

9. **File No. 1-5-05-FW-536:** On January 30, 2006, the Service issued a non-jeopardy intra-Service programmatic biological opinion for the Proposed Muddy River MOA, regarding the groundwater withdrawal by multiple parties of 16,100 afy from the regional carbonate aquifer in the Coyote Spring Valley and California Wash Basins. Given that there will be groundwater withdrawn from the same regional carbonate aquifer concurrently by different users and at different locations, it was difficult to assign loss to a specific action. The most accurate way to establish incidental take is at the landscape-level, which was analyzed in the Programmatic Biological Opinion. In that parent document, the cumulative withdrawal of 16,100 afy from all parties associated with the MOA predicted a loss of approximately 22 percent riffle and 16 percent pool habitat (as measured at the Warm Springs West gage downstream from the Pedersen Unit) when the flows reach 2.78 cfs. This amount included habitat losses potentially occurring under both the CSI development and SNWA pipeline. Three tiered biological opinions have been issued under this programmatic opinion:

a. **File No. 1-5-05-FW-536 Tier 1:** On March 2, 2006, the Service issued a non-jeopardy tiered biological opinion to the Corps for the issuance of a Section 404 permit under the Clean Water Act of 1972, as amended, for the CSI residential development project. The Service concluded the proposed residential development is an interdependent activity with the Corps' action and will result in the permanent loss of 6,881 acres of desert tortoise habitat and take of no more than 645 desert tortoises. The proposed action falls within the scope and coverage of the 10(a)(1)(B) permit issued to Clark County for its multiple species habitat conservation plan (MSHCP), and exemption for the anticipated take of the desert tortoise is provided via the incidental take statement for the MSHCP. The Service estimated that the proposed action will result in the incidental take of Moapa dace associated with the loss of 6 percent of riffle habitat and 5 percent of pool habitat, in the Pedersen Unit. Incidental take was authorized, and reasonable and prudent measures were identified to minimize take of the species.

b. **File No. 1-5-05-FW-536 Tier 2:** On May 9, 2007, the Service issued a non-jeopardy tiered biological opinion to BLM for a right-of-way to the SNWA to construct a water conveyance pipeline. SNWA's appropriated water right of 9,000 afy from Coyote Spring Valley would be pumped in order to participate in the Nevada State Engineer Study (Order 1169), and to provide water to the Moapa Valley area for residential and commercial purposes. The right-of-way would allow construction of approximately 16 miles of 24-inch diameter pipeline to transport water from three existing groundwater pumping wells in the southern end of the Coyote Spring Valley to an existing storage tank and pipeline. The Service estimated that 12 percent of riffle habitat and 9 percent of pool habitat will be lost due to the withdrawal of 9,000 afy associated with the SNWA action; however there were other factors which complicated the establishment of incidental take at this level for the proposed action.

c. **File No. 1-5-05-FW-536 Tier 3:** On August 6, 2007, the Service issued a non-jeopardy tiered biological opinion to the U.S. Department of Housing and Urban Development for construction of a water pipeline from an existing well on the Moapa River Indian Reservation to the Moapa Valley of Fire Travel Plaza. The use of 7 of the 16,100 afy for the proposed Travel Plaza will independently have no significant impact on the Muddy River Springs area discharge and subsequently the Moapa dace, but was authorized under the Programmatic Biological Opinion.

On October 22, 2008, the Service issued a non-jeopardy intra-service biological opinion for the Coyote Springs Investment Planned Development Project Multiple-Species Habitat Conservation Plan (MSHCP) (File No. 84320-2008-F-0113). The Service subsequently issued a 40-year incidental take permit to CSI under the authority of section 10(a)(1)(B) of the Act. The Permit covers take of desert tortoise on up to 21,454 acres of private lands in Lincoln County, and management of 13,767 acres of lease lands in Clark and Lincoln counties as the Coyote Springs Investment Conservation Lands. Groundwater withdrawal is not a Covered Activity in the CSI MSHCP. Groundwater withdrawals and their effects to the Moapa dace are subject to evaluation under separate biological opinions for several groundwater development projects, and any appropriate incidental take would be authorized through those biological opinions when issued, or under section 10 (a)(1)(B) if these actions did not involve a Federal agency.

E. Effects of the Proposed Action on the Listed Species/Critical Habitat

Effects of the action refer to the direct and indirect effects of the proposed action on the listed species, together with the effects of other activities that are interrelated and interdependent with that action. Direct effects encompass the immediate, often obvious effect of the proposed action on the listed species or its habitat. Indirect effects are caused by or will result from the proposed action and are later in time, but still reasonably certain to occur. In contrast to direct effects, indirect effects can often be more subtle, and may affect listed species populations and habitat quality over an extended period of time, long after project activities have been completed. Interrelated actions are those that are part of a larger action and depend on the larger action for their justification. Interdependent actions are those that have no independent utility apart from the action under consideration.

1. Effects to the Desert Tortoise (Mojave Population)

Linear construction projects can negatively affect desert tortoise populations. Studies suggest that differences in the extent of the threat are related to the scale of the project, the ability of crews to avoid disturbing burrows, and timing of construction to avoid peak activity periods of tortoises (Boarman 2002). In addition to the discrete disturbance points formed by towers and lines, maintenance roads and repeated operations can (1) introduce continuous sources of disturbance and (2) provide potential sites for invasion of exotic species. Rights-of-way can cause habitat destruction and alteration where vegetation is minimal, possibly increasing mortality, directly or indirectly (Boarman 2002).

Direct impacts to the desert tortoise would be the permanent and temporary loss of habitat utilized by tortoises for foraging, breeding, and cover. Approximately 21 acres will be permanently lost by the construction of well houses and well power substations, water storage tanks, access roads, ancillary pipeline facilities, and power poles. Approximately 188 acres will be temporarily lost by the construction of the pipelines, power lines, fiber optic line, temporary access roads, and temporary workspaces such as pipe and power line laydown areas, power line pulling sites, staging areas, and construction easements. Many of these activities will involve blading and excavation of the area. These areas will be rehabilitated as described in the Revegetation Plan in the Plan of Development; however, it will likely take a long time (potentially more than 10 years) before these areas can provide foraging and cover sites for the desert tortoise.

Other areas that have heavy machinery moving over them will have crushed vegetation and compacted soil. LCWD and BLM propose to salvage topsoil during excavation and to reuse the topsoil later as cover on disturbed areas to facilitate re-growth of vegetation. LCWD and BLM will also flag the work areas so that unauthorized habitat removal does not occur.

Any tortoise within the construction area during work activities would be highly vulnerable. Desert tortoises may be killed or injured by project vehicles and equipment in the project area. Construction equipment and vehicles could crush tortoises or collapse burrows both occupied and unoccupied if not located during clearance surveys. Project vehicles and equipment that stray away from designated access roads and areas may crush desert tortoises aboveground or in their burrows. Tortoises may take refuge underneath project vehicles and equipment and be killed or injured when the equipment or vehicle is moved. Blasting during construction could collapse burrows and injure tortoises. Tortoises that wander into the project area could also fall into holes or trenches from which they are unable to escape. The following measures proposed by LCWD and BLM should reduce these potential effects to desert tortoises: 1) conduct tortoise clearance surveys within the project area; 2) enforce a 25 mph speed limit on project access roads; 3) cease project activities that may endanger a tortoise until it is moved out of harm's way by an authorized desert tortoise biologist; 4) present a worker education program; 5) cover construction holes left open overnight and check trenches twice daily to check for entrapment of wildlife; and 6) restrict vehicles and equipment to the work area boundaries and designated access roads.

Tortoises moved during clearance surveys and tortoises that are physically moved out of harm's way to prevent mortality or injury could be inadvertently harmed if not handled properly. Urine and large amounts of urates are frequently voided during handling and may represent a severe water loss, particularly to juveniles (Luckenbach 1982). Overheating can occur if tortoises are not placed in the shade when ambient temperatures equal or exceed temperature maximums for the species (Desert Tortoise Council 1994, revised 1999). Tortoise eggs moved during clearance surveys could also be harmed if not handled properly. The following measures proposed by LCWD and BLM should reduce these potential effects to desert tortoises: 1) implementing a worker education program; 2) utilizing Service-approved protocols for handling desert tortoises and tortoise eggs; and 3) ensuring that only authorized individuals handle tortoises.

The resulting indirect impacts to the desert tortoise may include the risk of death, injury, or lower reproductive potential through increased predation and degradation and fragmentation of the habitat surrounding the project area. There is a potential for an increase in the number of predatory and scavenger species due to the presence of humans and improper disposal of trash. Workers associated with the proposed project may provide food in the form of trash and litter; or water, which attracts important tortoise predators such as the common raven, kit fox, and coyote (BLM 1990, Boarman and Berry 1995). Natural predation in undisturbed, healthy ecosystems is generally not an issue of concern. However, predation rates may be altered when natural habitats are disturbed or modified (BLM 1990). Ravens likely would be attracted to human activities and buildings for perch sites and food sources, increasing the potential for predation on juvenile desert tortoise in adjacent habitats. LCWD and BLM will implement a litter-control program and a worker education program to avoid or minimize these potential effects.

The project may degrade habitat in the surrounding landscape by introducing non-native weeds or plants into the project area, which later spread in to the surrounding desert, increasing fuel loads for wildfires and competing with native forbs and shrubs. Land clearing activities in the project area may lead to increased soil erosion especially on steeper slopes. The following measures proposed by LCWD and BLM should help reduce these potential effects to desert tortoise habitat: 1) implementation of a Stormwater and Pollution Prevention Plan; 2) implementation of a Revegetation Plan; and 3) implementation of a Noxious Weed Management Plan.

Following construction, the public may use project access roads which may result in adverse effects to tortoise populations. Humans use the desert for off-road exploration, casual shooting and target practice, personal or commercial collection of animals and plants, searches and digging for minerals and gems, geocaching (GPS guided stash hunts), and even the production of illegal drugs. Desert tortoise shells found in the Mojave Desert with bullet holes were examined forensically with the finding that the tortoises were alive when they were shot (Berry 1986), suggesting that illegal shooting of tortoises could occur. Project personnel could illegally collect tortoises for pets or bring dogs to the project area. Measures proposed by LCWD and BLM to 1) clear project areas of tortoises, 2) prohibit pets from the project area, 3) impose a speed limit, and (4) close unnecessary roads following construction and control public access, should minimize the potential effects to the tortoise described above.

2. Effects to Critical Habitat for the Desert Tortoise (Mojave Population)

Direct impacts to desert tortoise critical habitat would be the permanent and temporary loss of areas that contain the PCEs of desert tortoise critical habitat. Approximately 18 acres will be permanently lost by the construction of well houses and well power substations, water storage tanks, access roads, ancillary pipeline facilities, and power poles. Approximately 155 acres will be temporarily lost by the construction of the pipelines, power lines, fiber optic line, temporary access roads, and temporary workspaces such as pipe and power line laydown areas, power line pulling sites, staging areas, and construction easements. Many of these activities that temporarily impact areas will involve blading and excavation of the area which would remove all of the PCEs of critical habitat. These areas will be recontoured and rehabilitated as described in the Revegetation Plan; however, it will likely take a long time before these areas can provide a sufficient quantity and quality of forage species (PCE 2) and sufficient vegetation to provide shelter from temperature extremes and predators (PCE 5). Other areas that have heavy machinery moving over them, will impact PCE 3 (suitable substrates for burrowing, nesting, and overwintering), PCE 4 (burrow, caliche caves, and other shelter sites), and PCE 5. These areas will also likely take a long time to recover and may also need some revegetation or soil de-compaction treatments. LCWD proposes to salvage topsoil during excavation and to reuse the topsoil later as cover on disturbed areas to facilitate re-growth of vegetation. As per the Revegetation Plan only native species will be used and cacti and yucca will be salvaged when possible.

Indirect impacts to the desert tortoise critical habitat may include fragmentation of the habitat surrounding the project area which will degrade PCE 1 (space to support viable populations and to provide for movement, dispersal, and gene flow). Since the project is linear, it has a greater potential to fragment habitat, although it does follow the existing Kane Springs Road. The project is in the LCCRDA corridor which is 0.5 miles wide. This project is the first to use this designated utility corridor so it may have greater impacts than future projects, although the proposed development on CSI lands in Lincoln County will be a greater barrier to tortoise movement.

Indirect impacts also include the introduction or spread of non-native plants in the project area and into the surrounding landscape which may impact PCE 2 and PCE 5. If red brome increases in the project area or surrounding landscape, this could increase the fuel load which increases the chance of large scale fires. Red brome can often out-compete native species because red brome extracts soil water and nutrients more rapidly than similar native annuals (DeFalco *et al.* 2003) and also reduces the growth of mature native perennials (DeFalco *et al.* 2007b). The project could also introduce new non-native plants into the area which could impact PCE 2 and PCE 5 in the future. LCWD and BLM should help reduce these potential effects to critical habitat by the implementation of a Noxious Weed Management Plan and the implementation of a Fire Management Plan. The Noxious Weed Management Plan includes the following measures: survey of area prior to land clearing, cleaning of vehicles and equipments, treating weed infestations, post-construction monitoring and employee education.

Project activities could also increase soil erosion. Increased soil erosion could negatively impact PCE 2, PCE 4, and PCE 5. LCWD and BLM should help reduce these potential effects to critical habitat by the implementation of a Stormwater and Pollution Prevention Plan.

3. Effects to the Moapa Dace

The Moapa dace will not be directly affected by the physical construction of the proposed groundwater wells, pipelines, and power facilities; however, groundwater pumping will likely indirectly affect the headwater spring discharges of the Muddy River, and therefore, the Moapa dace. The magnitude and timing of impacts from pumping in Kane Springs Valley are uncertain. Differences in boundary conditions relating to the areal extent of the aquifer, location of the pumping, transmissivity, and permeability, all influence the magnitude and timing of pumping impacts. Also, if the proposed pumping lowers carbonate water levels in the Warm Springs Area further, not all springs will be affected equally. The decrease in spring discharge will be proportional to the decrease in head elevation at each spring. Higher elevation springs have a lower head difference initially and are therefore more susceptible to decreases in groundwater levels. Therefore, the higher elevation springs will be affected proportionately more for a given decline in groundwater levels. The highest elevation springs occur on the Pedersen Unit of the Moapa Valley NWR, an area which also comprises some of the most important spawning habitat for Moapa dace in the system.

As discussed in the programmatic biological opinion for the Muddy River MOA (Service 2006c), existing data suggests that current groundwater pumping of the Arrow Canyon Well is causing a decline in the regional carbonate aquifer levels locally and in the Coyote Spring Valley, and a decrease in spring discharge in the Warm Springs Area (Mayer 2004). The average pumping rate at the Arrow Canyon Well since 1998 has been 3.3 cfs or 2,400 afy. Pumping rates will increase with commencement of the pump test, and may further increase pending the outcome of the pump test and associated monitoring. The proposed action includes pumping of an additional 1,000 afy from the same regional carbonate aquifer. The pumping will be located along the same flow path that supplies the Warm Springs Area and is within the low-gradient, high-transmissivity zone that connects Kane Springs Valley, Coyote Spring Valley and the Warm Springs Area.

Under the terms of the stipulated agreement, if the Average Flow Level reaches 3.15 cfs or less but greater than 3.0 cfs at the Warm Springs West gage, LWCD and VWC agree to reduce pumping from all wells in Kane Springs Valley by 50 percent. This would mean pumping at these flow levels would be reduced to 500 afy. If the Average Flow Level reaches 3.0 cfs or less, LWCD and VWC agree to cease pumping from all wells in Kane Springs Valley until the Average Flow Level exceeds 3.0 cfs. The exact magnitude and timing of the impacts from pumping groundwater from the carbonate aquifer in Kane Springs Valley are unknown at this time, as are the effects of reduced or cessation of groundwater pumping or whether there will be some equilibration of the aquifer to the proposed pumping.

In the programmatic biological opinion for the MOA, the Service (2006c) used the potential effects on spring discharge at the Warm Springs West gage to predict potential effects to Moapa dace habitat. The results indicated that both spring discharge and dace habitat are reduced with declines in groundwater levels. Flows and habitat loss were projected as a function of incremental declines in groundwater levels (Service 2006c). If flows were reduced to 3.02 cfs at the Warm Springs West gage this would be a 25 percent reduction of flows from the 1998 conditions which would reduce riffle habitat by 17 percent and pool habitat by 13 percent in the Petersen Unit. Because pumping for the Kane Springs project will occur concurrently with the potential pumping of 16,100 afy in the carbonate aquifer of White River Flow System, only a very small amount of this possible reduction would be attributable to pumping in Kane Springs Valley. Given the amount of 1,000 afy authorized by the State Engineer, effects from this project will be difficult to tease apart from effects of pumping 16,100 afy as described in the programmatic biological opinion for the MOA. However, monitoring of the Kane Springs wells concurrent with other monitoring under the MOA will lend greater understanding to the overall effects.

The primary effect to the Moapa dace of diminished flows within the spring channels will be a decrease in the hydraulic conditions that create the diversity of habitat. A decrease in velocity and depth within riffles would result in a decrease of invertebrate and phytoplankton (food) production. Drift stations in pools are maintained by the scouring effect of turbulent flow. Scour will decrease in pools as water velocity and depth at the upstream end of the pool decreases. Perhaps the most prominent impact that would occur, as a result of decreased discharge and subsequent depth, is the reduction of overall volume of water that will be available to the species within the channel. Scoppettone *et al.* (1992) demonstrated that Moapa dace size is scaled to water volume. Thus, larger water volumes provide the habitat necessary for increased food production and subsequently larger fish, therefore greater fecundity. Hence, more numerous, larger eggs provide a better opportunity for the long-term survival of the species.

Additional factors that would influence channel and hydraulic characteristics within the stream channels following a decline in spring discharge include, but are not limited to, changes in sediment transportation rates, and the alteration of riffle and pool maintenance that is accomplished at the present rate of discharge in each spring channel. Additionally, vegetative encroachment and subsequent channel obstruction may also occur as the wetted cross sectional area of the channel decreases, and new surfaces become exposed for vegetation growth. Decreases in these parameters will likely have an adverse impact on the overall diversity and quantity of hydraulic habitat.

The Pedersen Unit of the Moapa Valley NWR is one of the six spring complexes that the Moapa dace depends on for successful reproduction. It includes the highest elevation spring, presumed most susceptible to groundwater level declines. The analysis presented in the programmatic biological opinion for the MOA (Service 2006c) estimated that at 3.02 cfs, there is a 25 percent loss in flow on the Pedersen Unit from 1998 conditions. This loss is estimated to reduce available riffle habitat by 17 percent and pool habitat by 13 percent within the Pedersen Unit. In addition to the loss of habitat, decreased flows would also result in a loss of temperature that would extend downstream, thereby reducing the thermal load in the system and thus the amount of available habitat at the appropriate spawning temperature. The additional 1,000 afy of groundwater pumping under the Kane Springs Groundwater Development Project would potentially increase overall habitat loss and temperature declines, however, trigger levels identified in the Monitoring, Management and Mitigation Plan (starting at 3.2 cfs or less) are a higher threshold than those established under the MOA. Accordingly, adverse effects on Moapa dace habitat should be prevented.

Conservation Measures Identified to Minimize Effects of the Proposed Action

Guaranteed Groundwater Pumping Reductions (Trigger ranges): LCWD and VWC have agreed to reduce groundwater pumping by half in the Kane Springs Valley should stream flows reach 3.15 cfs or less but greater than 3.0 cfs at the Warm Springs West gage. The groundwater pumping will be stopped in the Kane Springs Valley should stream flows reach 3.0 cfs or less at the Warm Springs West gage. This conservation measure will result in a reduction in the rate of decline of water levels and spring discharge. Further reduction in the rate of decline will depend on the effect of remaining groundwater pumping by other parties in the Coyote Spring Valley, California Wash, and the Warm Springs Area.

Restore Moapa Dace Habitat Outside of the Moapa Valley NWR Boundary: LCWD and VWC agreed to provide funds annually for five years to be used for habitat restoration outside of the Moapa Valley NWR boundary to promote recovery of the Moapa dace. This funding will be applied towards various on-going or proposed activities that would improve and secure habitat that is currently not being utilized due to degraded conditions (i.e. illegal diversions or non-native species presence). The funding will provide a mechanism to restore habitat to a level that would provide a higher quality of habitat for the species. These habitat improvements would contribute to the long-term survival of the species by increasing the food production potential, providing additional habitat types that would be available for the various life stages and providing an environment that is devoid of predatory non-native fishes.

F. Cumulative Effects

Cumulative effects are those effects of future non-Federal (State, local government, or private) activities that are reasonably certain to occur in the action area considered in this biological opinion. Future Federal actions that are unrelated to the proposed action are not considered in this section because they require separate consultation pursuant to section 7 of the Act.

1. Desert Tortoise (Mojave Population)

The action area is on both Federal and private lands. The Service determined that future actions in the action area would likely require section 7 consultation or fall under purview of an HCP (section 10 of the Act). Thus, no future non-Federal activities are reasonably certain to occur in the action area; thus, there are no cumulative effects to the desert tortoise as a result of the proposed action. Private lands in the action area include CSI property. These activities are proposed to be covered under the Coyote Springs Investment MSHCP and associated incidental take permit, which are currently under development.

2. Critical Habitat for the Desert Tortoise (Mojave Population)

The Mormon Mesa Critical Habitat unit occurs mostly on Federal lands with CSI private land along US 93 and private property along Meadow Valley Wash. The Service determined that future actions in the action area would likely require section 7 consultation or fall under purview of an HCP (section 10 of the Act). No future non-Federal activities are reasonably certain to occur in the action area; thus, there are no cumulative effects to designated critical habitat as a result of the proposed action. Activities on CSI lands in Clark County are covered under the approved Clark County MSHCP and associated incidental take permit, and the activities in Lincoln County are proposed to be covered under the CSI MSHCP and associated incidental take permit, which are currently under development. The Southeastern Lincoln County Habitat Conservation Plan and associated incidental take permit, which are currently under development, will cover activities on private land along Meadow Valley Wash.

3. Moapa Dace

Future demand for groundwater will continue to threaten spring flows and surface water important for aquatic species such as the Moapa dace. In the Warm Springs Area, MVWD's existing permit would allow more groundwater to be pumped from the Arrow Canyon Well in the future. The maximum permitted pumping rate at the Arrow Canyon Well is 7,200 afy, as compared with the annual average of 2,400 afy pumped currently. Depending on the outcome of the pump study mandated in the State Engineer Order 1169 and subsequent ruling by the State Engineer, additional groundwater could potentially be pumped in Coyote Spring Valley. The maximum volume that could be removed from the Coyote Spring Valley and Muddy River Springs Area basins under existing permits is 31,100 afy. This represents more than a tenfold increase from current withdrawals in the system. In addition to the existing permitted water rights, there are pending applications for a far greater volume of groundwater above and beyond the permitted amount in the Coyote Spring Valley, Muddy River Springs Area, and Kane Springs Valley hydrographic basins.

G. Conclusion

1. Desert Tortoise (Mojave Population)

After reviewing the current status of the desert tortoise, the environmental baseline for the action area, the effects of the proposed project, and the cumulative effects, it is the Service's biological opinion that the project, as proposed and analyzed, is not likely to jeopardize the continued existence of the threatened desert tortoise (Mojave population). This conclusion for the desert tortoise is based on the following:

a. The proposed project will not result in a level of take of desert tortoise that would significantly affect the rangewide number, distribution, or reproduction of the species; tortoises that are taken as a result of the project are anticipated to remain in the wild with no long-term effects except for two desert tortoise estimated to be killed or injured by project activities.

b. The desert tortoise densities in the project area are considered low and measures have been proposed by LCWD and BLM to minimize the effects of the proposed action on the desert tortoise.

2. Critical Habitat for Desert Tortoise (Mojave Population)

The Service has reviewed the current rangewide status of designated critical habitat for the desert tortoise (Mojave population), the environmental baseline, the effects of the project, and the cumulative effects. Based on this review, it is the Service's biological opinion that these actions are not likely to destroy or adversely modify designated critical habitat for the desert tortoise (Mojave population). The project actions will not diminish the capability of the area to serve its role for recovery by continuing to provide the PCEs of critical habitat. The basis for this conclusion is summarized as follows:

a. The amount of critical habitat permanently and temporarily disturbed by the project is 173 acres, approximately 0.05 percent of the Mormon Mesa CHU.

b. Measures have been proposed by LCWD and BLM to minimize the effects of the proposed action on critical habitat for the desert tortoise.

3. Moapa Dace

After reviewing the current status of and environmental baseline for the Moapa dace, the effects of the project, and the cumulative effects, it is the Service's biological opinion that the action, as proposed and analyzed, is not likely to jeopardize the continued existence of the endangered Moapa dace. The project could contribute to groundwater level declines and spring flow reductions; however, implementation of the project's conservation actions will minimize these impacts.

INCIDENTAL TAKE STATEMENT

Section 9 of the Act, as amended, prohibits take (harass, harm, pursue, hunt, shoot, wound, kill, trap, capture or collect, or attempt to engage in any such conduct) of listed species of fish or wildlife without a special exemption. "Harm" is further defined to include significant habitat modification or degradation that results in death or injury to listed species by significantly impairing behavioral patterns such as breeding, feeding, or sheltering (50 CFR § 17.3). "Harass" is defined as actions that create the likelihood of injury to listed species to such an extent as to significantly disrupt normal behavior patterns which include, but are not limited to, breeding, feeding, or sheltering (50 CFR § 17.3). Incidental take is any take of listed animal species that results from, but is not the purpose of, carrying out an otherwise lawful activity conducted by the

Federal agency or applicant. Under the terms of sections 7(b)(4) and 7(o)(2) of the Act, taking that is incidental to and not intended as part of the agency action is not considered a prohibited taking provided that such taking is in compliance with the terms and conditions of this incidental take statement.

The terms and conditions may include: (1) restating measures proposed by BLM; (2) modifying the measures proposed by BLM; or (3) specifying additional measures considered necessary by the Service. Where these terms and conditions vary from or contradict the minimization measures proposed under the Description of the Proposed Action, specifications in these terms and conditions shall apply. The measures described below are nondiscretionary and must be implemented by BLM so that they become binding conditions of any project, contract, grant, or permit issued by BLM or other jurisdictional Federal agencies as appropriate, in order for the exemption in section 7(o)(2) to apply. The Service's evaluation of the effects of the proposed actions includes consideration of the measures developed by BLM, and repeated in the section entitled "Description of the Proposed Action" of this biological opinion, to minimize the adverse effects of the proposed action on the desert tortoise. Any subsequent changes in the minimization measures proposed by BLM may constitute a modification of the proposed action and may warrant reinitiation of formal consultation, as specified at 50 CFR § 402.16. These reasonable and prudent measures are intended to clarify or supplement the protective measures that were proposed by BLM as part of the proposed action.

BLM, or other jurisdictional Federal agencies as appropriate, have a continuing duty to regulate the activity that is covered by this incidental take statement. If BLM, or other jurisdictional Federal agencies as appropriate, fail to adhere to the terms and conditions of the incidental take statement through enforceable terms that are added to permits or grant documents, and/or fails to retain oversight to ensure compliance with these terms and conditions, the protective coverage of section 7(o)(2) may lapse.

A. Amount of Take

Desert Tortoise (Mojave Population)

Based on the analysis of effects provided above, measures proposed by BLM, and anticipated project duration the Service anticipates that the following take could occur as a result of the proposed action:

1. No more than two adults and an unknown number of hatchling and juvenile desert tortoises would be incidentally killed or injured as a result of the proposed project. Should any desert tortoise be killed or injured in association with the proposed action, all activity in the vicinity of the incident shall cease and the project proponent shall contact the Service within 24 hours to assess the circumstances and discuss if additional protective measures are necessary.

2. All desert tortoises located during clearance surveys or located in harm's way in work areas may be harassed by capture and removal from the project area. Based on survey data, timing of the proposed project, and description of the project area, the Service estimates that no more than 33 desert tortoises may be taken (other than killed or injured) by non-lethal means as a result of project activities.

3. An unknown number of desert tortoise nests with eggs may be excavated and relocated. The Service determined that no desert tortoise nests with eggs are anticipated to be destroyed as a result of project activities.

4. An unknown number of desert tortoises may be preyed upon by ravens or other subsidized desert tortoise predators drawn to trash in the project area; however, the Service estimates that the potential increase in ravens will be minimized by litter-control measures proposed by BLM.

Moapa Dace

The Service anticipates that incidental take of Moapa dace through harm (i.e., habitat modification or degradation that results in death or injury) will occur, but the actual death or injury of fish will be difficult to detect for the following reasons: the species has a small body size and finding a dead or impaired specimen is unlikely in a flowing stream environment. On the other hand, significant habitat modification or degradation that could result in take of Moapa dace will be detectable and measurable. Therefore, we are expressing take of Moapa dace in terms of habitat loss resulting from changes in habitat characteristics, such as water temperature or chemistry and water flows. Although the extent of effects to the species as a result of the proposed action is not yet known, future and on-going biological and hydrological studies will assist us in determining how flow reductions and thermal load losses will affect Moapa dace habitat, food availability, reproduction, and fecundity.

Perhaps the most significant impact to Moapa dace habitat that could result from implementation of the proposed action, as a result of decreased discharge and subsequent wetted area, is the reduction of overall volume of water that would be available to the species within the channel. The amount of groundwater pumping permitted under the Kane Springs Groundwater Development Project (1,000 afy) is substantially smaller than the amount of pumping that could potentially co-occur under Order 1169 (16,100 afy). A small but unquantifiable amount of take in the form of habitat loss would occur in the Pedersen Unit if flows reached 3.0 cfs at the Warm Spring West gage. Should flows at the Warm Springs West gage decline below 3.0 cfs, the amount of incidental take for this project would be exceeded for the Moapa dace.

B. Effect of Take

In the accompanying biological opinion, the Service determined that this level of anticipated take is not likely to result in jeopardy to the desert tortoise or Moapa dace. These determinations are based in part on the implementation of conservation measures detailed in the BA for this project.

C. Reasonable and Prudent Measures with Terms and Conditions

The Service believes that the following reasonable and prudent measures (RMPs) are necessary and appropriate to minimize take of desert tortoise or Moapa dace.

RPM 1: *BLM, LCWD, VWC, and other jurisdictional Federal agencies as appropriate, shall ensure implementation of measures to minimize injury or mortality of desert tortoises due to surface-disturbing activities and operation of project vehicles or equipment:*

Terms and Conditions:

1.a. An authorized desert tortoise biologist shall be onsite at all locations where ground-disturbing activities are occurring within desert tortoise habitat. The authorized biologist will be responsible for approving, evaluating, and supervising monitors to assist in implementing the desert tortoise measures of this biological opinion. Potential biologists shall complete the Qualifications Form (Attachment A) and submit it to the Service for review and approval as appropriate. Allow 30 days for Service review and response.

1.b. Prior to initiation of construction, an authorized biologist or approved monitor shall present a desert tortoise awareness program to all personnel who will be onsite, including but not limited to contractors, contractors' employees, supervisors, inspectors, and subcontractors. This program will contain information concerning the biology and distribution of the desert tortoise and other sensitive species, their legal status and occurrence in the project area; the definition of "take" and associated penalties; the terms and conditions of this biological opinion; the means by which employees can help facilitate this process; responsibilities of workers, approved monitors, and biologists; and reporting procedures to be implemented in case of desert tortoise encounters or non-compliance with this biological opinion. The name of every individual trained will be recorded on a sign-in sheet. Each trained individual will be given evidence indicating they have received this training and will keep that evidence with them at all times when they are in the project area.

1.c. Immediately prior to surface-disturbing activities or traveling off of main access roads on the right-of-way, the authorized biologist shall survey for desert tortoises and their burrows using techniques providing 100-percent coverage of the right-of-way and an additional area approximately 90 feet from both sides of the right-of-way. Transects will be no greater than 30 feet apart. All potential desert tortoise burrows will be examined to determine occupancy of each burrow by desert tortoises and handled in accordance with Term and Condition 1.d. – 1.f and 2.a – 2.c. below.

1.d. All potential desert tortoise burrows located within the project area that are at risk for damage shall be excavated by hand by an authorized biologist, tortoises removed, and burrows collapsed or blocked to prevent occupation by desert tortoises.

1.e. Desert tortoises located in the project area, but outside of an area to be disturbed by ground disturbing activities, sheltering in a burrow during a period of reduced activity (*e.g.,* winter), may be temporarily penned. Tortoises shall not be penned in areas of moderate or heavy public use. Penning shall be accomplished by installing a circular fence, approximately 20 feet in diameter to enclose the tortoise/burrow. The pen should be constructed with durable materials (*i.e.,* 16 gauge or heavier) suitable to resist desert environments. Fence material should consist of ½-inch hardware cloth or 1-inch horizontal by 2-inch vertical, galvanized welded wire. Pen material should be 24 inches in width. Steel T-posts or rebar (3 to 4 feet) should be placed every 5 to 6 feet to support the pen material. The pen material should extend 18 to 24 inches aboveground. The bottom of the enclosure will be buried several inches; soil mounded along the base; and other measures should be taken to ensure zero ground clearance. Care shall be taken to minimize visibility of the pen by the public. An authorized biologist, approved monitor, or designated worker shall check the pen daily.

1.f. Desert tortoises and eggs found within construction sites shall be removed by an authorized biologist in accordance with the most current protocols identified by BLM and the Service. Desert tortoises will be moved solely for the purpose of moving them out of harm's way. Desert tortoises shall be relocated up to 1,500 feet into adjacent undisturbed habitat on protected public land in accordance with Service-approved handling protocol (Desert Tortoise Council 1994, revised 1999). The disposition of all tortoises handled shall be documented in accordance with 6.b. below.

1.g. All fuel, transmission or brake fluid leaks, or other hazardous materials shall not be drained onto the ground or into streams or drainage areas. All petroleum products and other potentially hazardous materials shall be removed to a disposal facility authorized to accept such materials. Waste leaks, spills or releases shall be reported immediately to BLM. BLM or the project proponent shall be responsible for spill material removal and disposal to an approved off-site landfill.

Servicing of construction equipment will take place only at a designated area. All fuel or hazardous waste leaks, spills, or releases will be stopped or repaired immediately and cleaned up at the time of occurrence. Service and maintenance vehicles will carry a bucket and pads to absorb leaks or spills.

1.h. Vehicles shall not exceed 25 mph on access roads. Authorized desert tortoise biologists and/or approved monitors will ensure compliance with speed limits during construction.

1.i. Project personnel shall exercise caution when commuting to the project area and obey speed limits to minimize any chance for the inadvertent injury or mortality of species encountered on roads leading to and from the project site. All desert tortoise observations, including mortalities, shall be reported directly to an authorized biologist and the Service.

1.j. Any vehicle or equipment on the right-of-way within desert tortoise habitat shall be checked underneath for tortoises before moving. This includes all construction equipment and the area under vehicles should be checked any time a vehicle is left unattended, as well as in the morning before any construction activity begins. If a desert tortoise is observed, an authorized biologist will be contacted.

1.k. Project activity areas shall be clearly marked or flagged at the outer boundaries before the onset of construction. All activities shall be confined to designated areas. The authorized biologist and approved monitors shall ensure that no habitat is disturbed outside designated areas as a result of the project, including ensuring that all vehicles and equipment remain on the right-of-way or areas devoid of native vegetation.

1.l. To prevent mortality, injury, and harassment of desert tortoises and damage to their burrows and coversites, no pets shall be permitted in any project construction area.

1.m. All desert tortoises observed within the project area or access road shall be reported immediately to the authorized biologist. The authorized biologist shall halt activities as necessary to avoid harm to a desert tortoise. Project activities that may endanger a desert tortoise shall cease until the desert tortoise moves out of harm's way or is moved out of harm's way by an authorized biologist.

1.n. Only water or an alternative substance approved by BLM shall be used as a dust suppressant. Water application shall avoid pooling of water on roadways. Pools of water may act as an attractant to desert tortoises.

1.o. In the event that blasting is required, a 200-foot-radius area around the blasting site shall be surveyed by an authorized biologist for desert tortoises prior to blasting, using 100-percent-coverage survey techniques. All tortoises located above ground or in pallets within this 200-foot radius of the blasting site shall be moved 500 feet from the blasting site. Additionally, tortoises in burrows within 75 feet of the blasting will be placed into an artificial or unoccupied burrow 500 feet from the blasting site. This will prevent tortoises that leave their burrow upon translocation from returning to the blasting site. Tortoises in burrows at a distance of 75 to 200 feet from the blasting site will be left in their burrows. Burrow locations will be flagged and recorded using a GPS unit and burrows would be stuffed with newspapers. Immediately after blasting, newspaper and flagging will be removed. Blasting would only occur in the brief time period after an area has been cleared by an authorized biologist, but before any relocated tortoises could return to the site.

1.p. If possible, overnight parking and storage of equipment and materials shall be located in previously-disturbed areas or areas to be disturbed that have been cleared by an authorized tortoise biologist. If not possible, areas for overnight parking and storage of equipment shall be designated by the authorized biologist.

1.q. Within desert tortoise habitat, any construction pipe, culvert, or similar structure with a diameter greater than 3 inches stored less than 8 inches above ground on the construction site for one or more nights shall be inspected for tortoises before the material is moved, buried, or capped. As an alternative, all such structures may be capped before being stored on the construction site.

1.r. Flagging and wire shall be removed from the project area at the end of project to ensure debris is not consumed by desert tortoises.

1.s. All project activities in desert tortoise habitat shall be conducted from dawn until dusk.

1.t. Any excavated holes left open overnight shall be covered, and/or tortoise-proof fencing (Attachment B) shall be installed to prevent the possibility of tortoises falling into the open holes.

1.u. Open pipeline trenches shall be fenced with temporary tortoise-proof fencing or inspected by an authorized biologist or approved monitor periodically throughout and at the end of the day, and immediately prior to backfilling, and tortoise escape ramps (of at least 3:1 slope) shall be installed at least every quarter mile. Any tortoise that is found in a trench or excavation shall be promptly removed by an authorized biologist in accordance with Service-approved protocol or alternative method approved by the Service if the biologist is not allowed to enter the trench for safety reasons.

1.v. In areas to be encircled by a security fence, such as well yards and well substations, the fence shall be installed at least one foot below the surface of the ground or install permanent desert tortoise fencing around the area, to ensure that tortoises do not get trapped inside. See Attachment B for the Service's recommendations on tortoise exclusion fencing, dated September 2005. Fences should be checked during regular maintenance of the facilities to ensure zero ground clearance.

1.w. Any tortoise injured as a result of the proposed project shall immediately be transported to a qualified veterinarian and reported to the Service's Nevada Fish and Wildlife Office in Las Vegas at (702) 515-5230.

RPM 2: *BLM, LCWD, and other jurisdictional Federal agencies as appropriate, shall ensure implementation of the following measures to ensure that tortoises are not injured as a result of capture and handling:*

Terms and Conditions:

2.a. All appropriate NDOW permits or letters of authorization shall be acquired prior to handling desert tortoises and their parts, and prior to initiation of any activity that may require handling tortoises.

2.b. Tortoises and nests shall be handled and relocated by an authorized tortoise biologist in accordance with the Service-approved protocol (Desert Tortoise Council 1994, revised 1999). If the Service or Desert Tortoise Council releases a revised protocol for handling of desert tortoises before initiation of project activities, the revised protocol shall be implemented for the project area. A pair of new, disposable latex gloves shall be used for each tortoise that must be handled. After use, the gloves will be properly disposed. Burrows containing tortoises or nests shall be excavated by hand, with hand tools, to allow removal of the tortoise or eggs. Desert tortoises moved during the tortoises less active season or those in hibernation, regardless of date, must be placed into an adequate burrow; if one is not available, one shall be constructed in accordance with Desert Tortoise Council (1994, revised 1999) criteria. Desert tortoises that are located aboveground and need to be moved from the project area shall be placed in the shade of a shrub. All desert tortoises removed from burrows shall be placed in an unoccupied burrow of approximately the same size and orientation as the one from which it was removed.

2.c. Special precautions shall be taken to ensure that desert tortoises are not harmed as a result of their capture and movement during extreme temperatures (i.e., air temperatures below 55° F or above 95° F). Under such adverse conditions, tortoises captured will be monitored continually by an authorized biologist or approved monitor until the tortoise exhibits normal behavior. If a desert tortoise shows signs of heat stress, procedures will be implemented as identified in the Service-approved protocol (Desert Tortoise Council 1994, revised 1999). The disposition of all tortoises handled shall be documented in accordance with 6.b. below.

RPM 3: *BLM, LCWD, and other jurisdictional Federal agencies as appropriate, shall ensure implementation of the following measures to minimize predation on desert tortoises by predators drawn to the project area:*

Terms and Conditions:

Trash and food items shall be disposed properly in predator-proof containers with resealing lids. During construction activities, trash containers will be emptied and waste will be removed from the project area daily. Trash removal reduces the attractiveness of the area to opportunistic predators such as desert kit fox, coyotes, and common ravens.

RPM 4: *BLM, LCWD, and other jurisdictional Federal agencies as appropriate, shall ensure implementation of the following measures to minimize loss and long-term degradation and fragmentation of desert tortoise habitat, such as soil compaction, erosion, crushed vegetation, and introduction of weeds or contaminants as a result of construction activities:*

Terms and Conditions:

4.a Off-road travel outside construction zones shall be prohibited.

4.b. The designated utilities shall follow the Noxious Weed Management Plan which includes the following: washing vehicles and equipment prior to mobilizing to the project area, providing onsite personnel with BLM weed identification information, reseeding the project area with a BLM-approved certified weed-free seed mix, and controlling noxious weeds should they be introduced as a result of the proposed action.

4.c. After completion of the project, the designated utilities shall follow the Revegetation Plan to restore all temporarily-disturbed areas to functioning desert tortoise habitat, using native seeds or plants.

4.d. BLM shall ensure payment of remuneration fees by the project proponents, the designated utilities, for compensation of the loss of desert tortoise habitat as a result of the proposed project. BLM shall require a receipt of payment from each designated utility prior to issuing the Notice to Proceed.

The right-of-way applicant is required to submit a Final Plan of Development to the BLM, which must be approved by BLM prior to issuance of the Notice to Proceed. It is likely that the amount of disturbance will change with the final engineering design; therefore, BLM will reevaluate the project disturbance and adjust the total compensation fee accordingly. A copy of the Final Plan of Development and a breakdown of the final compensation fee will be provided to the Service. The applicant will be made aware that, depending on final engineering designs, the final compensation fee may be lower than the estimated value provided in this document.

Currently, the basic compensation rate for disturbance to desert tortoise habitat is $753 per acre. For disturbance to desert tortoise critical habitat a multiplier is used to increase the cost per acre as described in Hastey *et al.* (1991). For each project, this multiplier for critical habitat is based on assignment of ratings to the following five factors:

- Category of Habitat (value of the land to tortoise populations)
- Term of Effect (short term vs. long term)
- Existing Disturbance on Site
- Growth Inducement (growth inducing effects of the proposed action)
- Effect of Adjacent Lands (whether adjacent lands will be affected)

The proposed project will disturb 209 acres of desert tortoise habitat on lands in Lincoln County. The total compensation fee for this project is $808,722. Attachment C shows a breakdown of these calculations. Fees for disturbances on Federal land will be deposited into the Lincoln County Section 7 Account, while fees for disturbance on private land will be deposited into the CSI MSHCP Section 10 Trust Fund. The payee will fill out the attached fee payment forms (Attachment D) and include these with the payments.

Each year these fees will be indexed for inflation based on the Bureau of Labor Statistics Consumer Price Index for All Urban Consumers (CPI-U). Information on the CPI-U can be found on the internet at: http://stats.bls.gov/news.release/cpi.nr0.htm. The next rate adjustment will occur on March 1, 2009.

Fees deposited in the Lincoln County Section 7 account will be managed consist with an MOA to be developed between BLM and the Service. The development of a MOA will be initiated within 30 days of the ROD.

Section 7 fees collected under this biological opinion may be used in coordination with the mitigation program of the CSI MSHCP, to implement conservation and recovery measures within the Mormon Mesa critical habitat unit.

RPM 5: *BLM, LCWD, VWC, and other jurisdictional Federal agencies as appropriate, shall ensure implementation of the following measures to minimize impacts to Moapa dace that may result from groundwater pumping associated with the project in the Kane Springs Valley:*

Terms and Conditions:

BLM shall assure that all provisions of the proposed actions including the Monitoring, Management and Mitigation Plan of the Stipulated Agreement are fully implemented.

RPM 6: *BLM, LCWD, and other jurisdictional Federal agencies as appropriate, shall ensure implementation of the following measures to comply with the reasonable and prudent measures, terms and conditions, reporting requirements, and reinitiation requirements contained in this biological opinion:*

Terms and Conditions:

6.a. LCWD shall designate a field contact representative. The field representative will be responsible for overseeing compliance with protective stipulations for the desert tortoise and coordinating directly with BLM and the Service. The field contact representative shall have the authority to halt activities or construction equipment that may be in violation of the stipulations. A copy of the terms and conditions of this biological opinion shall be provided to the field contact representative, biologists, and monitors for the project.

6.b. The authorized biologist shall record each observation of desert tortoise handled. Information will include the following: location, date and time of observation; whether tortoise was handled, general health and whether it voided its bladder; location tortoise was moved from and location moved to; and unique physical characteristics of each tortoise. A final report will be submitted to the Service's Nevada Fish and Wildlife Office in Las Vegas within 90 days of completion of the project.

The reasonable and prudent measures, with their implementing terms and conditions, are designed to minimize the impact of incidental take that might otherwise result from the proposed action. If, during the course of the action, the level of incidental take or loss of habitat identified is exceeded, such incidental take and habitat loss represents new information requiring reinitiation of consultation and review of the reasonable and prudent measures provided. The designated utilities must immediately provide an explanation of the causes of the taking and review with the Service the need for possible modification of the reasonable and prudent measures.

D. Reporting Requirements

Upon locating a dead or injured endangered or threatened species within the action area, notification must be made to the Service's Nevada Fish and Wildlife Office in Las Vegas at (702) 515-5230. Care should be taken in handling sick or injured endangered or threatened species to ensure effective treatment and be taken for handling of dead specimens to preserve biological material in the best possible state for later analysis of cause of death. In conjunction with the care of injured endangered or threatened species or preservation of biological materials from a dead animal, the finder has the responsibility to carry out instructions provided by the Service to ensure that evidence intrinsic to the specimen is not unnecessarily disturbed. All deaths, injuries, and illnesses of endangered or threatened species, whether associated with project activities or not, will be summarized in an annual report.

Desert Tortoise (Mojave Population)

The following actions should be taken for injured or dead tortoises if directed by the Service:

1. Injured desert tortoises shall be delivered to any qualified veterinarian for appropriate treatment or disposal.

2. Dead desert tortoises suitable for preparation as museum specimens shall be frozen immediately and provided to an institution holding appropriate Federal and State permits per their instructions.

3. Should no institutions want the desert tortoise specimens, or if it is determined that they are too damaged (crushed, spoiled, etc.) for preparation as a museum specimen, then they may be buried away from the project area or cremated, upon authorization by the Service.

4. The designated utilities shall bear the cost of any required treatment of injured desert tortoises, euthanasia of sick desert tortoises, or cremation of dead desert tortoises.

5. Should sick or injured desert tortoises be treated by a veterinarian and survive, they may be transferred as directed by the Service.

Moapa Dace

The following action should be taken for injured or dead Moapa dace if directed by the Service: Dead Moapa dace suitable for preparation as museum specimens shall be frozen immediately and provided to the Service's Nevada Fish and Wildlife Office in Las Vegas.

CONSERVATION RECOMMENDATIONS

Section 7(a)(1) of the Act directs Federal agencies to use their authorities to further the purposes of the Act by carrying out conservation programs for the benefit of endangered and threatened species. Conservation recommendations are discretionary agency activities to minimize or avoid adverse effects of a proposed action on listed species or critical habitat, to help implement recovery plans, or to develop information. The Service provides no conservation recommendations at this time.

REINITIATION

This concludes formal consultation on the actions outlined in your requested dated September 27, 2007. As required by 50 CFR § 402.16, reinitiation of formal consultation is required where the discretionary Federal agency involvement or control over an action has been retained (or is authorized by law) and if: (1) the amount or extent of incidental take is exceeded; (2) new information reveals effects of the agency action that may affect listed species or critical habitat in a manner or to an extent not considered in this opinion; (3) the agency action is subsequently modified in a manner that causes an effect to the listed species or critical habitat that was not considered in this opinion; or (4) a new species is listed or critical habitat designated that may be affected by the action. In instances where the amount or extent of incidental take is exceeded, any operations causing such take must cease pending reinitiation. In particular, if the State Engineer grants additional water rights beyond the currently permitted 1,000 afy for the Kane Springs Groundwater Development Project, then formal consultation should be reinitiated.

The incidental take statement provided with this Biological Opinion authorizes take of the Moapa dace as may occur in connection with the pumping and transfer of 1,000 afy of groundwater under Phase I of the Project, and implementation of the Monitoring, Management, and Mitigation Plan established under the amended stipulated agreement for the Kane Springs Valley Hydrographic Basin. In June 2008, the LCWD, VWC, and the Service executed a Memorandum of Understanding to ensure additional consultation on this project should additional water rights be appropriated to LCWD and VWC in the Kane Springs Valley Hydrographic Basin (Attachment E). Specifically, the Memorandum requires that the Service reinitiate Section 7 consultation, and, if required, LCWD and VWC will apply for an incidental take permit under Section 10(a)(1)(B) of the Act to cover any take that may occur due to the pumping and transfer of such additional groundwater.

If we can be of further assistance regarding this consultation, please contact me at (775) 861-6300, or Janet Bair in the Nevada Fish and Wildlife Office in Las Vegas at (702) 515-5230.

Sincerely,

Robert D. Williams
Field Supervisor

Attachments

cc:
Lincoln County Treasurer, Pioche, Nevada
Supervisory Biologist - Habitat, Nevada Department of Wildlife, Las Vegas, Nevada
Field Manager, Caliente Field Office, Bureau of Land Management, Caliente, Nevada
Nevada Groundwater Projects Office, Nevada State Office, Bureau of Land Management, Reno, Nevada
T&E Species Coordinator, Nevada State Office, Bureau of Land Management, Reno, Nevada

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ATTACHMENT A

GENERAL DESERT TORTOISE QUALIFICATIONS STATEMENT

This form should be used to provide your qualifications to agency officials if you wish to undertake the duties of an authorized biologist with regard to desert tortoises during construction or other projects authorized under Sections 7 (Biological Opinions) or 10(a)(1)(B) (i.e. Habitat Conservation Plans) of the Endangered Species Act.

(If you seek approval to attach/remove/insert any devices or equipment to/into desert tortoises, withdraw blood, or conduct other procedures on desert tortoises, a recovery permit or similar authorization may be required. Application for a recovery permit requires completion of Form 3-200-55, which can be downloaded at http://www.fws.gov/forms/3-200-55.pdf.)

1. Contact Information:

Name	
Address	
City, State, Zip Code	
Phone Number(s)	
Email Address	

2. Date:

3. Areas in which authorization is requested (check all that apply):

□ San Bernardino, Kern, and Los Angeles Counties, California (Ventura office)
□ Riverside and Imperial Counties, California (Carlsbad office)
□ Nevada □ Utah □ Arizona

4. Please provide information on the project:

USFWS Biological Opinion or HCP Permit No.		**Date:**
Project Name		
Federal Agency		
Proponent or Contractor		

5. If you hold, or have held, any relevant state or federal wildlife permits provide the following:

Species	**Dates**	**State (specify) or Federal Permit Number**	**Authorized Activities**

6. Education: Provide up to three schools, listing most recent first:

Institution	**Dates attended**	**Major/Minor**	**Degree received**

7. Desert Tortoise Training.

Name/Type of Training	**Dates (From/To)**	**Location**	**Instructor/Sponsor**
1. Classes			
2. Field Training			
3. Translocation			
4.			

8. Experience – Include only those positions relevant to the requested work with desert tortoises. Distinguish between Mojave desert tortoise and other experience. Include only your experience, not information for the project you worked on (e.g., if 100 tortoises were handled on a project and you handled 5 of those tortoises, include only those 5. List most recent experience first. Handling a Mojave desert tortoise must be authorized by a Biological Opinion or other permit and reported to the USFWS. Information provided in this section will be used by the USFWS to track the numbers of tortoises affected by previous projects (baseline). **Be sure to include a project supervisor or other contact that can verify your skills and experience in relation to your job performance.** Attach additional sheets as necessary.

ATTACHMENT A

Experience by project and activity:

Project Name, Job Title, Dates	Project Contact name, phone no., & Email address		Conduct Clearance Surveys (Hrs/Days)	Excavate DT burrows (No.)	Locate DT No. < 100mm ≥100mm	Relocate DTs (No.)	Excavate, and relocate DT nests (No.)
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							
9.							
10.							

Experience by project and activity (continued): Each project number should correspond with the project listed on the previous page

Project Number (Corresponds to previous page)		**Construct Artificial Burrows (No.)**	**Monitor project equipment and activities (Hrs/Days)**	**Oversee project compliance (Hrs/Days)**	**Supervise field staff (Hrs/Days)**	**DT fence Installation and inspection (Hrs/Days)**	**Present DT Awareness Training (No.)**
1.							
2.							
3.							
4.							
5.							
6.							
7.							
8.							
9.							
10.							

Summary of experience:

Total time spent for all desert tortoise-related field activities (referenced above):
Specify total number of hours
OR total number of 8-hour days: ____________________________

Total number of miles/kilometers walked conducting survey transects:

Total number of wild, free-ranging desert tortoises you personally handled:

<100 mm: _______

≥100 mm: _______

I certify that the information submitted in this form is complete and accurate to the best of my knowledge and belief.
I understand that any false statement herein may subject me to the criminal penalties of 18 U.S.C. Ch.47, Sec. 1001.

Signed: ______________________________ **Date:** ____________________

ATTACHMENT B

RECOMMENDED SPECIFICATIONS FOR DESERT TORTOISE EXCLUSION FENCING
September 2005

These specifications were developed to standardize fence materials and construction procedures to confine tortoises or exclude them from harmful situations, primarily roads and highways. Prior to commencing any field work, all field workers should comply with all stipulations and measures developed by the jurisdictional land manager and the U.S. Fish and Wildlife Service for conducting such activities in desert tortoise habitat, which will include, at a minimum, completing a desert tortoise education program.

FENCE CONSTRUCTION

Materials

Fences should be constructed with durable materials (*i.e.,* 16 gauge or heavier) suitable to resist desert environments, alkaline and acidic soils, wind, and erosion. Fence material should consist of 1-inch horizontal by 2-inch vertical, galvanized welded wire, 36 inches in width. Other materials include: Hog rings, steel T-posts, and smooth or barbed livestock wire. Hog rings should be used to attach the fence material to existing strand fence. Steel T-posts (5 to 6-foot) are used for new fence construction. If fence is constructed within the range of bighorn sheep, 6-foot T-posts should be used (see New Fence Construction below). Standard smooth livestock wire fencing should be used for new fence construction, on which tortoise-proof fencing would be attached.

Retrofitting Existing Livestock Fence

Option 1 (see enclosed drawing). Fence material should be buried a minimum of 12 inches below the ground surface, leaving 22-24 inches above ground. A trench should be dug or a cut made with a blade on heavy equipment to allow 12 inches of fence to be buried below the natural level of the ground. The top end of the tortoise fence should be secured to the livestock wire with hog rings at 12 to 18-inch intervals. Distances between T-posts should not exceed 10 feet, unless the tortoise fence is being attached to an existing right-of-way fence that has larger interspaces between posts. The fence must be perpendicular to the ground surface, or slightly angled away from the road, towards the side encountered by tortoises. After the fence has been installed and secured to the top wire and T-posts, excavated soil will be replaced and compacted to minimize soil erosion.

Option 2 (see enclosed drawing). In situations where burying the fence is not practical because of rocky or undigable substrate, the fence material should be bent at a 90° angle to produce a lower section approximately 14 inches wide which will be placed parallel to, and in direct contact with, the ground surface; the remaining 22-inch wide upper section should be placed vertically against the existing fence, perpendicular to the ground and attached to the existing fence with hog rings at 12 to18-inch intervals. The lower section in contact with the ground should be placed within the enclosure in the direction of potential tortoise encounters and level with the ground surface. Soil and cobble (approximately 2 to 4 inches in diameter; can use larger rocks where soil is shallow) should be placed on top of the lower section of fence material on the ground covering it with up to 4 inches of material, leaving a minimum of 18 inches of open space between the cobble surface and the top of the tortoise-proof fence. Care should be taken to ensure that the fence material parallel to the ground surface is adequately covered and is flush with the ground surface.

New Fence Construction

Options 1 or 2 should be followed except in areas that require special construction and engineering such as wash-out sections (see below). T-posts should be driven approximately 24 inches below the ground surface spaced approximately 10 feet apart. Livestock wire should be stretched between the T-posts, 18 to 24 inches above the ground to match the top edge of the fence material; desert tortoise-proof fencing should be attached to this wire with hog rings placed at 12 to 18-inch intervals. Smooth (barb-less) livestock wire should be used except where grazing occurs.

If fence is constructed within the range of bighorn sheep, two smooth-strand wires are required at the top of the T-post, approximately 4 inches apart, to make the wire(s) more visible to sheep. A 20 to 24-inch gap must exist between the top of the fence material and the lowest smooth-strand wire at the top of the T-post. The lower of the top two smooth-strand wires must be at least 43 inches above the ground surface.

(72-inch T-posts: 24 inches below ground + 18 inches of tortoise fence above ground + 20 to 24-inch gap to lower top wire + 4 inches to upper top wire = 66 to 70 inches).

INSPECTION OF DESERT TORTOISE BARRIERS

The risk level for a desert tortoise encountering a breach in the fence is greatest in the spring and fall, particularly around the time of precipitation including the period during which precipitation occurs and at least several days afterward. All desert tortoise fences and cattleguards should be inspected on a regular basis sufficient to maintain an effective barrier to tortoise movement. Inspections should be documented in writing and include any observations of entrapped animals; repairs needed including bent T-posts, leaning or non-perpendicular fencing, cuts, breaks, and gaps; cattleguards without escape paths for tortoises or needed maintenance; tortoises and tortoise burrows including carcasses; and recommendations for supplies and equipment needed to complete repairs and maintenance.

All fence and cattleguard inventories should be inspected at least twice per year. However, during the first 2 to 3 years all inspections will be conducted quarterly at a minimum, to identify and document breaches, and problem areas such as wash-outs, vandalism, and cattleguards that fill-in with soil or gravel. GPS coordinates and mileages from existing highway markers should be recorded in order to pinpoint problem locations and build a database of problem locations that may require more frequent checking. Following 2 to 3 years of initial inspection, subsequent inspections should focus on known problem areas which will be inspected more frequently than twice per year. In addition to semi-annual inspections, problem areas prone to wash-outs should be inspected following precipitation that produces potentially fence-damaging water flow. A database of problem areas will be established whereby checking fences in such areas can be done efficiently.

REPAIR AND MAINTENANCE OF DESERT TORTOISE BARRIERS

Repairs of fence wash-outs: (1) realign the fence out of the wash if possible to avoid the problem area, or (2) re-construct tortoise-proof fencing using techniques that will ensure that an effective desert tortoise barrier is established that will not require frequent repairs and maintenance. Gaps and breaks will require either: (a) repairs to the existing fence in place, with similar diameter and composition of original material, (b) replacement of the damaged section to the nearest T-post, with new fence material that original fence standards, (c) burying fence, and/or (d) restoring zero ground clearance by filling in gaps or holes under the fence and replacing cobble over fence constructed under Option 2. Tortoise-proof fencing should be constructed and maintained at cattleguards to ensure that a desert tortoise barrier exists at all times.

All fence damage should be repaired in a timely manner to ensure that tortoises do not travel through damaged sections. Similarly, cattleguards will be cleaned out of deposited material underneath them in a timely manner. In addition to periodic inspections, debris should be removed that accumulates along the fence. All cattleguards that serve as tortoise barriers should be installed and maintained to ensure that any tortoise that falls underneath has a path of escape without crossing the intended barrier.

Attachment C

Calculation of Desert Tortoise Remuneration Fees

Table 1. Project specific multiplier for calculating remuneration fees for critical habitat.

COMPENSATION FACTOR*	DESCRIPTION	RATING
Category of Habitat	The habitat has been rated as Category I, which is the most valuable and protected (i.e. critical habitat).	3.0
Term of Effect	The term of effect has been rated as long term (> 10 years)	1.0
Existing Disturbance on Site	The existing disturbance has been rated as little or no existing habitat disturbance	1.0
Growth Inducement	The proposed action has been rated as having growth inducing effects	0.5
Effect of Adjacent Lands	The proposed action has been rated as having a direct or indirect deleterious impacts	0.5
TOTAL RATING FOR COMPENSATION FACTORS = MULTIPLIER		6.0
MULTIPLIER X CURRENT COST/ACRE (6 x $753)**		$4,518/acre

Table 2. Calculation of remuneration fees for the Kane Springs Valley Groundwater Development Project.

ACRES	COST PER ACRE**	COST
Compensation for disturbance <u>not</u> within designated critical habitat on Federal land:		
36 acres	$753/acre	$27,108
Compensation for disturbance <u>within</u> designated critical habitat:		
148 acres Federal land	$4,518/acre	$668,664
25 acres private land	$4,518/acre	$112,950
TOTAL COST		**$808,722**

*Compensation Factors are rated based on the *Compensation for the Desert Tortoise; A Report Prepared for the Desert Tortoise Management Oversight Group* (Hastey *et al.*, 1991).

** Each year these fees will be indexed for inflation based on the Bureau of Labor Statistics Consumer Price Index for All Urban Consumers (CPI-U). Information on the CPI-U can be found on the internet at: http://stats.bls.gov/news.release/cpi.nr0.htm. The next rate adjustment will occur on March 1, 2009.

Attachment D

LINCOLN COUNTY SECTION 7
LAND DISTURBANCE FEE
PAYMENT FORM
Entire form is to be completed by project proponent

Biological Opinion File Number: 84320-2008-F-0007

Biological Opinion issued by: Nevada Fish and Wildlife Office, Las Vegas, Nevada

Species: Desert tortoise (*Gopherus agassizii*) (Mojave population)

Project: Kane Springs Valley Groundwater Development Project

Number of acres anticipated to be disturbed: 184 acres on Federal land (148 acres critical habitat, 36 acres non-critical habitat)

Fee rate (per acre): $4,518 for critical habitat, $753 for non-critical habitat______

Total payment required: $________________________

Amount of payment received: ____________________

Date of receipt: ____________________

Check or money order number: ________________

Project proponent: __________________________

Telephone number:

Authorizing agencies: Bureau of Land Management, Ely, Nevada

Make checks payable to: Lincoln County Treasurer

Deliver check to:
Lincoln County Habitat Conservation Section 7 Account
Lincoln County Treasurer
Attn: Ms. Cathy Hiatt
P.O. Box 416
Pioche, Nevada 89043
(775) 962-5805

If you have questions, you may call the Nevada Fish and Wildlife Office in Las Vegas at (702) 515-5230.

Attachment D (continued)

CSI MSHCP SECTION 10 TRUST FUND
LAND DISTURBANCE FEE
PAYMENT FORM
Entire form is to be completed by project proponent

Biological Opinion File Number: 84320-2008-F-0007

Biological Opinion issued by: Nevada Fish and Wildlife Office, Las Vegas, Nevada

Species: Desert tortoise (*Gopherus agassizii*) (Mojave population)

Project: Kane Springs Valley Groundwater Development Project

Number of acres anticipated to be disturbed: 25 acres of critical habitat on private land

Fee rate (per acre): $4,518 for critical habitat

Total payment required: $________________________

Amount of payment received: ____________________

Date of receipt: ____________________

Check or money order number: ________________

Project proponent: ___________________________

Telephone number:

Authorizing agencies: Bureau of Land Management, Ely, Nevada

Make checks payable to: Coyote Springs Investment, LLC/CSI MSHCP Section 10 Trust Fund

Deliver check to:
CSI MSHCP Section 10 Trust Fund
Coyote Springs Investment, LLC
Attn: Mr. James England
3100 State Route 168
Coyote Springs, Nevada 89037

If you have questions, you may call the Nevada Fish and Wildlife Office in Las Vegas at (702) 515-5230.

ATTACHMENT E

Memorandum of Understanding Between
Lincoln County Water District, Vidler Water Company, Inc.
and Nevada Fish and Wildlife Office, US Fish and Wildlife Service

The Nevada Fish and Wildlife Office of the US Fish and Wildlife Service (SERVICE), Lincoln County Water District (LCWD) and Vidler Water Company, Inc. (VIDLER) have entered into this memorandum of understanding (MOU) with reference to the following facts and circumstances:

1) The SERVICE is responsible for administering and implementing the Endangered Species Act of 1973, as amended, (ESA) (16 U.S.C. §§ 1531 – 1544), including conducting consultation pursuant to Sections 7 and 10 of the ESA and as described in its implementing regulations (50 CFR Part 402).

2) LCWD and VIDLER propose to complete the Kane Springs Valley Groundwater Development Project (Project), which involves the pumping and transfer of up to 5,000 acre-feet of groundwater from the Kane Springs Valley Hydrographic Basin for use in the Coyote Spring Valley Hydrographic Basin in Lincoln County, Nevada. The Project will be completed in three phases. Phase I of the Project involves the pumping and transfer of 1,000 acre-feet per year of groundwater.

3) LCWD and VIDLER applied to the Nevada State Engineer for authorization to appropriate up to 5,000 acre-feet per year of groundwater from Kane Springs Valley for use in Coyote Spring Valley, and the SERVICE filed protests to the applications.

4) The SERVICE, LCWD and VIDLER entered into an Amended Stipulation for Withdrawal of Protests under which the SERVICE, LCWD and VIDLER agreed to implement a Monitoring, Management and Mitigation Plan and the SERVICE agreed to withdraw its protests to the applications.

5) The purpose of the Monitoring, Management and Mitigation Plan is to obtain accurate and reliable information regarding the aquifer's response to pumping and the impact of pumping on water-related resources within the regional carbonate-rock aquifer and overlying basin-fill aquifer systems so that the Project can be managed to avoid adverse impacts to the Moapa Dace or its habitat.

6) The Nevada State Engineer has authorized LCWD and VIDLER to appropriate 1,000 acre-feet of groundwater from Kane Springs Valley for use in Coyote Spring Valley and may in the future authorize LCWD and VIDLER to appropriate up to 5,000 acre-feet of groundwater from Kane Springs Valley for use in Coyote Spring Valley.

7) The Bureau of Land Management is expected to issue a Record of Decision granting a right-of-way for the Project.

8) The SERVICE is expected to issue a biological opinion concluding that the Project "may affect, is likely to adversely affect" the Moapa dace or its habitat.

9) The extent of any impact to the Moapa dace or its habitat is uncertain and cannot be known until pumping begins and reliable data is collected under the Monitoring, Management and Mitigation Plan.

10) The sole purpose of this MOU is to ensure ongoing cooperation and consultation between LCWD, VIDLER and the SERVICE, the timely, economical and successful completion of the Project and the protection of the Moapa Dace and its habitat.

11) By entering into this MOU, the SERVICE is taking "action" as defined in 50 CFR §402.02.

12) By entering into this MOU, the SERVICE, LCWD, and VIDLER seek to create a federal nexus to enable the SERVICE to reinitiate consultation under Section 7 of the ESA concerning impacts to the Moapa dace that may occur if the Nevada State Engineer authorizes LCWD and VIDLER to appropriate more than 1,000 acre-feet of groundwater from the Kane Springs Valley Hydrographic Basin.

Now, therefore, in consideration of the mutual promises contained in this MOU, LCWD, VIDLER and the SERVICE agree as follows:

A. The SERVICE will issue a biological opinion for the Project. The biological opinion will include an incidental take statement authorizing such take of the Moapa dace as may occur in connection with the pumping and transfer of 1,000 acre-feet of groundwater under Phase I of the Project and implementation of the Monitoring, Management and Mitigation Plan.

B. Upon receiving authorization from the Nevada State Engineer to appropriate more than 1,000 and up to 5,000 acre-feet per year of groundwater from the Kane Springs Valley for use in Coyote Springs Valley, the SERVICE will reinitiate consultation for the Project pursuant to Section 7 of the ESA; and if necessary, LCWD and VIDLER will apply for an incidental take permit under Section 10(a)(1)(B) of the ESA to cover any take of the Moapa dace that may occur due to the pumping and transfer of such additional groundwater.

US Fish and Wildlife Service
Nevada Fish and Wildlife Office

[signature] 6/30/08

Robert Williams — Date
Field Supervisor

Lincoln County Water District

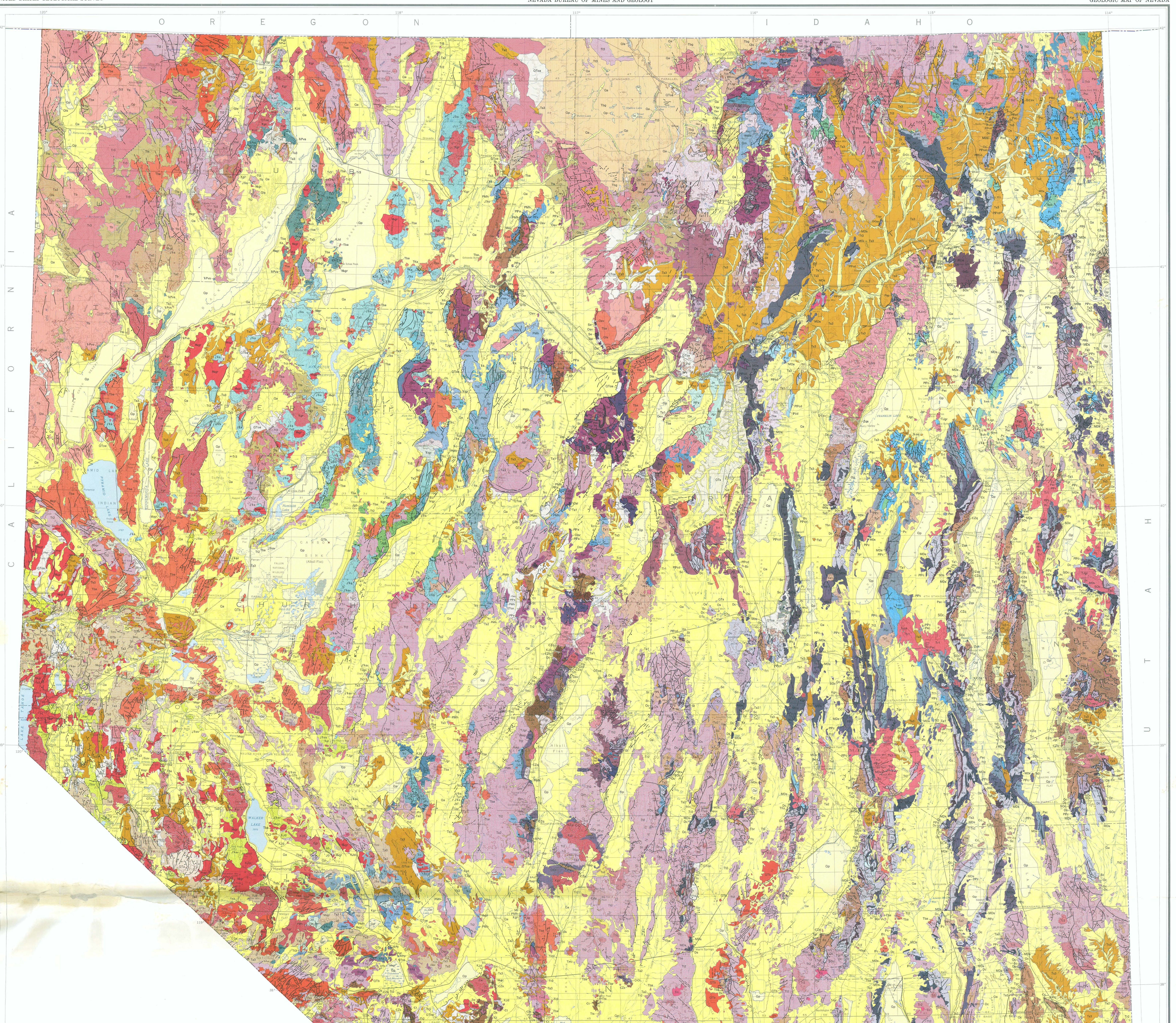
By George T. Rowe
Title: Chairman LCWD

6/16/08
Date

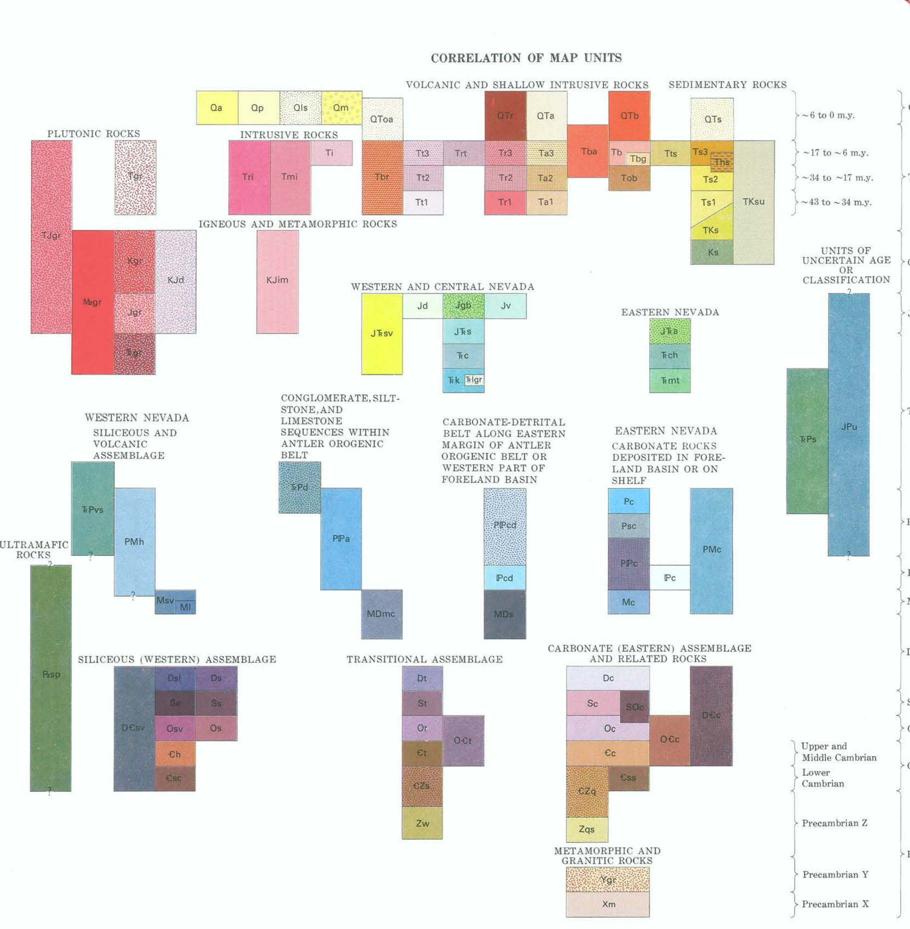
Vidler Water Company, Inc.

By Dorothy A. Timian
Title: President

6/26/08
Date



CORRELATION OF MAP UNITS



PREPARED BY THE
UNITED STATES GEOLOGICAL SURVEY
IN COOPERATION WITH THE
NEVADA BUREAU OF MINES AND GEOLOGY

GEOLOGIC MAP OF NEVADA

Compiled by
John H. Stewart and John E. Carlson

SCALE 1:500 000

10 20 30 40 50 MILES

10 20 30 40 50 60 70 KILOMETERS

CONTOUR INTERVAL 500 FEET
DATUM IS MEAN SEA LEVEL

1978

DESCRIPTION OF MAP UNITS

Qa — ALLUVIAL DEPOSITS—Locally includes beach and sand dune deposits

Qp — PLAYA, MARSH, AND ALLUVIAL-FLAT DEPOSITS, LOCALLY ERODED

Qls — LANDSLIDE DEPOSITS

Qm — MORAINAL DEPOSITS

QToa — OLDER ALLUVIAL DEPOSITS

QTr — RHYOLITIC FLOWS AND SHALLOW INTRUSIVE ROCKS

QTa — ANDESITE FLOWS AND BRECCIAS

QTb — BASALT FLOWS—Locally includes maar deposits

QTs — SEDIMENTARY ROCKS—Mostly lake deposits

Tri — RHYOLITIC INTRUSIVE ROCKS

Tmi — INTRUSIVE ROCKS OF MAFIC AND INTERMEDIATE COMPOSITION

Ti — INTRUSIVE ROCKS—Aphanitic, porphyritic, and coarsely granular rocks ranging in composition from diorite to granite. Clark County

Tbr — BRECCIA—Volcanic, thrust, and jasperoid breccia and landslide megabreccia

Tt3 — WELDED AND NONWELDED SILICIC ASH-FLOW TUFFS—Locally includes thin units of air-fall tuff and sedimentary rock

Trt — ASH-FLOW TUFFS, RHYOLITIC FLOWS, AND SHALLOW INTRUSIVE ROCKS

Tr3 — RHYOLITIC FLOWS AND SHALLOW INTRUSIVE ROCKS

Ta3 — ANDESITE AND RELATED ROCKS OF INTERMEDIATE COMPOSITION—Flows and breccias

Tba — ANDESITE AND BASALT FLOWS—Mostly in ~17 to ~6 m.y. age range. In Humboldt County, locally includes rocks as old as 21 m.y. May include rocks younger than 6 m.y. in places

Tb — BASALT FLOWS

Tbg — BANBURY FORMATION—Basalt, gravel, and tuffaceous sediments locally. Northeast Humboldt County and northwest Elko County

Tts — ASH-FLOW TUFFS AND TUFFACEOUS SEDIMENTARY ROCKS

Ts3 — TUFFACEOUS SEDIMENTARY ROCKS—Locally includes minor amounts of tuff

Ths — HORSE SPRING FORMATION—Tuffaceous sedimentary rocks, southern Nevada

TKsu — CONTINENTAL SEDIMENTARY ROCKS—Clark County

Tt2 — WELDED AND NONWELDED SILICIC ASH-FLOW TUFFS—Locally includes thin units of air-fall tuff and sedimentary rock

Tr2 — RHYOLITIC FLOWS AND SHALLOW INTRUSIVE ROCKS

Ta2 — ANDESITE AND RELATED ROCKS OF INTERMEDIATE COMPOSITION—Flows and breccias

Tob — OLDER BASALT ROCKS

Ts2 — TUFFACEOUS SEDIMENTARY ROCKS—locally includes minor amounts of tuff

Tt1 — WELDED AND NONWELDED SILICIC ASH-FLOW TUFFS—Locally includes thin units of air-fall tuff and sedimentary rock

Tr1 — RHYOLITIC FLOWS AND SHALLOW INTRUSIVE ROCKS

Ta1 — ANDESITE AND RELATED ROCKS OF INTERMEDIATE COMPOSITION—Flows and breccias

Ts1 — SEDIMENTARY ROCKS—Includes Sheep Pass Formation (Eocene) and related units and unnamed tuffaceous sedimentary rocks

TKs — CONTINENTAL SEDIMENTARY ROCKS—Includes units such as Pansy Lee Conglomerate in Humboldt County, part of Cretaceous(?) and Tertiary rocks of Kleinhampl and Ziony (1967) in northern Nye County, and part of "older clastic rocks" of Tschanz and Pampeyan (1970) in Lincoln County

Ks — CONTINENTAL DEPOSITS OF SILTSTONE, SHALE, CONGLOMERATE, AND LIMESTONE—Includes units such as King Lear Formation in Humboldt County, Newark Canyon Formation in Eureka County, Willow Tank Formation and Baseline Sandstone in Clark County

PLUTONIC ROCKS

TJgr — GRANITIC ROCKS, CENTRAL AND EASTERN NEVADA—Mostly quartz monzonite and granodiorite. Inconclusively dated or not dated radiometrically

Tgr — GRANITIC ROCKS—Mostly quartz monzonite and granodiorite

Mzgr — GRANITIC ROCKS, WESTERN NEVADA (Mesozoic)—Mostly quartz monzonite and granodiorite. Inconclusively dated or not dated radiometrically.

Kgr — GRANITIC ROCKS—Mostly quartz monzonite and granodiorite

KJd — DIORITE

Jgr — GRANITIC ROCKS—Mostly quartz monzonite and granodiorite

Trgr — GRANITIC ROCKS—Quartz monzonite in northern Esmeralda County

IGNEOUS AND METAMORPHIC ROCKS

KJim — IGNEOUS AND METAMORPHIC COMPLEX—Pegmatitic granite and other granitic rocks complexly intermixed with metasedimentary rocks. Considered to be Mesozoic igneous complex intruding lower Paleozoic and possibly Precambrian Z sedimentary rocks. Grades into units shown on map as lower Paleozoic. Ruby Mountains and East Humboldt Range, Elko County

JURASSIC AND TRIASSIC ROCKS IN WESTERN AND CENTRAL NEVADA

JTrsv — SHALE, SANDSTONE, VOLCANOGENIC CLASTIC ROCKS, ANDESITE, RHYOLITE, AND LOCALLY THICK CARBONATE UNITS—Undivided sequence locally containing recognizable equivalents of the Luning and Dunlap Formations

Jd — DUNLAP FORMATION (Lower and Middle Jurassic)—Conglomerate, sandstone, greenstone, felsite, and tuff. Locally contemporaneous with folding and thrusting. Mineral County and adjacent parts of Esmeralda and Nye Counties

Jgb — GABBROIC COMPLEX (Lower and Middle Jurassic)—Includes gabbro, basalt, and synorogenic quartz sandstone (Boyer Ranch Formation). Churchill and Pershing Counties

Jv — VOLCANIC SANDSTONE, FELSIC ASH-FLOW TUFFS, RHYOLITE, AND RHYODACITE FLOWS (Upper? Jurassic)—Pony Trail Group of Cortez Mountains, Eureka County

JTrs — SHALE, MUDSTONE, SILTSTONE, SANDSTONE, AND CARBONATE ROCK; SPARSE VOLCANIC ROCK (Upper Triassic and Lower Jurassic)—Includes Auld Lang Syne Group, Nightingale sequence of Bonham (1969), and Gabbs and Sunrise Formations

Trc — LIMESTONE, MINOR AMOUNTS OF DOLOMITE, SHALE, AND SANDSTONE; LOCALLY THICK CONGLOMERATE UNITS (Lower, Middle, and Upper Triassic)—Includes Tobin, Dixie Valley, Favret, Augusta Mountain, and Cane Spring Formations and Star Peak Group in central Nevada and Grantsville and Luning Formations in west-central Nevada

Trk — KOIPATO GROUP AND RELATED ROCKS (Lower Triassic)—Altered andesitic flows, rhyolitic tuffs and flows, and clastic rocks. Includes rocks mapped by Silberling (1959) as Pablo Formation and originally considered to be Permian in the Shoshone Mountains, Nye County. Includes Tallman Fanglomerate (Permian?) in Humboldt County

Trlgr — LEUCOGRANITE AND RHYOLITE PORPHYRY

JURASSIC AND TRIASSIC ROCKS IN EASTERN NEVADA

JTra — AZTEC SANDSTONE (Triassic? and Jurassic)—Friable fine- to medium-grained sandstone with conspicuous large-scale cross strata; considered eolian. Age based on correlation with Navajo Sandstone

Trch — CHINLE FORMATION AND ASSOCIATED ROCKS (Upper Triassic)—Continental deposits of variegated bentonitic claystone, siltstone, and clayey sandstone; ledge-forming sandstone; and red siltstone

Trmt — MOENKOPI FORMATION, THAYNES FORMATION, AND RELATED ROCKS (Lower Triassic)—Marine deposits of siltstone, limestone, and sparse conglomerate

UNITS OF UNCERTAIN AGE OR CLASSIFICATION

JPu — VOLCANOGENIC SEDIMENTARY ROCKS, TUFF, ANDESITIC AND FELSITIC FLOWS, AND CARBONATE ROCKS—Age uncertain. Mineral, Esmeralda, and northwest Nye Counties

TrPs — SILTY LIMESTONE, MINOR AMOUNTS OF SHALE, AND SOME GREENSTONE—Unnamed sequence in Adobe Range, northern Elko County

WESTERN NEVADA SILICEOUS AND VOLCANIC ASSEMBLAGE (UPPER PALEOZOIC AND TRIASSIC)

Eugeogynclinal rocks originally deposited west of Antler orogenic belt. In most places, allochthonous and thrust eastward as the upper plate of the Golconda thrust

TrPvs — VOLCANIC FLOWS AND FLOW BRECCIAS, CHIEFLY OF ANDESITIC COMPOSITION, TUFFS, SPARSE SANDSTONE AND GRAYWACKE—Includes Happy Creek Volcanic Series and related rocks in Humboldt County and similar rocks in Washoe and Pershing Counties; includes andesite breccias and volcanogenic sedimentary rocks in Mineral County

PMh — HAVALLAH SEQUENCE OF SILBERLING AND ROBERTS (1962)—Chert, argillite, shale, greenstone, and minor amounts of siltstone, sandstone, conglomerate, and limestone. Includes Schoonover Formation of Fagan (1962) and Reservation Hill Formation in Elko County, Farrel Canyon Formation in southwestern Humboldt County, Havallah and Pumpernickel Formations in Pershing, Lander, and parts of Humboldt Counties, and rocks originally considered a part of the Pablo and Excelsior Formations in northern Nye, northern Esmeralda, and southern Mineral Counties. Assignment of some rocks to the Havallah sequence in the East Range, Pershing County, is highly uncertain. Includes rocks ranging in age from Late Mississippian to Early Permian

Msv — SILICEOUS AND VOLCANIC ROCKS—In Humboldt County, consists of altered pillow lavas, coarse volcanic breccias, clastic limestone, and minor amounts of sandstone, shale, siliceous shale, and chert of the Goughs Canyon Formation (Lower and Upper Mississippian). In the East Range, Pershing County, consists of quartzite, conglomerate, slate, limestone, chert, and greenstone of the Inskip Formation (Mississippian?)

Ml — MASSIVE L[illegible] Nye County

CONGLOMERATE, SILTSTONE, AND LIMESTONE SEQUENCES WITHIN ANTLER OROGENIC BELT

Each sequence [illegible]

TrPd — CONGLOME[illegible] OF DIAB[illegible] STONE, A[illegible] MATION A[illegible] Mineral, Es[illegible]

PPa — ANTLER SE[illegible] (Middle Pe[illegible] Conglomera[illegible] stone, and [illegible] within mai[illegible] Sunflower [illegible] Formation, [illegible] mation in [illegible] Peak Form[illegible]

MDmc — CONGLOME[illegible] LITE, AN[illegible] Mountain C[illegible]

CARBONATE-DETRITAL BELT ALONG EASTERN MARGIN OF ANTLER OROGENIC BELT OR WESTERN PART OF FORELAND BASIN

PPcd — SANDY AN[illegible] SILTSTON[illegible] cludes unit[illegible] Buckskin [illegible] mations of [illegible] Garden Val[illegible]

IPcd — LIMESTONE[illegible] AND CHE[illegible] Pennsylvan[illegible] mations of [illegible]

MDs — SHALE, SI[illegible] GLOMERA[illegible] Pilot Shal[illegible] Peak Form[illegible] Canyon Li[illegible] in southern[illegible]

CARBONAT[illegible]

Pc — CHERTY L[illegible] AND SA[illegible] units such [illegible] Nevada a[illegible] southern N[illegible]

PMc — LIMESTONE[illegible] Includes Va[illegible]

Psc — SILTSTONE[illegible] (COMMON[illegible] Permian)[illegible] Formation [illegible] and Arctu[illegible] Sandstone [illegible] stone in Cla[illegible]

PPc — LIMESTONE[illegible] SANDSTO[illegible] cludes unit[illegible] (1960) and [illegible] Pine, and [illegible] Formation [illegible] Counties. [illegible] in Leppy P[illegible]

IPc — LIMESTONE[illegible] Pennsylvan[illegible]

Mc — LIMESTONE[illegible] SHALE—[illegible] Limestones[illegible]

ULTRAMAFIC ROCKS

Pzsp — SERPENTIN[illegible] eastern Hu[illegible]

SILICEOUS (WESTERN) ASSEMBLAGE (LOWER PALEOZOIC)

Eugeosynclinal rocks. Mainly allochthonous rocks in upper plate of Roberts Mountains thrust. Contacts between units are mostly faults. Includes some strata (Comus Formation, Ordovician, in Humboldt County and most strata mapped as Palmetto Formation, Ordovician, in Esmeralda County) that may be para-autochthonous or autochthonous and in lower plate

D€sv — CHERT, SHALE, ARGILLITE, SILTSTONE, QUARTZITE, AND GREENSTONE—Undivided siliceous assemblage. Mostly Ordovician

Dsl — SLAVEN CHERT—Chert and sparse limy sandstone, siltstone, and limestone. Lander County

Ds — SHALE, SILICEOUS SILTSTONE, CHERT, AND MINOR AMOUNTS OF LIMESTONE—Includes Cockalorum Wash Formation of northern Nye County and Woodruff Formation and unnamed rocks in Elko County

Se — ELDER SANDSTONE—Feldspathic sandstone, siltstone, shale, and chert. Lander County

Ss — SHALE AND CHERT—Includes Fourmile Canyon Formation in Eureka County and Noh Formation of Riva (1970) and unnamed rocks in Elko County

Osv — SILICEOUS AND VOLCANIC ROCKS—Chert, shale, quartzite, greenstone, and minor amounts of limestone. Includes units such as Valmy Formation of north-central Nevada and some rocks mapped as Palmetto Formation in northern part of Esmeralda County and adjacent parts of Mineral and Nye Counties. Locally includes rocks of Silurian and Devonian age

Os — SHALE, CHERT, AND MINOR AMOUNTS OF QUARTZITE, GREENSTONE, AND LIMESTONE—Includes units such as Vinini Formation of north-central Nevada, Palmetto Formation in southern and central parts of Esmeralda County, and Comus Formation in Humboldt County. Locally includes rocks of Silurian and Devonian age

€h — HARMONY FORMATION (Upper Cambrian)—Feldspathic and arkosic sandstone and minor amounts of shale, limestone, and chert

€sc — SCOTT CANYON FORMATION (Lower or Middle Cambrian)—Chert, shale, greenstone, and sparse limestone and quartzite. Southeast Humboldt County and northwest Lander County

TRANSITIONAL ASSEMBLAGE

Para-autochthonous or autochthonous with respect to the Roberts Mountains thrust. In places interstratified with carbonate assemblage

Dt — ARGILLACEOUS LIMESTONE, CHERT, AND SHALE—Elko and Eureka Counties

St — PLATY LIMESTONE AND LIMY SILTSTONE, CHERT AT [illegible]

[illegible]

DCc — DOLOMITE AND LIMESTONE (Lower Paleozoic)

Sc — DOLOMITE—Includes units such as Laketown and Lone Mountain Dolomites. Locally includes rocks of Early Devonian age at top

SOc — DOLOMITE—Includes uppermost part of Ordovician System (Ely Springs Dolomite and equivalent rocks) and all of Silurian System

Oc — LIMESTONE, DOLOMITE, SHALE, AND QUARTZITE—Includes units such as Pogonip Group, Eureka Quartzite, and Ely Springs Dolomite. Where Ely Springs Dolomite or equivalent rocks are included in SOc unit, this unit includes only the Pogonip Group and Eureka Quartzite or their equivalents

O€c — DOLOMITE AND LIMESTONE—Undivided Cambrian and Ordovician rocks in part of Clark County; mostly Cambrian

€c — LIMESTONE AND DOLOMITE, LOCALLY THICK SEQUENCES OF SHALE AND SILTSTONE—Includes units such as Pioche Shale, Eldorado Dolomite, Geddes Limestone, Secret Canyon Shale, Hamburg Dolomite, Dunderberg Shale, and Windfall Formation of northern Nevada and Carrara, Bonanza King, and Nopah Formations of southern Nevada

€Zq — QUARTZITE AND MINOR AMOUNTS OF CONGLOMERATE, PHYLLITIC SILTSTONE, LIMESTONE, AND DOLOMITE—Includes Prospect Mountain Quartzite, Osgood Mountain Quartzite, and Gold Hill Formation in northern Nevada and Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite in southern Nevada

€ss — SANDSTONE AND QUARTZITE—Includes Tapeats Sandstone and related rocks. Rests on Precambrian metamorphic rocks

Zqs — QUARTZITE, PHYLLITIC SILTSTONE, CONGLOMERATE, LIMESTONE, AND DOLOMITE—Includes McCoy Creek Group (excluding Stella Lake Quartzite) of Misch and Hazzard (1962) in east-central Nevada and Johnnie Formation in southern Nevada

METAMORPHIC AND GRANITIC ROCKS

Ygr — GRANITIC ROCKS—Porphyritic rapakivi granite; 1,450±25 m.y. (L. T. Silver, oral commun., 1973)

Xm — METAMORPHIC ROCKS—Gneiss and schist and lesser amounts of gneissic granite, pyroxenite, hornblendite, migmatite, pegmatite, and marble. Includes highly folded granite lenses 1,740 ±25 m.y. old (L. T. Silver, oral commun., 1973). In southern Nye County, may be Precambrian Z rocks metamorphosed during the Mesozoic

Contact

High-angle fault—Dashed where inferred or uncertain; dotted where concealed. Bar and ball on downthrown side

Low-angle fault—Dashed where inferred or uncertain; dotted where concealed. Sawteeth on upper plate

Strike-slip fault—Dashed where inferred or uncertain; dotted where concealed. Arrows indicate relative movement

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Base by U.S. Geological [illegible] Lambert conformal con[illegible] based on standard paralle[illegible]

Note: Map sources for compilation published by U.S. [illegible] of data for geologic map [illegible]

The discrepancy (0.5-0.32) may probably be accounted for by the liberal coating of white paint that was put on the insulating material to protect it from the weather and to reflect as much direct radiation as possible. The paint doubtless permeated into the material so as to increase its conductivity. Moreover, in spite of the white paint, the outer surfaces of the slabs receiving direct solar radiation must have been kept at a temperature somewhat higher than the dry bulb. Since the prevailing direction of heat-leakage was into the water, this increase of temperature of the surface of the insulating material must have had the effect of an apparent increase in conductivity.

Figure 4 shows the relation between h as computed from the phototube-pyrheliometer readings and H as obtained from the pan.

It is not surprising that equation (2) yields fairly consistent results when we remember that in the morning and evening the light entering the window of the phototube comes chiefly from the sky and is therefore richer in short waves than it is during the middle part of the day. Toward the ends of the day there are, accordingly, pulses which are not accompanied by much heat. The kt-term subtracts these out.

The errors shown by Figure 4 are due to several causes, but perhaps one of the most serious is the warping of the walls of the pan due to temperature-changes. If some means can be found for measuring nocturnal back-radiation, the seriousness of this difficulty can be eliminated by making a continuous run of several days' duration. The total algebraic result of warping would then be negligible. Arrangements are being undertaken for carrying out this plan.

The writer desires to express appreciation to Dr. White of the Physics Department of the University of California for his suggestion of covering the thyratron with a hood in order to help minimize erratic behavior due to temperature-changes. Thanks are also extended to Dr. Nicholas Ricciardi, President of the San Bernardino Valley Junior College and to Dean Frank B. Lindsay for assigning Federal Emergency Relief Administration students to this work, as well as to the students themselves. Most of the observations were made by Newell Call and William Hand, but Guy Harris and Robert Whaling also helped. Hayden Gordon, technician of the College, assisted in various ways. Mr. Moore and Mr. Watson of the Smithsonian Institution at Table Mountain rendered valuable aid in some preliminary investigations.

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THE RELATION BETWEEN THE LOWERING OF THE PIEZOMETRIC SURFACE AND THE RATE AND DURATION OF DISCHARGE OF A WELL USING GROUND-WATER STORAGE

Charles V. Theis

When a well is pumped or otherwise discharged, water-levels in its neighborhood are lowered. Unless this lowering occurs instantaneously it represents a loss of storage, either by the unwatering of a portion of the previously saturated sediments if the aquifer is nonartesian or by release of stored water by the compaction of the aquifer due to the lowered pressure if the aquifer is artesian. The mathematical theory of ground-water hydraulics has been based, apparently entirely, on a postulate that equilibrium has been attained and therefore that water-levels are no longer falling. In a great number of hydrologic problems, involving a well or pumping district near or in which water-levels are falling, the current theory is therefore not strictly applicable. This paper investigates in part the nature and consequences of a mathematical theory that considers the motion of ground-water before equilibrium is reached and, as a consequence, involves time as a variable.

To the extent that Darcy's law governs the motion of ground-water under natural conditions and under the artificial conditions set up by pumping, an analogy exists between the hydrologic conditions in an aquifer and the thermal conditions in a similar thermal system. Darcy's law is analogous to the law of the flow of heat by conduction, hydraulic pressure being analogous to temperature, pressure-gradient to thermal gradient, permeability to thermal conductivity, and specific yield to specific heat. Therefore, the mathematical theory of heat-conduction developed by Fourier and subsequent writers is largely applicable to hydraulic theory. This analogy has been recognized, at least since the work of Slichter, but apparently no attempt has been made to introduce the function of time into the mathematics of ground-water hydrology. Among the many problems in heat-conduction analogous to those in ground-water hydraulics are those concerning sources and sinks, sources being analogous to recharging wells and sinks to ordinary discharging wells.

C. I. Lubin, of the University of Cincinnati, has with great kindness prepared for me the following derivation of the equation expressing changes in temperature due to the type of source or sink that is analogous to a recharging or discharging well under certain ideal conditions, to be discussed below.

The equation given by H. S. Carslaw (Introduction to the mathematical theory of the conduction of heat in solids, 2nd ed., p. 152, 1921) for the temperature at any point in an infinite plane with initial temperature zero at any time due to an "instantaneous line-source coinciding with the axis of z of strength Q" (involving two-dimensional flow of heat) is

$$v = (Q/4\pi\kappa t)\, e^{-(x^2 + y^2)/4\kappa t} \tag{1}$$

where v = change in temperature at the point x,y at the time t; Q = the strength of the source or sink--in other words, the amount of heat added or taken out instantaneously divided by the specific heat per unit-volume; κ = Kelvin's coefficient of diffusivity, which is equal to the coefficient of conductivity divided by the specific heat per unit-volume; and t = time.

The effect of a continuous source or sink of constant strength is derived from equation (1) as follows: Let $Q = \varphi(t')dt'$; then $v_{(x,y,t)} = \int_0^t [\varphi(t')/4\pi\kappa(t-t')]\, e^{-(x^2+y^2)/4\kappa(t-t')}\, dt'$. Let $\varphi(t') = \lambda$, a constant; then $v_{(t)} = (\lambda/4\pi\kappa) \int_0^t [e^{-(x^2+y^2)/4\kappa(t-t')}/(t-t')]\, dt'$. Let $u = (x^2+y^2)/4\kappa(t-t')$; then

$$v_{(t)} = (\lambda/4\pi\kappa) \int_{(x^2+y^2)/4\kappa t}^{\infty} [e^{-u}/(t-t')]\, [(x^2+y^2)/4\kappa]\, [du/u^2]$$

$$= (\lambda/4\pi\kappa) \int_{(x^2+y^2)/4\kappa t}^{\infty} (e^{-u}/u)du \tag{2}$$

The definite integral, $\int_{(x^2+y^2)/4\kappa t}^{\infty} (e^{-u}/u)du$, is a form of the exponential integral, tables of which are available (Smithsonian Physical Tables, 8th rev. ed., table 32, 1933; the values to be used are those given for Ei (-x), with the sign changed). The value of the integral is given by the series

$$\int_x^{\infty} (e^{-u}/u)du = -0.577216 - \log_e x + x - x^2/2\cdot 2! + x^3/3\cdot 3! - x^4/4\cdot 4! + \ldots\ldots \tag{3}$$

Equation (2) can be immediately adapted to ground-water hydraulics to express the draw-down at any point at any time due to pumping a well. The coefficient of diffusivity, , is analogous to the coefficient of transmissibility of the aquifer divided by the specific yield. (The term "coefficient of transmissibility" is here used to denote the product of Meinzer's coefficient of permeability and the thickness of the saturated portion of the aquifer; it quantitatively describes the ability of the aquifer to transmit water. Meinzer's coefficient of permeability denotes a characteristic of the material; the coefficient of transmissibility denotes the analogous characteristic of the aquifer as a whole.) The continuous strength of the sink is analogous to the pumping rate divided by the specific yield. Making these substitutions, we have

$$v = (F/4\pi T) \int_{r^2 s/4Tt}^{\infty} (e^{-u}/u)du \tag{4}$$

in which the symbols have the meanings given with equation (5). In equation (4) the same units must of course be used throughout. Equation (4) may be adapted to units commonly used

$$v = (114.6F/T) \int_{1.87r^2 s/Tt}^{\infty} (e^{-u}/u)du \tag{5}$$

where v = the draw-down, in feet, at any point in the vicinity of a well pumped at a uniform rate; F = the discharge of the well, in gallons a minute; T = the coefficient of transmissibility of aquifer, in gallons a day, through each 1-foot strip extending the height of the aquifer, under a unit-gradient--this is the average coefficient of permeability (Meinzer) multiplied by the thickness of the aquifer; r = the distance from pumped well to point of observation, in feet; s = the specific yield, as a decimal fraction; and t = the time the well has been pumped, in days.

Equation (5) gives the draw-down at any point around a well being pumped uniformly (and continuously) from a homogeneous aquifer of constant thickness and infinite areal extent at any time. The introduction of the function, time, is the unique and valuable feature of the equation. Equation (5) reduces to Thiem's or Slichter's equation for artesian conditions when the time of pumping is large.

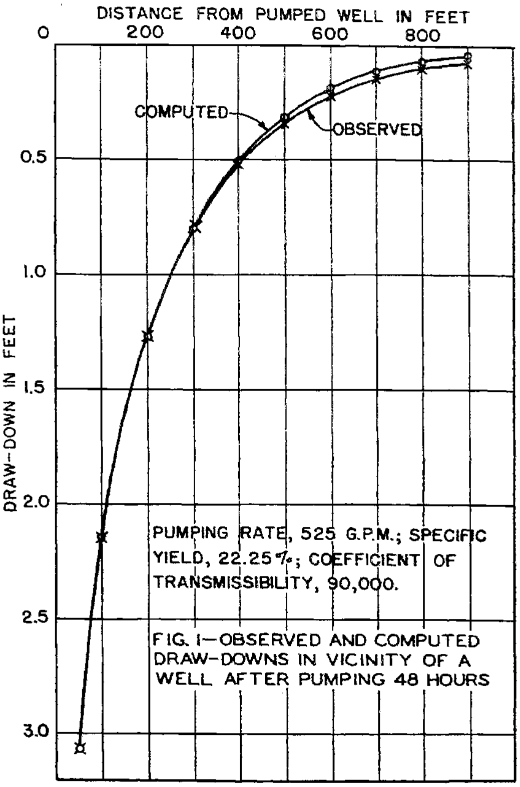

FIG. 1—OBSERVED AND COMPUTED DRAW-DOWNS IN VICINITY OF A WELL AFTER PUMPING 48 HOURS

Empirical tests of the equation are best made with the data obtained by L. K. Wenzel (Recent investigations of Thiem's method for determining permeability of water-bearing sediments, Trans. Amer. Geophys. Union, 13th annual meeting, pp. 313-317, 1932; also Specific yield determined from a Thiem's pumping test, Trans. Amer. Geophys. Union, 14th annual meeting, pp. 475-477, 1933) from pumping tests in the Platte Valley in Nebraska. Figure 1 presents the comparison of the computed and observed draw-downs after two days of pumping. The observed values are those of the generalized depression of the water-table as previously determined by Mr. Wenzel. The computed values are obtained by equation (5), using values of permeability and specific yield that are within one per cent of those determined by Mr. Wenzel by other methods. The agreement represented may be regarded as showing either that the draw-downs have been computed from known values of transmissibility and specific yield or that these factors have been computed from the known draw-downs.

Theoretically, the equation applies rigidly only to water-bodies (1) which are contained in entirely homogeneous sediments, (2) which have infinite areal extent, (3) in which the well penetrates the entire thickness of the water-body, (4) in which the coefficient of transmissibility is constant at all times and in all places, (5) in which the pumped well has an infinitesimal diameter, and (6) - applicable only to unconfined water-bodies - in which the water in the volume of sediments through which the water-table has fallen is discharged instantaneously with the fall of the water-table.

These theoretical restrictions have varying degrees of importance in practice. The effect of heterogeneity in the aquifer can hardly be foretold. The effect of boundaries can be considered by more elaborate analyses, once they are located. The effect of the well failing to penetrate the entire aquifer is apparently negligible in many cases. The pumped well used in the set-up that yielded the data for Figure 1 penetrated only 30 feet into a 90-foot aquifer. The coefficient of transmissibility must decrease during the process of pumping under water-table conditions, because of the diminution in the cross-section of the area of flow due to the fall of the water-table; however, it appears from Figure 1 that if the water-table falls through a distance equal only to a small percentage of the total thickness of the aquifer the errors are not large enough to be observed. In artesian aquifers the coefficient of transmissibility probably decreases because of the compaction of the aquifer, but data on this point are lacking. The error due to the finite diameter of the well is apparently always insignificant.

In heat-conduction a specific amount of heat is lost concomitantly and instantaneously with fall in temperature. It appears probable, analogously, that in elastic artesian aquifers a specific amount of water is discharged instantaneously from storage as the pressure falls. In nonartesian aquifers, however, the water from the sediments through which the water-table has fallen drains comparatively slowly. This time-lag in the discharge of the water made available from storage is neglected in the mathematical treatment here given. Hence an error is always present in the equation when it is applied to water-table conditions. However, inasmuch as the rate of fall of the water-table decreases progressively after a short initial period, it seems probable that as pumping continues the rate of drainage of the sediments tends to catch up with the rate of fall of the water-table, and hence that the error in the equation becomes progressively smaller.

For instance, although the draw-downs computed for a 24-hour period of pumping in Mr. Wenzel's test showed a definite lack of agreement with the observations, similar computations for a

48-hour period gave the excellent agreement shown in Figure 1. Unfortunately data for peri of pumping longer than 48 hours have not been available.

The equation implies that any two observations of draw-down, whether at different plac at the same place at different times, are sufficient to allow the computation of specific y .d and transmissibility. However, more observations are always necessary in order to guard against the possibility that the computations will be vitiated by the heterogeneity of the aquifer. Moreover, it appears that the time-lag in the drainage of the unwatered sediments makes it impossible at present to compute transmissibility and specific yield from observations on water-levels in only one observation-well during short periods of pumping. Good data from artesian wells have not been available, but such data as we have hold out the hope that transmissibility and specific yield may be determined from data from only one observation-well.

A useful corollary to equation (5) may be derived from an analysis of the recovery of a pumped well. If a well is pumped for a known period and then left to recover, the residual draw-down at any instant will be the same as if pumping of the well had been continued but a recharge well with the same flow had been introduced at the same point at the instant pumping stopped. The residual draw-down at any instant will then be

$$v' = (114.6F/\tau)\ [\int_{1.87r^2s/\tau t}^{\infty} (e^{-u}/u)du - \int_{1.87r^2s/\tau t'}^{\infty} (e^{-u}/u)du \qquad (6)$$

where t is the time since pumping started and t' is the time since pumping stopped.

In and very close to the well the quantity $(1.87r^2s/\tau t')$ will be very small as soon as t' ceases to be small, because r is very small. In many problems ordinarily met in ground-water hydraulics, all but the first two terms of the series of equation (3) may be neglected, so that, if $Z = (1.87r^2s/\tau t)$ and $Z' = (1.87r^2s/\tau t')$ equation (6) may be approximately rewritten

$$v' = (114.6F/\tau)\ [-0.577 - \log_e Z + 0.577 + \log_e Z(t/t')] = (114.6F/\tau)\ \log_e(t/t')$$

Transposing and converting to common logarithms, we have

$$\tau = (264F/v')\ \log_{10}\ (t/t') \qquad (7)$$

This equation permits the computation of the coefficient of transmissibility of an aquifer from an observation of the rate of recovery of a pumped well.

Figure 2 shows a plot of observed recovery-curves. The ordinates are log (t/t'); the abscissas are the distances the water-table lies below its equilibrium-position. According to equation (7) the points should fall on a straight line passing through the origin. Curve A is a plot of the recovery of a well within 3 feet of the well pumped for Mr. Wenzel's test, previously mentioned. Most of the points lie on a straight line, but the line passes below the origin. This discrepancy is probably due to the fact that the water-table rises faster than the surrounding pores are filled. The coefficient of permeability computed from the equation is about 1200, against a probably correct figure of 1000. Curve B is plotted from data obtained from an artesian well near Salt Lake City. The points all fall according to theory.

Curve C shows the recovery of a well penetrating only the upper part of a nonartesian aquifer of comparatively low transmissibility. It departs markedly from a straight line. This curve probably follows equation (6), but it does not follow equation (7), for in this case $(1.87r^2s/\tau t')$ is not small. Equation (6), involving r and s, neither of which may be known in practice, is not of practical value for the present purpose. Further empirical tests may show that it is feasible to project the curve to the origin, in the neighborhood of which $(1.87r^2s/\tau t')$ becomes small, owing to the increase in t and t', and apply equation (7) to the extrapolated values so obtained in order to determine at least an approximate value of the transmissibility.

The paramount value of equation (5) apparently lies in the fact that it gives part of the theoretical background for predicting the future effects of a given pumping regimen upon the water-levels in a district that is primarily dependent on ground-water storage. Such districts may include many of those tapping extensive nonartesian bodies of ground-water. Figure 3 shows the vertical rate of fall of the water-level in an infinite aquifer, the water being all taken from storage. The curves are plotted for certain definite values of pumping rate, transmissibility, and specific yield, but by changing the scales either curve could be made applicable to any values set up.

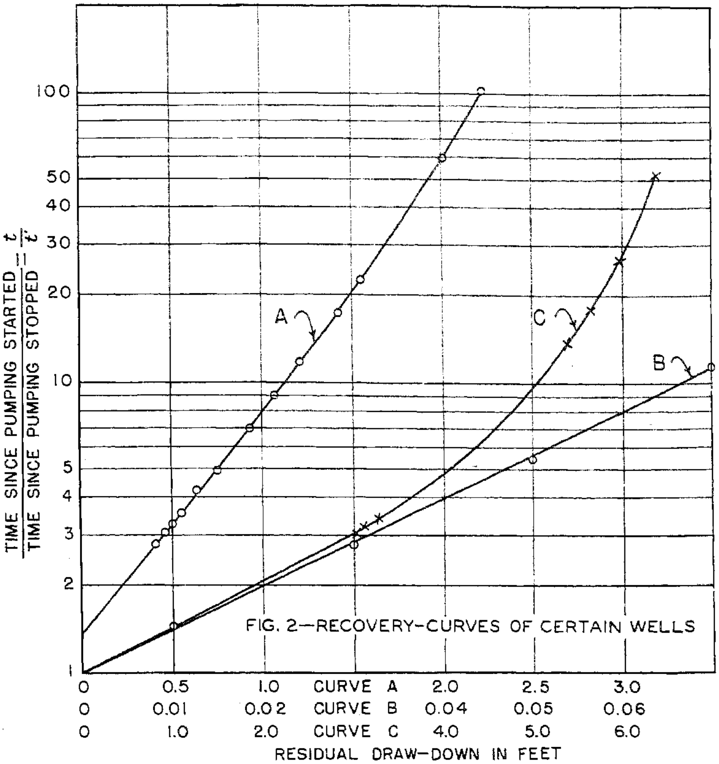

FIG. 2—RECOVERY-CURVES OF CERTAIN WELLS

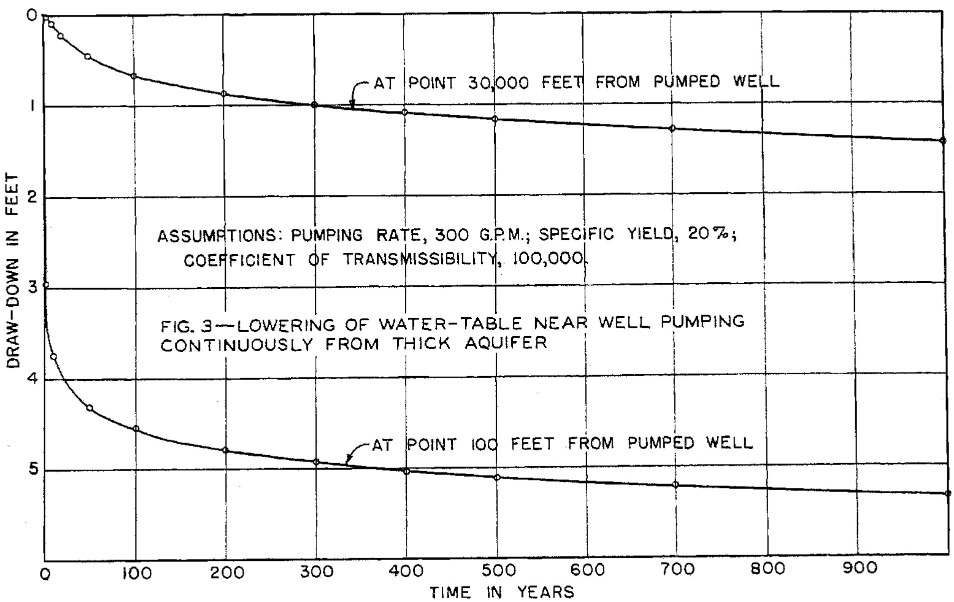

FIG. 3—LOWERING OF WATER-TABLE NEAR WELL PUMPING CONTINUOUSLY FROM THICK AQUIFER

These theoretical curves agree qualitatively with the facts generally observed when a well is pumped. The water-level close to the well at first falls very rapidly, but the rate of fall soon slackens. In the particular case considered in Figure 3 the water-level at a point 100 feet from the pumped well would fall during the first year of pumping more than half the distance it would fall in 1000 years. A delayed effect of the pumping is shown at distant points.

The water-level at a point about 6 miles from the pumped well of Figure 3 would fall only minutely for about five years but would then begin to fall perceptibly, although at a much less rate than the water-level close to the well. Incidentally the rate of fall after considerable pumping is so small that it might easily lead to a false assumption of equilibrium. The danger in a pumping district using ground-water storage lies in the delayed interference of the wells. For instance, although in 50 years one well would cause a draw-down of only 6 inches in another well 6 miles away, yet the 100 wells that might lie within 6 miles of a given well would cause in it a total draw-down of more than 50 feet.

In the preparation of this paper I have had the indispensable help not only of Dr. Lubin, who furnished the mathematical keystone of the paper, but also of Dr. C. E. Van Orstrand, of the United States Geological Survey, and of my colleagues of the Ground Water Division of the Survey, who cordially furnished data and criticism.

U. S. Geological Survey,
Washington, D. C.

THE PIEZOMETRIC SURFACE OF ARTESIAN WATER IN THE FLORIDA PENINSULA

V. T. Stringfield

Introduction

The ground-water of the Florida Peninsula constitutes one of its most valuable natural resources and is of importance as a source of water-supplies throughout the area. The problems relating to the development of ground-water supplies are both quantitative and qualitative. They include such problems as the decline in yield of wells in areas of large withdrawals of water and salt-water contamination of ground-water supplies. In order to facilitate a better understanding and interpretation of hydrologic conditions relating to these local ground-water problems, a general survey of the artesian water in the Florida Peninsula was made by the United States Geological Survey in 1934.

As part of the results of the investigation a contour-map representing the piezometric surface of the artesian water was prepared, and the general areal extent of highly mineralized ground-water was outlined. The piezometric map shows the height to which water would rise above sea-level in tightly cased wells in 1934. It indicates the hydraulic gradient and the direction of movement of the ground-water, and therefore the areas of recharge and the areas of large discharge.

General artesian conditions

The geologic formations exposed at the surface in different parts of the Peninsula probably represent a thickness of about 1000 to 1500 feet of the geologic section and include the Ocala limestone, of Eocene age, and the younger formations of the Miocene, Pliocene, Pleistocene, and Recent. These formations constitute the rocks that yield the ground-water supplies. The formations of the Peninsula form an arch or broad anticline that trends southeast and plunges toward the southern part of the State. The anticline constitutes the structural feature favorable for artesian conditions in the Peninsula. A general outline of the structure is represented in Figure 1.

The principal formations that yield artesian water are the Ocala Limestone, the Tampa Limestone, and the Hawthorn Formation.

The Ocala Limestone underlies all of Florida. In the northwestern part of the Peninsula it lies at or near the surface on the eroded crest of the large anticline, and elsewhere it extends under the younger formations that are exposed on the flanks of the anticline. It consists essentially of limestone and has an estimated thickness of about 500 feet.

The Tampa Limestone, of Miocene age, overlies the Ocala Limestone. It is at or near the surface in the west-central and northwestern parts and occurs as erosion remnants in a few areas where the Ocala Limestone is near the surface. Well-records indicate that the formation is absent in the eastern and northeastern part of the Peninsula. The Formation consists essentially of limestone and has an estimated thickness of about 200 feet.

The Hawthorn Formation, of Miocene age, overlies the Tampa Limestone or in some places rests

NEVADA BUREAU OF MINES AND GEOLOGY

BULLETIN 73

GEOLOGY AND MINERAL DEPOSITS OF LINCOLN COUNTY, NEVADA

(Prepared cooperatively by the United States Geological Survey)

C.M. TSCHANZ and E.H. PAMPEYAN

MACKAY SCHOOL OF MINES
UNIVERSITY OF NEVADA, RENO

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Advanced Methods for Modeling Water-Levels and Estimating Drawdowns with SeriesSEE, an Excel Add-In

Techniques and Methods 4–F4

U.S. Department of the Interior
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JA_15552

Cover art: Screen showing SeriesSEE toolbar and example workbook that was created with SeriesSEE

SE ROA 50152

Advanced Methods for Modeling Water-Levels and Estimating Drawdowns with SeriesSEE, an Excel Add-In

By Keith Halford, C. Amanda Garcia, Joe Fenelon, and Benjamin Mirus

U. S. Department of Energy, National Nuclear Security Administration,
Environmental Restoration Program, Underground Test Area Project

Techniques and Methods 4–F4

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Suggested citation:
Halford, K., Garcia, C.A., Fenelon, J., and Mirus, B., 2012, Advanced methods for modeling water-levels and estimating drawdowns with SeriesSEE, an Excel add-In, U.S. Geological Survey Techniques and Methods 4–F4, 28 p.

Preface

This report documents a spreadsheet add-in for viewing time series and modeling water levels that was developed in Microsoft® Excel 2010. Use of trade names does not constitute endorsement by the U.S. Geological Survey (USGS). The spreadsheet add-in has been tested for accuracy by using multiple datasets. If users find or suspect errors, please contact the USGS.

Every effort has been made by the USGS or the United States Government to ensure the spreadsheet add-in is error free. Even so, errors possibly exist in the spreadsheet add-in. The distribution of the spreadsheet add-in does not constitute any warranty by the USGS, and no responsibility is assumed by the USGS in connection therewith.

Acknowledgments

The report was prepared in cooperation with the U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office, Office of Environmental Management under Interagency Agreement DE-AI52-12NA30865.

The tide-challenged authors are indebted to Devin Galloway for clarifying the ebb and flow of tides.

Contents

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Advanced Methods for Modeling Water-Levels and Estimating Drawdowns with SeriesSEE, an Excel Add-In

By Keith Halford, C. Amanda Garcia, Joe Fenelon, and Benjamin Mirus

Abstract

Water-level modeling is used for multiple-well aquifer tests to reliably differentiate pumping responses from natural water-level changes in wells, or "environmental fluctuations." Synthetic water levels are created during water-level modeling and represent the summation of multiple component fluctuations, including those caused by environmental forcing and pumping. Pumping signals are modeled by transforming step-wise pumping records into water-level changes by using superimposed Theis functions. Water-levels can be modeled robustly with this Theis-transform approach because environmental fluctuations and pumping signals are simulated simultaneously. Water-level modeling with Theis transforms has been implemented in the program SeriesSEE, which is a Microsoft® Excel add-in. Moving average, Theis, pneumatic-lag, and gamma functions transform time series of measured values into water-level model components in SeriesSEE. Earth tides and step transforms are additional computed water-level model components. Water-level models are calibrated by minimizing a sum-of-squares objective function where singular value decomposition and Tikhonov regularization stabilize results. Drawdown estimates from a water-level model are the summation of all Theis transforms minus residual differences between synthetic and measured water levels. The accuracy of drawdown estimates is limited primarily by noise in the data sets, not the Theis-transform approach. Drawdowns much smaller than environmental fluctuations have been detected across major fault structures, at distances of more than 1 mile from the pumping well, and with limited pre-pumping and recovery data at sites across the United States. In addition to water-level modeling, utilities exist in SeriesSEE for viewing, cleaning, manipulating, and analyzing time-series data.

Introduction

Multiple-well, aquifer testing provides the most direct, integrated assessment of bulk hydraulic properties within complex geologic systems (Bohling and others, 2003; Sepúlveda, 2006; Yeh and Lee, 2007; Walton, 2008). The aquifer volume investigated with multi-well aquifer tests increases with increasing distance at which drawdown, or the pumping signal, can be detected (Risser and Bird, 2003; Halford and Yobbi, 2006). Drawdown analyses at distances of more than 1 mile (mi) often fail because environmental water-level fluctuations typically overwhelm the pumping signal. Barometric change, tidal forces, surface-water stage changes, or other external stresses induce these natural water-level changes in wells, which collectively are referred to here as "environmental fluctuations."

Barometric change and tidal forces can induce water-level fluctuations in a well greater than 1 foot (ft) during periods of less than a few days (Fenelon, 2000). Daily barometric changes alone typically exceed 0.3 ft where aquifers are confined or the unsaturated zone is thicker than 500 ft (Weeks, 1979; Merritt, 2004). Episodic recharge events can cause water-level rises that exceed 1 ft (O'Reilly, 1998). Climatic variations in recharge can induce long-term rising trends of more than 3 feet per year that affect detection of small pumping signals (Elliott and Fenelon, 2010; Fenelon, 2000). Drawdowns can be a fraction of the environmental fluctuations in distant observation wells that are more than a mile from a pumping well.

Environmental fluctuations have been modeled previously to differentiate natural water-level changes from pumping responses. Barometric and tidal effects typically are modeled independently and removed from water-level records (Erskine, 1991; Rasmussen and Crawford, 1997; Toll and Rasmussen, 2007). These approaches do not remove regional trends, such as long-term recharge, and are difficult to automate because all significant stresses that affect water levels other than pumping are not simulated simultaneously.

Water levels from background wells can be used to explicitly model water-level changes from recharge responses, surface-water stage changes, or any other external stress (Halford, 2006; Criss and Criss, 2011). A background well monitors water levels that are affected by tidal potential-rock interaction, imperfect barometric coupling, and all other stresses, excluding analyzed pumping, that affect water levels in observation wells. The need for antecedent data and background water levels has long been recognized (Stallman, 1971), but these trends and corrections typically have been estimated qualitatively.

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Environmental fluctuations can be simulated as synthetic water levels, which represent the summation of multiple time series of barometric-pressure change, tidal potential, and background water levels, if available (Halford, 2006). Synthetic water levels are fitted to measured water levels for a period just prior to pumping, which should be more than three times greater than the period affected by pumping (Halford, 2006). Amplitude and phase of each time series are adjusted to minimize differences between synthetic and measured water levels. These synthetic water levels are projected into the pumping period, and drawdown is the difference between synthetic and measured water levels. This approach is referred to here as the "projection approach" to water-level modeling. The projection approach becomes unreliable where most of the analyzed period is affected by pumping.

Simultaneous modeling of environmental fluctuations and pumping signals overcomes the limitations of long-term extrapolation by using the projection approach. Environmental fluctuations can be defined during the entire period of record, which includes pumping and prolonged recovery periods. Variable pumping rates, as defined by a schedule of step changes, can be transformed to pumping signals by superimposing multiple Theis functions (Theis, 1935). Simultaneous simulation of all significant stresses affecting water-level changes is discussed as the "Theis-transform approach" to water-level modeling.

These water-level modeling approaches have been implemented in the program SeriesSEE, which is a Microsoft® Excel add-in. Water levels to be modeled, component fluctuations, and period of analysis are defined interactively and viewed in workbooks that are created by SeriesSEE. Water levels are modeled with a FORTRAN program that is called from Excel. Differences between synthetic and measured water levels are minimized with *PEST* (Doherty, 2010a and 2010b). Water-level models are calibrated rapidly because PEST files are created and executed seamlessly.

Water-level modeling with SeriesSEE differs from existing applications that filter environmental fluctuations or simulate pumping (Toll and Rasmussen, 2007; Harp and Vesselinov, 2011). This is because models of environmental fluctuations, Theis transforms, and parameter estimation are integrated in SeriesSEE. BETCO (barometric and earth tide correction) and similar programs simulate barometric and tidal water-level fluctuations but not regional trends and pumping effects (Toll and Rasmussen, 2007). Theis transforms have been applied previously in other water-level models, but environmental fluctuations were simulated with linear trends (Harp and Vesselinov, 2011).

Purpose and Scope

The purpose of this report is to document the approach used in SeriesSEE. This is the supporting software for modeling water levels that respond to environmental fluctuations and pumping. Water levels are modeled so pumping signals can be differentiated from environmental fluctuations. A method for fitting these water-level models to measured series by adjusting the selected parameters of each component is reported. The spreadsheet add-in is compatible with Microsoft® Excel 2010 (version 14.0) or higher. Use of the spreadsheet add-in requires basic knowledge of Excel. Use and applicability of this software is documented in this report. The hydrologic concepts and methods used in the data processing also are described briefly.

Environmental Fluctuations

Environmental fluctuations in measured water levels, or natural water-level changes, can be modeled by using pertinent time series, such as barometric pressure, tidal potential, background water levels, and stream stage. These time series represent potential components used to create synthetic water levels in a water-level model. Relevant components can be selected where a relation is expected with the water-level record. For example, water-level fluctuations in well b4mwh appear to be related to earth tide, barometric pressure fluctuations, recharge, and pumping (fig. 1). Simulating these environmental fluctuations in well b4mwh requires that earth tide, barometric pressure, and background water level (wells rw204 and sct4) components are included so that synthetic water levels can replicate measured water levels.

Barometric Effects

Barometric pressure induced water-level fluctuations are greatest in deep, confined aquifers where the rock matrix absorbs most of the atmospheric load (Merritt, 2004). Fluctuations increase because pressure instantly affects water levels in wells, whereas a stiff rock matrix transfers little of the increased atmospheric load to the confined water column. Atmospherically induced water-level fluctuations typically are less than 0.2 ft during a day. Large barometric-pressure changes from regional storms can cause water-level fluctuations of more than 1 ft during a week.

Barometric changes also measurably affect water levels in unconfined aquifers (Weeks, 1979). Pressure changes do not propagate instantaneously through the unsaturated zone because air is highly compressible. The relatively low pneumatic diffusivity of the unsaturated zone creates substantial phase lags between atmospheric and water-level changes. Unconfined water-level fluctuations can approach the magnitude of confined water-level fluctuations where the depth to water exceeds 500 ft. This is because atmospheric loading through the wellbore is not balanced by diffusion through the unsaturated zone.

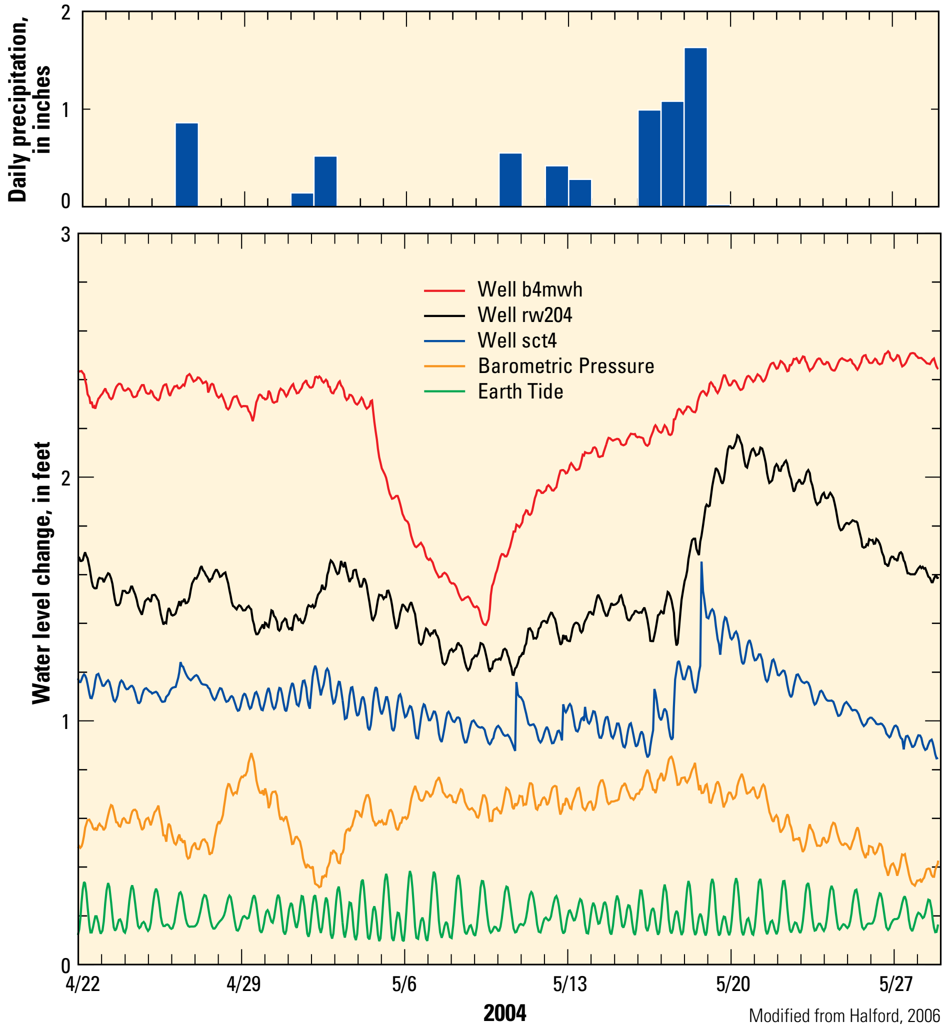

Figure 1. Daily precipitation, groundwater levels, barometric change, and earth tide at Air Force Plant 6, Marietta, Georgia, April 22 to May 28, 2004.

Tidal Effects

Tidal forces distort the crust of the earth, which creates water-level fluctuations in mid-continent wells (Bredehoeft, 1967; Marine, 1975; Hanson and Owen, 1982; Narasimhan and others, 1984). Earth tides periodically deform (dilate and compress) the skeleton of the aquifer system, changing the porosity and causing measurable water-level fluctuations of as much as 0.1 ft or more in wells penetrating aquifers with small storage coefficients (fig. 1). Coupling between the mechanical deformation and the fluid filling the secondary porosity amplifies water-level response in wells hydraulically connected to the secondary-porosity features, such as fractures or faults. The presence of secondary porosity typically renders the formation more compliant to imposed stresses, depending on orientation of the fractures or faults with respect to the principal component directions of the imposed stress. The theoretical crustal strain tensors that result from the two principal lunar daily and semidiurnal tides are largely horizontal and orthogonal to one another. Subvertical fractures with azimuths oriented perpendicular to the strain tensor for a particular tide tend to amplify the strain and, thereby, the water-level response (Bower, 1983).

The diurnal rise and fall of ocean levels are the most common manifestation of varying gravitational forces and are referred to as ocean tides. Ocean tides affect coastal groundwater levels through direct head changes in an aquifer or as loads applied through a confining unit (Merritt, 2004). Ocean-tide effects are better approximated with a nearby tidal gage than calculated tides because wind and coastal geometry also affect ocean tides in addition to direct gravitational forcing.

Background Water Levels

Recharge events, regional pumping, and change in surface-water stage are identifiable stresses that typically affect large areas but are not predicted easily with independent time series such as barometric change and tidal potential. Recharge events and regional pumping stresses can create similar water-level changes in multiple wells over areas of many square miles. Change in surface-water stages locally affects groundwater levels and can be measured directly. Water levels in wells sufficiently removed from an aquifer test can simulate these regional stresses, local changes in surface-water stages, and any other unidentified pervasive stresses. Water levels in these remote wells are referred to as background water levels (Halford, 2006).

Background water levels can be more effective correctors than independent barometric and tidal time series even where only barometric and tidal stresses are significant (Halford, 2006). Barometric forcing through the unsaturated zone lags behind water-level changes because of the small permeability of unsaturated rock relative to an open well (Weeks, 1979). The complex relation between barometric pressure and water level in a well is explained poorly with barometric efficiency where the unsaturated zone is thick. Background water levels from another well of similar construction better approximate this relation. Likewise, rock properties and fracture orientation in an aquifer control tidal water-level fluctuations as much as tidal forcing. Water levels from background wells can better approximate the rock-tide interaction than theoretical tidal components alone. Independent barometric and tidal time series frequently remain necessary because of differences in rock properties, fracture orientation, and well completions around measured and background wells.

Water-Level Modeling

Water-level modeling assumes that measured water-level fluctuations can be approximated by summing multiple-component fluctuations (Halford, 2006). Input series of barometric pressure, input series of background water levels, and computed earth tides explain most environmental fluctuations (fig. 2). Pumping signals are simulated with multiple Theis solutions that transform pumping schedules to water-level fluctuations.

Water-level model components are summed to create a synthetic water level. A synthetic water level at time, t, is determined:

$$SWL(t) = C_0 + \sum_{i=1}^{n} WLMC_i \qquad (1)$$

where

C_0 is an offset (L) that allows mean values of synthetic water levels to match mean values of measured water levels,

n is the number of water-level model (WLM) components, and

$WLMC_i$ is the i[th] WLM component in units of the modeled water level.

Water-level model results are denoted with the word synthetic rather than simulated to differentiate between water-level and groundwater-flow model results.

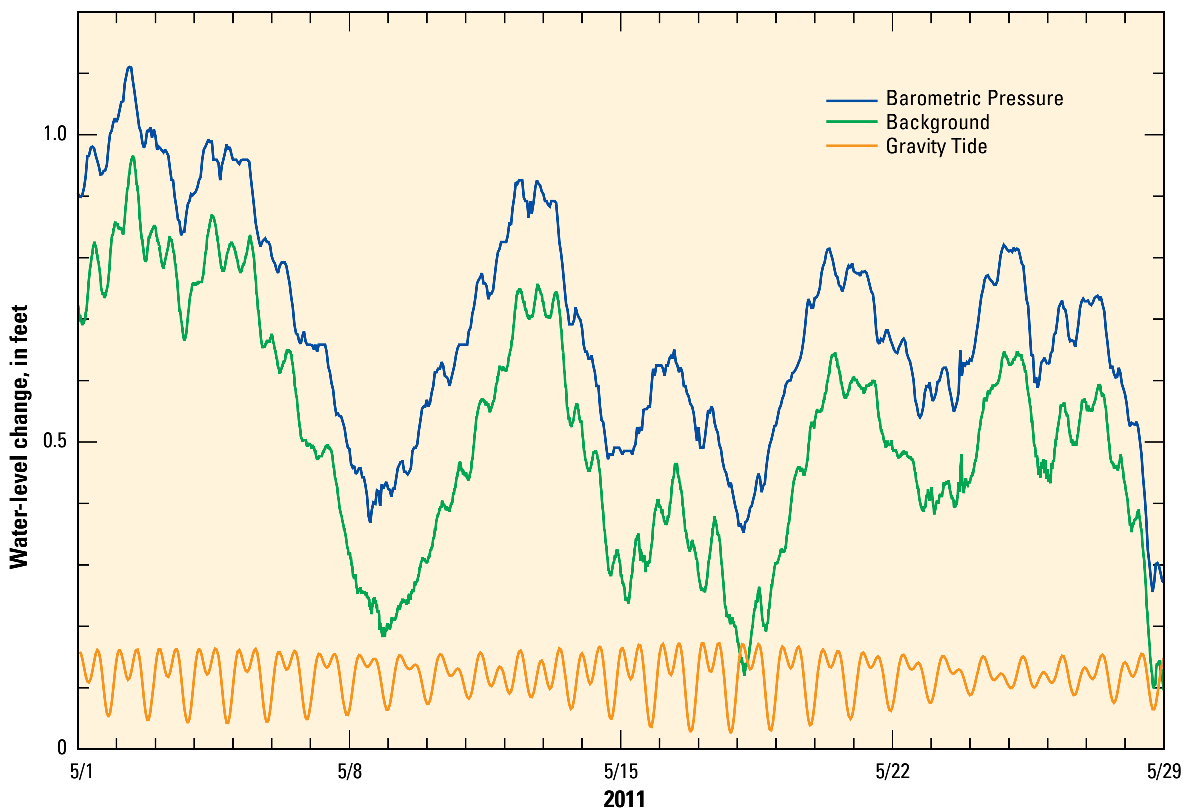

Figure 2. Input series of barometric pressure, input series of background water level, and computed gravity tide.

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Water-Level Model Components

Input series are measured water levels, barometric pressures, or pumping schedules that are transformed to represent water-level change. All input series are assumed to be continuous between each discrete measurement where continuity can be piecewise linear or stepwise. Water levels and barometric pressures typically are used as piecewise linear functions. Pumping schedules typically are used as stepwise functions. All input series are transformed into WLM components that are smooth, differentiable functions.

WLM components are created from input series with one of six transforms. The parameters that define each transform generically are referred to as coefficients because characteristics and terminology are not consistent among transforms (table 1). Moving averages are most frequently used to transform interpolated time series of barometric pressure and background water levels into WLM components. Pumping schedules are transformed into water-level fluctuations with Theis transforms. Earth tides are computed for a given observation well location (Harrison, 1971). Transducer displacement, as a result of resetting a transducer in a well, is simulated with the step transform following a user-specified time. Lag and attenuation of barometric-pressure changes between land surface and water table are simulated with the pneumatic-lag transform. Water-level rises from infiltration events are simulated with the gamma transform.

WLM components are smooth functions because values are interpolated linearly between consecutive data pairs or transformed from stepwise data to a smooth function. Interpolation or transformation allows data to be collected at variable intervals within a time series. Collection frequencies can differ among time series and do not need to be synchronized because interpolation or transformation synchronizes comparisons (fig. 3).

Moving Average

Fluctuations of different frequencies exist in input series such as barometric changes and background water levels. Barometric changes exhibit diurnal, weekly, and seasonal fluctuations that differ in amplitude and frequency. Frequency-dependent differences in water-level fluctuations also exist between wells because of differences in well construction and aquifer properties. Diurnal water-level fluctuations will be less where communication between well and aquifer is impeded and wellbore storage is increased. Poorly developed wells with large casing diameters and short screens damp high-frequency water-level fluctuations. Aquifers with large storage coefficients and small transmissivity values also will damp water-level fluctuations.

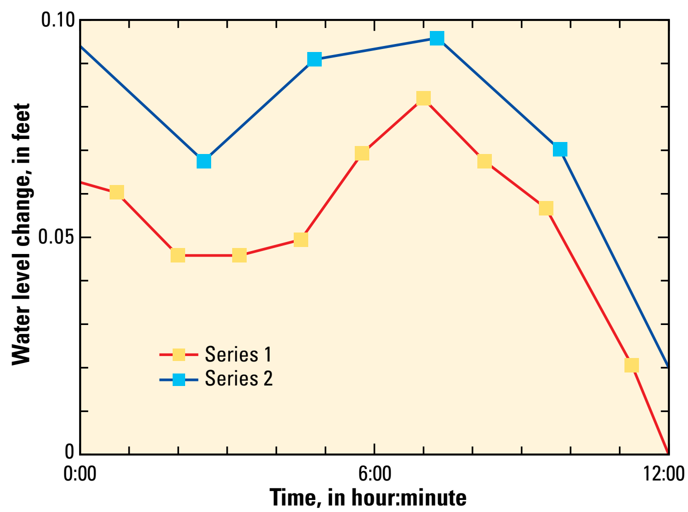

Figure 3. Two time series with different collection frequencies and sampling times.

Table 1. Water-level model (WLM) components.

[— is not applicable]

WLM component	Time series	Coefficient 1	2	3	4	5
Moving average	Any series	Multiplier	Phase	Averaging period	—	—
Theis transform	Pumping schedule	Transmissivity	Storage coefficient	Radial distance	Flow-rate conversion	—
Tide	Computed	Multiplier	Phase	Latitude	Longitude	Altitude
Step	—	Time	Offset	—	—	—
Pneumatic lag [a]	Barometric pressure	K_{AIR}	S_{AIR}	Thickness of unsaturated zone	—	—
Gamma[1]	Infiltration	Multiplier	k	n	Time conversion	Multiplication series

[a] Hydraulic properties of the Pneumatic-lag transform, K_{AIR} & S_{AIR}, are with respect to air. K_{AIR} is hydraulic conductivity of air and is about 60 times greater than K_{WATER}.S_{AIR} is average air-filled porosity divided by mean air pressure.

[1] The k and n terms represent scale and shape parameters, respectively in the Gamma Probability Distribution Function.

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Input series frequently are composed of multiple signals of different frequencies. These different frequencies can be separated into multiple WLM components with multiple moving averages of the input series (fig. 4). Water levels can be averaged over periods of hours to days where duration of averaging periods and the number of WLM components are arbitrary quantities. More than a half dozen WLM components frequently are created from a single input series because a broad range of averaging periods are more likely to simulate the environmental fluctuations. An excess of WLM components generally does not degrade results. High-frequency signals are approximated indirectly by summing multiple WLM components with ranges of averaging periods. The original input series and WLM component are one and the same where an averaging period of 0 is specified (table 1).

The moving-average transform is applied to i[th] WLM component at time, *t*:

$$WLMC_i = a_i V_i (t + \phi_i) \qquad (2)$$

where

- a_i is the amplitude multiplier of the i[th] component in units of the modeled water level divided by units of the i[th] component,
- Φ_i is the phase-shift of the i[th] component (*t*), and
- $V_i(t+\Phi_i)$ is the value of the moving average of i[th] input series at time $t+\Phi_i$ in units of i[th] component.

Amplitude (a) and phase (Φ) are estimated in equation 2 to minimize differences between synthetic and measured water-levels.

Moving averages are centered about the evaluation time, t, where averaging periods are defined by time, not the number of measurements. For example, a 12-hr, moving average at the time when sampling increased from hourly to 15-minute measurements would average 31 values. Six values were measured prior to the evaluation time, another value was measured at the evaluation time, and 24 values were measured after the evaluation time.

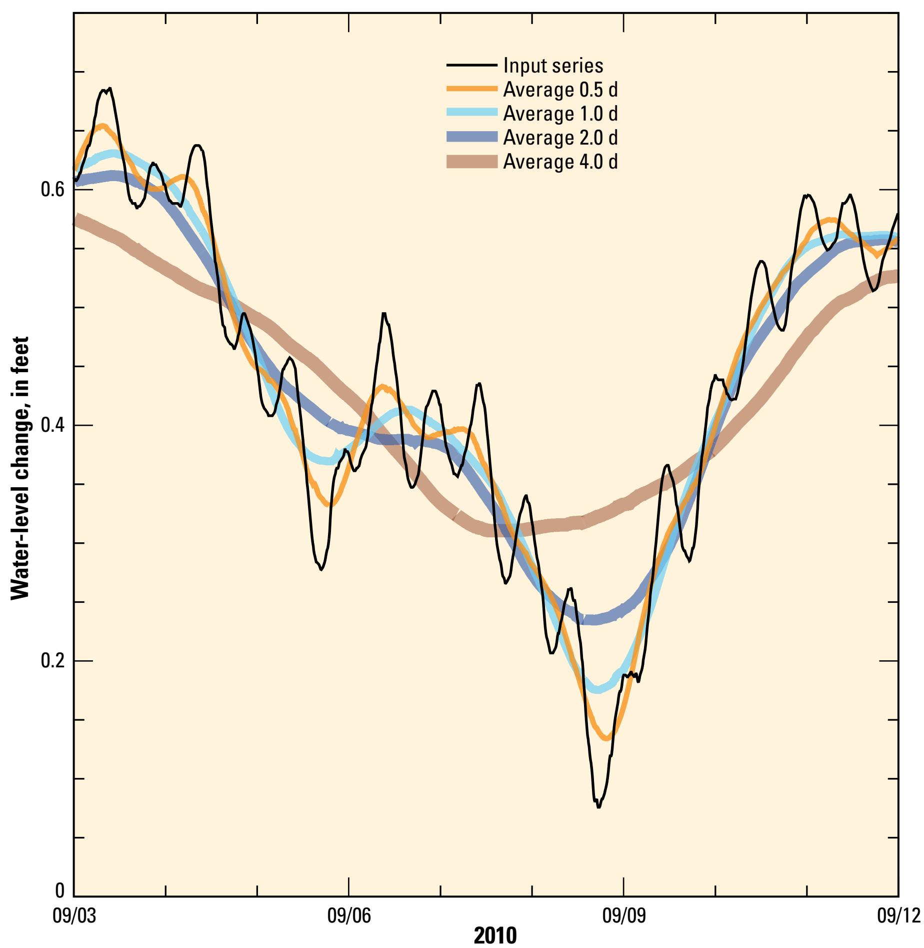

Figure 4. Input series and four additional water-level model components that were created by averaging in periods of 0.5, 1, 2, and 4 days (d).

Theis Transform

Pumping schedules are converted into water-level responses with a simple model: the Theis (1935) solution. Water-level changes or drawdown, s, from pumping-rate changes are simulated:

$$WLMC_i = s = \frac{Q}{4\pi T}W(u) = \frac{Q}{4\pi T}W\left(\frac{r^2 S}{4T\Delta t}\right) \quad (3)$$

where

- Q is the flow rate (L^3/t),
- T is the transmissivity (L^2/t),
- $W(u)$ is the exponential integral solution,
- u is dimensionless time,
- r is the radius (L),
- S is the storage coefficient (dimensionless), and
- Δt is the elapsed time since the flow rate changed (t).

Multiple Theis solutions are superimposed in time to simulate water-level responses to variable pumping schedules (fig. 5). The effects of multiple pumping wells also can be simulated by superposition in space (Harp and Vesselinov, 2011). Each pumping well with its unique pumping schedule and radial distance is simulated with a WLM component in SeriesSEE. Pumping signals are discussed here as drawdowns, regardless of pumping rate, because discrete drawdown and recovery periods do not exist when variable pumping schedules are simulated.

Superimposed Theis solutions serve as transform functions, where step-wise pumping records are translated into approximate water-level responses at observation wells. Log-transforms of transmissivity (T) and storage coefficient (S) are estimated in equation 3 to minimize differences between synthetic and measured water-levels. Estimates of T and S can characterize correctly the hydraulic properties of an aquifer if assumptions of the Theis solution are honored. These same

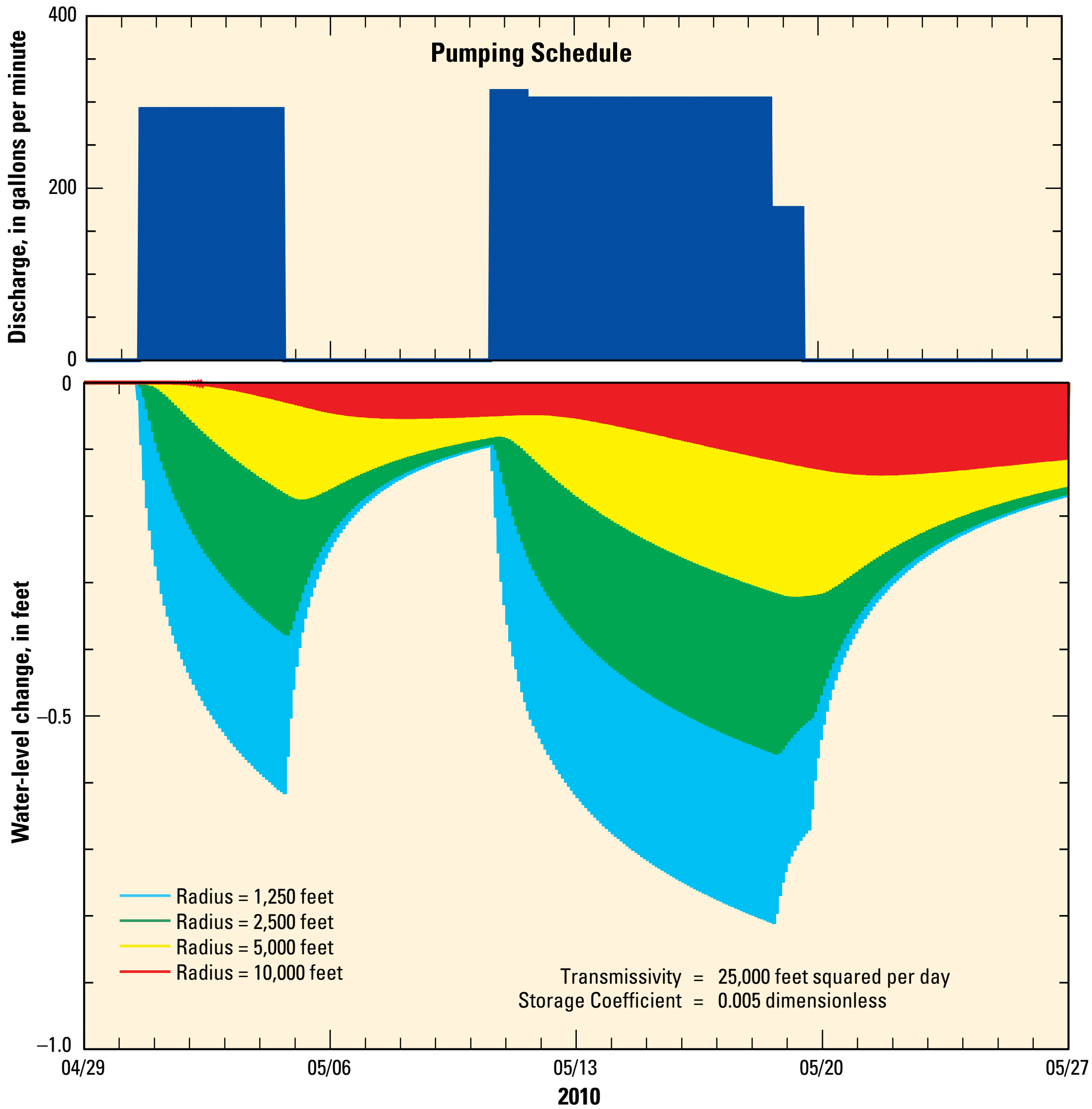

Figure 5. Theis transform of a pumping schedule to water-level changes at radial distances between 1,250 and 10,000 feet from a pumping well for a fixed transmissivity and storage coefficient.

parameters primarily are fitting terms with little physical significance in hydrogeologically complex aquifer systems because assumptions of the Theis solution are violated. This component of the water-level model is referred to as a "Theis transform," here, and applies to the pumping schedule of a single well.

Hydrogeologic complexity and uncertainty are addressed by applying multiple Theis transforms to a single pumping schedule. Relatively fast and slow elements of pumping signals propagate through complex aquifer systems. These fast and slow elements are approximated by Theis transforms with relatively high and low hydraulic diffusivities, respectively.

Computed Tides

The tides are displacements of the particles in a celestial body caused by the forces of attraction in a neighboring body. The terrestrial tides on Earth consist of the atmospheric tides, the earth tides, and the ocean tides and are related to the lunar and solar cycles (Defant, 1958). Simulated tidal forcing and body tides of a solid Earth (oceanless) produced by the moon and sun are computed from gravitational and astronomical theory for a specified point on the Earth for a specified time by using the Harrison (1971) model. Changes in the solid Earth caused by the ocean tides are not considered here. Many of the model parameters, and thus the computed tidal components, are functions of time based on the ephemerides, which are computed in the model but are not included here explicitly.

The earth tides result as the crust undergoes volumetric strains, ε_V, due to variations in tide-generating forces:

$$\varepsilon_V = \frac{1}{3}\left(\varepsilon_{\theta\theta} + \varepsilon_{\lambda\lambda} + \varepsilon_{rr}\right) \qquad (4)$$

where, $\varepsilon_{\Theta\Theta}$, $\varepsilon_{\lambda\lambda}$, and ε_{rr} (positive downwards) represent the principal components of the strain-tide tensor with respect to polar north, east, and radial, respectively. Most of the stress close to the Earth's surface is plane stress, and the resultant strain tide is predominately an areal strain, ε_A (Melchior, 1966:

$$\varepsilon_A = \frac{1}{2}\left(\varepsilon_{\theta\theta} + \varepsilon_{\lambda\lambda}\right) \qquad (5)$$

The areal strain produced by earth tides is computed from theoretical considerations (Harrison, 1971, 1985; Beaumont and Berger, 1975; Berger and Beaumont, 1976) by using the tidal potential, V (L^2/t^2), as formulated by Bartels (1957, 1985) and computed by Harrison (1971):

The areal strain tide component is formulated as a scaled function of the tidal potential (Munk and McDonald, 1960; Melchior, 1966, Bredehoeft, 1967):

$$\varepsilon_A = \left(2\bar{h} - 6\bar{l}\right)\frac{V}{rg} \qquad (7)$$

where

$\bar{h}$ and $\bar{l}$ are Love numbers at the Earth's surface, and
g is the gravitational acceleration (L/t^2).

Areal strain tide is computed by using $\bar{h}$ = 0.638 and $\bar{l}$ = 0.088 and is expressed in parts per billion strain (dimensionless). The resulting areal 'dry' (in the absence of saturating fluid) tidal dilatation at the Earth's surface, Δ_t can be expressed (Bredehoeft, 1967):

$$\Delta_t = \left[\frac{1-2v}{1-v}\right]\varepsilon_A \qquad (8)$$

where v is Poisson's ratio.

The gravity tide oriented downwards normal to the Earth's ellipsoid, g_N, is computed (Harrison, 1971):

$$g_N = \frac{\partial V}{\partial r} - \delta\frac{\partial V}{r\partial\theta} \qquad (9)$$

where

Θ is the geocentric polar angle of the observation point (radians), and
δ is the difference between the geodetic and geocentric latitudes.

For example, δ attains a value of about 3.37 × 10^{-3} radians at 45° latitude. Gravity tide is expressed in terms of microgals (L/t^2).

The tilt tide in a plane tangent to the Earth's ellipsoid along a specified azimuth oriented with respect to 0° N, γ_T is computed (Harrison, 1971):

$$\gamma_T = \frac{1}{g}\left[\left(\frac{\partial V}{r\partial\theta} + \delta\frac{\partial V}{\partial r}\right)\cos\alpha + \frac{1}{r\sin\theta}\frac{\partial V}{\partial\lambda}\sin\alpha\right] \qquad (10)$$

where

λ is the terrestrial east longitude of the observation point (radians) and
α is the specified azimuth of tilt (radians).

Tilt tide is expressed in nanoradians.

$$V = \frac{GMr^2}{R_s^3}\left\{\frac{3\cos^2 z_m - 1}{2} + \frac{r}{R_m}\frac{5\cos^2 z_m - 3\cos^2 z_m}{2}\right\} + \frac{GSr^2}{R_s^3}\left\{\frac{3\cos^2 z_s - 1}{2}\right\} \qquad (6)$$

where

G is the Newtonian constant of gravitation ($L^3 / M^1\text{-}t^2$),
M and S are the masses of the moon and sun, respectively (M),
r is the distance between the center of the Earth and the observation point on the Earth's surface (L),
R_m and R_s are the distances of the moon and sun, respectively, from the Earth's center (L), and
z_m and z_s are the zenith angles of the moon and sun, respectively (radians).

Dry, gravity, and tilt tides (Table 2) result from changes in gravitational forces as the relative positions of the sun, moon, and earth change (Harrison, 1971). These theoretical earth tides are computed functions that only require the location of an observation well.

Adjustable WLM components are created by multiplying computed dry, gravity, or tilt tide (table 2) by an amplitude. Zenith angles primarily are specified by longitude and time as referenced to Greenwich Mean Time. A phase shift can be applied to the zenith angles through the specified time. Amplitude (a) and phase (Φ) are estimated to minimize differences between synthetic and measured water-levels.

Step Change

Step changes in water-level records are introduced when a transducer is disturbed or replaced. Transducer submergence can change if the hanger position is moved. Replacing a transducer is likely to change submergence because the devices can differ and cable stretch can occur. A step-change WLM component is necessary because shifts of less than 0.03 ft are detectable in WLM results.

A step change in the water-level measurement is simulated as follows:

$$WLMC_i = \Delta h_i \quad \text{for } t \geq t_{STEP}$$
$$WLMC_i = 0 \quad \text{for } t < t_{STEP} \qquad (11)$$

where

Δh_i is the step change of the i[th] component and t is the time. The step change is estimated in equation 11 to minimize differences between synthetic and measured water-levels.

Pneumatic Lag

The pneumatic lag between barometric-pressure changes at land surface and the water table can be simulated with a one-dimensional diffusion equation instead of being approximated with multiple moving averages. This alternative approach is advantageous for estimating the hydraulic properties of the unsaturated zone and precludes using multiple moving averages of barometric pressure. The propagation of barometric changes through the unsaturated zone is solved analytically by using equivalent solutions for surface-water/groundwater interaction (Rorabaugh, 1964; Barlow and Moench, 1998).

Stage changes of a fully penetrating river that perturb groundwater levels behave similarly to barometric pressure changes that perturb air pressures in the unsaturated zone (fig. 6). This assumes that pressure changes are small relative to the mean air-pressure so air density and specific storage are affected minimally. Barometric changes typically are less than 2 ft while mean air-pressure ranges between 26 and 34 ft (Merritt, 2004; Fenelon, 2005). Boundary conditions for a one-dimensional, confined aquifer are equivalent to boundary conditions of an areally extensive, thick unsaturated zone. The water table is an impermeable boundary because air-filled pores cease to exist.

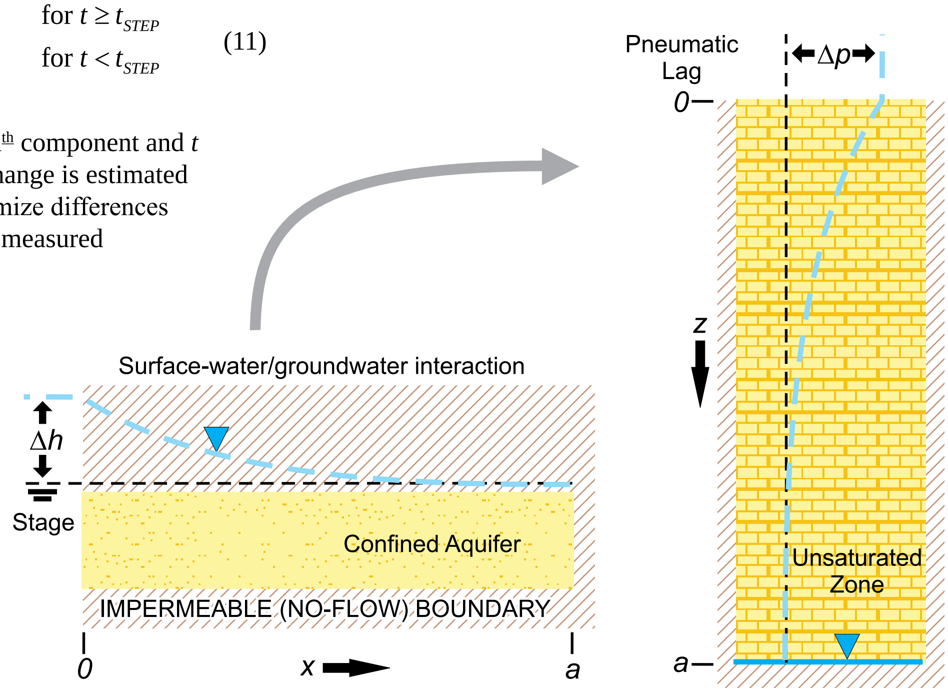

Figure 6. Schematics of one-dimensional, confined aquifer and an areally extensive, thick unsaturated zone that experience similar step-changes to a time-varying specified-head boundary such as a river or barometric-pressure difference.

Table 2. Abbreviations and descriptions of tides that are computed in SeriesSEE.

Tide	DESCRIPTION	Units	Equation
DRY	Areal strain tide	parts per billion	8
GRAVITY	Normal to the Earth ellipsoid	microgals	9
TILT	Plane tangent to the Earth ellipsoid	nanoradians	10

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Equivalent hydraulic conductivity and specific storage of the unsaturated zone differ from the confined aquifer solution because the pores are filled with air rather than water. Equivalent hydraulic conductivity is air permeability divided by the viscosity of air and is about 60 times greater than saturated hydraulic conductivity because the ratio of water-to-air viscosity ranges from 70 to 40 for temperatures between 10 and 30°C. Air permeability is affected negligibly by changes in barometric pressure (Baehr and Hult, 1991). Specific storage of the unsaturated zone is the air-filled porosity divided by the mean air pressure.

Pressure change at a given depth in the unsaturated zone from a step-change in pressure at land surface is simulated as follows:

$$WLMC_i = \Delta p - 2\sum_{m=1}^{\infty} \frac{-1^{m+1}}{\left(\pi m - \frac{1}{2}\right)} e^{-\pi^2\left(m-\frac{1}{2}\right)^2 \frac{\Delta t K_{AIR}}{S_{AIR} a^2}} \cos\left(\pi\left(m-\frac{1}{2}\right)\left(1-\frac{z}{a}\right)\right) \qquad (12)$$

where

- Δp is the step change in air pressure at land surface (L),
- m is an index,
- Δt is elapsed time since the step change (t),
- K_{AIR} is the air permeability divided by viscosity of air (L/t),
- S_{AIR} is air-filled porosity divided by the mean air-pressure (1/L), and
- a is the thickness of the unsaturated zone (L).

Multiple step changes are superimposed in time to simulate air-pressure changes at the water table by using barometric-pressure changes at land surface (fig. 7).

Water-table changes are assumed equal and opposite of air-pressure changes at the water table. Log-transforms of K_{AIR} and S_{AIR} are estimated in equation 12 to minimize differences between synthetic and measured water-levels. If the objective of a water-level model is to estimate hydraulic properties of the unsaturated zone by using equation 11, then multiple moving averages of barometric pressure cannot be used as WLM components.

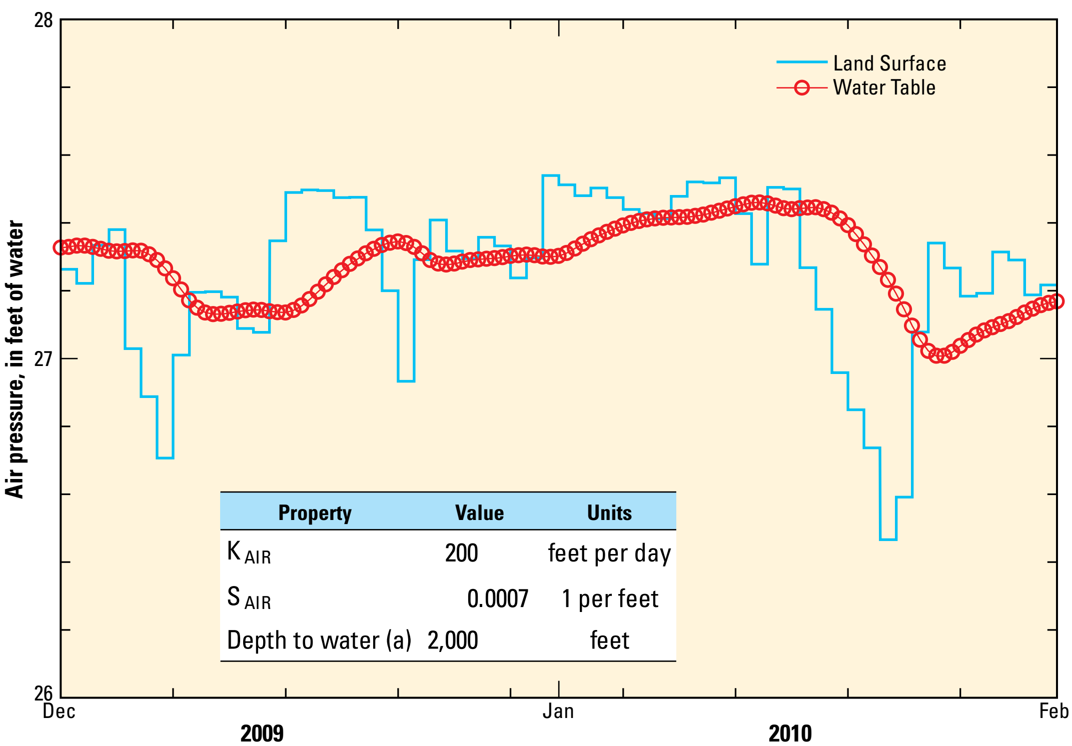

Figure 7. Average daily barometric pressure and simulated air pressure at the water table.

Gamma Transform

The gamma transform was adapted from a Water-Balance/Transfer Function (WBTF) model that simulates recharge to the water table from precipitation (O'Reilly, 2004). The gamma transform retains the transfer function from the WBTF model that translates a discrete pulse of infiltration below the root zone to recharge at the water table. The delay between infiltration and recharge at the water table increases as unsaturated-zone thickness increases. Recharge pulses also are attenuated and prolonged as unsaturated-zone thickness increases. The WBTF model was selected because the transfer function simulates these characteristics (O'Reilly, 2004).

Water-level rise, rather than recharge, is simulated with the gamma transform. Water-level rise equals recharge divided by specific yield, where the aquifer is unconfined, and consequently has a greater magnitude than recharge (fig. 8).

Water-table rise from each infiltration event is simulated as follows:

$$WLMC_i = a_i I \frac{e^{-\frac{\Delta t}{k}}}{k\Gamma(n)} \left(\frac{\Delta t}{k}\right)^{n-1} \qquad (13)$$

where

- a_i is the amplitude multiplier of the ith component,
- I is amount of infiltration during an event (L),
- Δt is elapsed time since the infiltration event(t),
- k is a scale parameter (t),
- n is a shape parameter (dimensionless) , and
- $\Gamma(n)$ is the gamma function, (dimensionless), which is equivalent to (n – 1) for integer values of *n* (Potter and Goldberg, 1987, p. 111).

Multiple step changes are superimposed in time to simulate water-table fluctuations from infiltration events below land surface (O'Reilly, 2004).

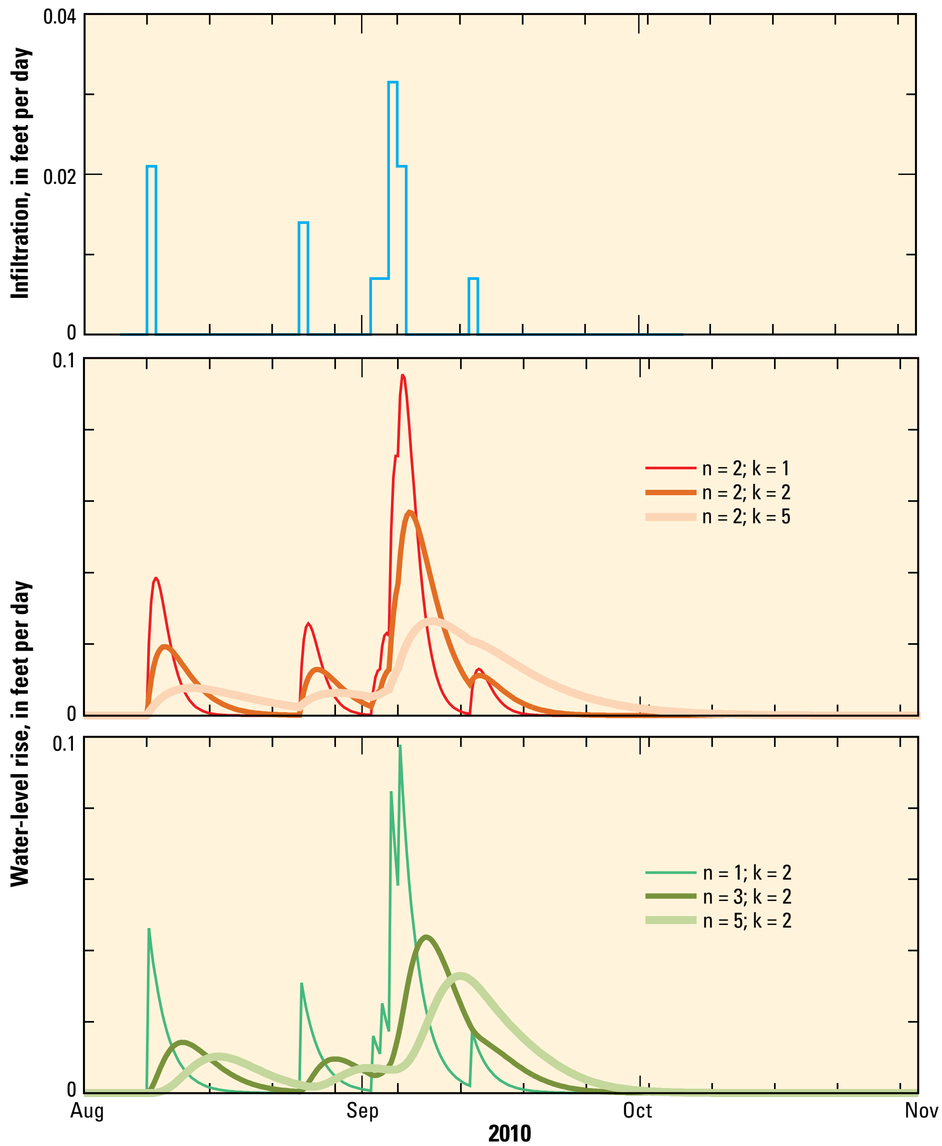

Figure 8. An infiltration schedule and water-level rises simulated with gamma transforms that were defined by six pairs of shape (n) and scale (k) parameters.

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Physical significances have been attributed to the fitting parameters a_i, k, and n (O'Reilly, 2004). The amplitude multiplier (a_i) converts recharge to water-level rise and should be proportional to the inverse of the storage coefficient. The scale parameter (k) controls the average delay time imposed by the unsaturated zone (Dooge, 1959). The shape parameter (n) has been characterized as "the number of linear reservoirs necessary to represent the unsaturated zone" by O'Reilly (2004). These explanations are interesting, but estimated values of a_i, k, and n should be interpreted with great skepticism, if at all.

Superimposed gamma transforms translate step-wise precipitation or infiltration records into approximate water-level responses at observation wells. Amplitude (a) and the log-transform of the scale parameter (k) are estimated in equation 13 to minimize differences between synthetic and measured water-levels. The shape parameter (n) is assigned and is not estimated. Multiple gamma transforms should be used with different values of n if the effect of n is investigated.

Calibration

Water-level models must be calibrated to reliably differentiate small pumping responses from environmental fluctuations. Efficient and effective calibration requires a quantitative measure of model misfit so model parameters can be estimated automatically as is done with the parameter estimation software PEST (Doherty, 2010a, 2010b). Differences between synthetic and measured water levels, or residuals, define the goodness-of-fit and are summed in the measurement objective function:

$$\Phi(x)_{MEAS} = \sum_{j=1}^{nobs} \left(SWL(x)_j - MWL_j \right)^2 \qquad (14)$$

where

x	is the vector of parameters being estimated,
nobs	is the number of observations compared,
$SWL(x)_j$	is the j^th synthetic water level, and
MWL_j	is the j^th measured water level.

Although the sum-of-squares error serves as the measurement objective function, root-mean-square (RMS) error,

$$RMS = \sqrt{\frac{\Phi(x)_{MEAS}}{nobs}} \qquad (15)$$

is reported because RMS is easily compared to measurements.

Residuals are not weighted in the measurement objective function because suspect measured water levels should be discarded rather than assigned a low weight. Each measured water level is assumed equally important so all water levels are weighted equally. Uniform weighting causes differences between synthetic and measured water levels to equally affect the measurement objective function (eq. 14).

Stable parameter-estimation results are ensured with selective parameter transformation and regularization. Log-transforms of hydraulic properties are estimated in the Theis, pneumatic lag, and gamma transforms to scale parameters and precluded negative hydraulic properties (table 3). Regularization avoids estimating insensitive parameters and guides estimates toward preferred values. Parameter estimates have little to no significance because the parameter values generally are not interpreted. Drawdown estimates are interpreted and are the ultimate water-level model result.

Parameter estimation for water-level modeling is unconditionally stable because singular-value decomposition (SVD) regularization is used (Doherty and Hunt, 2010). Insensitive or highly correlated parameters are not estimated and remain at their assigned values if eliminated by SVD regularization.

Tikhonov regularization guides estimates to preferred conditions (Doherty, 2010a, 2010b). Regularization observations are added to define preferred relations between parameters (Doherty and Johnston, 2003). Homogeneity within each of the three parameter groups of amplitude, phase, and hydraulic property was the preferred relation that was enforced with Tikhonov regularization (table 3).

The balance between fitting measurement and regularization observations is controlled by the sum-of-squares measurement error, PHIMLIM, in PEST (Doherty, 2010a, 2010b). An expected RMS error defines PHIMLIM, which equals the square of the expected RMS error times the number of measured water levels (*nobs*). The expected RMS error defaults to 0.003 (L) in SeriesSEE, but can be changed by the user.

Table 3. Summary of estimable parameters and parameter groups for water-level modeling (WLM) components.

[— is not applicable]

WLM component	Coefficient 1	Parameter group	Coefficient 2	Parameter group
Moving Average	a	Amplitude	ϕ	Phase
Theis Transform	T	Hydraulic Property	S	Hydraulic Property
Tide	a	Amplitude	ϕ	Phase
Step	—	—	a	Amplitude
Pneumatic Lag	K_{AIR}	Hydraulic Property	S_{AIR}	Hydraulic Property
Gamma	a	Amplitude	*k*	Hydraulic Property

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Drawdown Estimation

Drawdown estimates from a water-level model are the difference between measured water levels and synthetic water levels without the Theis transforms. Alternatively, drawdowns can be computed directly by summing all Theis transforms and subtracting residuals (fig. 9). The summation of all Theis transforms is the direct estimate of the pumping signal. Residuals represent all unexplained water-level fluctuations. These fluctuations should be random residuals during non-pumping periods, but can contain unexplained components of the pumping signal during pumping and recovery periods. This method of estimating drawdowns is called the Theis-transform approach.

A limited, application of water-level modeling, the projection approach, was developed prior to the Theis-transform approach (Halford, 2006). Synthetic water levels were developed and calibrated during a period prior to pumping with the projection approach. Calibrated, synthetic water levels were then projected forward during pumping and recovery. Drawdown was the difference between projected synthetic values and measured values. This approach ensures that environmental fluctuations and the pumping signal are uncorrelated because pumping is not simulated during model calibration to antecedent water levels.

The projection approach is limited primarily because regional water-level trends are simulated poorly. Excluding pumping and recovery periods from WLM calibration eliminated much of the regional trends from the calibration period. This drawback weakened the projection approach and limited the usefulness of background well information, particularly where pumping and recovery periods were greater than the antecedent data period.

The Theis-transform approach is a more robust application of water-level modeling because environmental fluctuations and pumping signal are simulated during pumping and recovery in addition to antecedent water levels. This allows for calibration of synthetic water-levels to all measured data. The effects of pumping on measured water levels are approximated by using a simple approach, Theis transforms, so that simulations are quick. Efficiency and speed are mandatory because water levels are modeled independently in every observation well. These requirements preclude numerical groundwater-flow models or any other laborious approach for translating pumping schedules to water-level responses.

Drawdown detection with the Theis-transform approach becomes ambiguous when the signal-to-noise ratio is low or where environmental fluctuations and pumping signals can be correlated. Signal and noise are defined herein as the maximum drawdown in a well during an aquifer test and the RMS

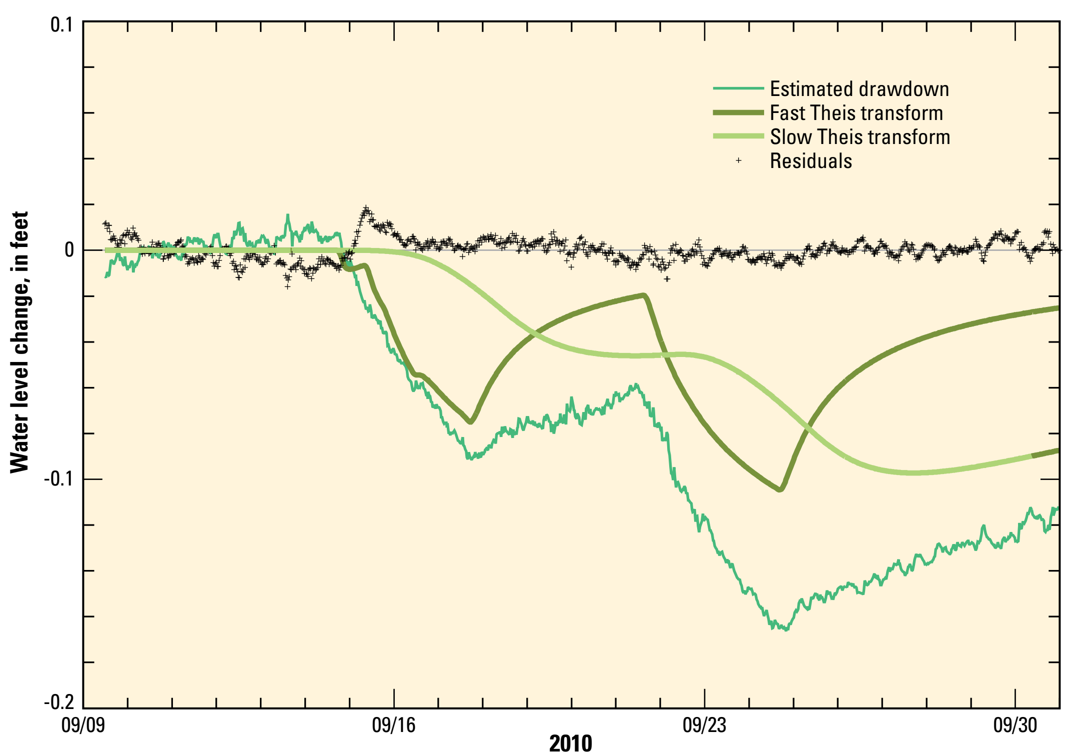

Figure 9. Estimated drawdown from summing Theis transforms and subtracting residuals. Fast and slow Theis transforms represent the relatively fast and slow elements of pumping signals that propagate through a complex aquifer system.

error, respectively. Drawdown has been detected definitively where the signal-to-noise ratio was greater than 10 and correlation was unlikely. Correlation is unlikely where sharply defined pumping signals (saw-tooth shape) exist or considerable recovery has been observed (fig. 10, ER-EC-6 deep, r = 6,800 ft). Correlation between environmental fluctuations and the pumping signal is possible where observed drawdown can be approximated by a linear trend during all or part of the period of analysis (fig. 10, ER-EC-12 shallow, r = 8,900 ft). The potential for correlation increases as hydraulic diffusivity decreases, distance between observation and pumping well increases, or recovery diminishes.

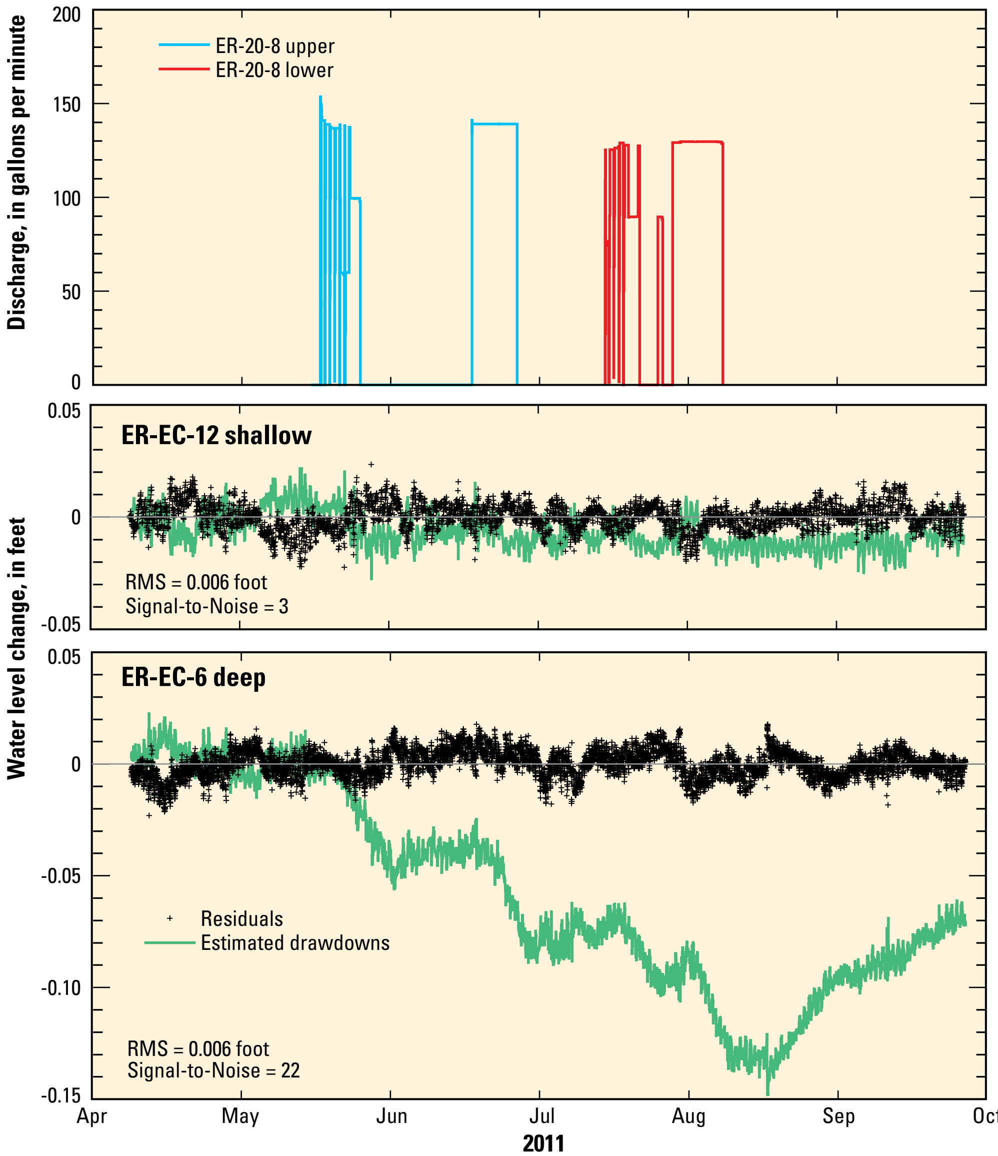

Figure 10. Discharge from pumping wells ER-20-8 upper and ER-20-8 lower, estimated drawdowns, residuals, RMS errors, and signal-to-noise ratios in observation wells ER-EC-12 shallow and ER-EC-6 deep.

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SeriesSEE

SeriesSEE is a Microsoft® Excel add-in for viewing, cleaning, manipulating, and analyzing time-series data where water-level modeling is a primary analysis tool. SeriesSEE creates a viewer file from a data workbook that can contain more than 16,000 series. The maximum number of series that can be viewed simultaneously is limited to twelve. Time series are displayed on two charts where all data are shown in one chart, and a magnified subset is shown in the other chart (fig. 11). Borehole geophysical logs also can be viewed, cleaned, manipulated, and analyzed with SeriesSEE, where the two charts are displayed top-to-bottom, rather than left-to-right. SeriesSEE software, installation instructions, and help for all tools can be downloaded in the zipped file, which is described in appendix A.

All source code that was developed for SeriesSEE can be downloaded freely (appendix B). All utilities, except WLM, are processed exclusively with VBA code in the SeriesSEE add-in or supporting add-in files named ***SSmodule_*.SerSee***. Source codes for these files are in the VBA folder of appendix B and are named ***SSmodule_*.xlsm***. Water levels to be modeled, input series, and period of analysis are defined with VBA routines. WLM components are transformed (table 1) and water levels are simulated with the FORTRAN program ***WLmodel,*** which reads ASCII files written by VBA programs. Differences between synthetic and measured water levels are minimized with *PEST* (Doherty, 2010a, 2010b). A copy of

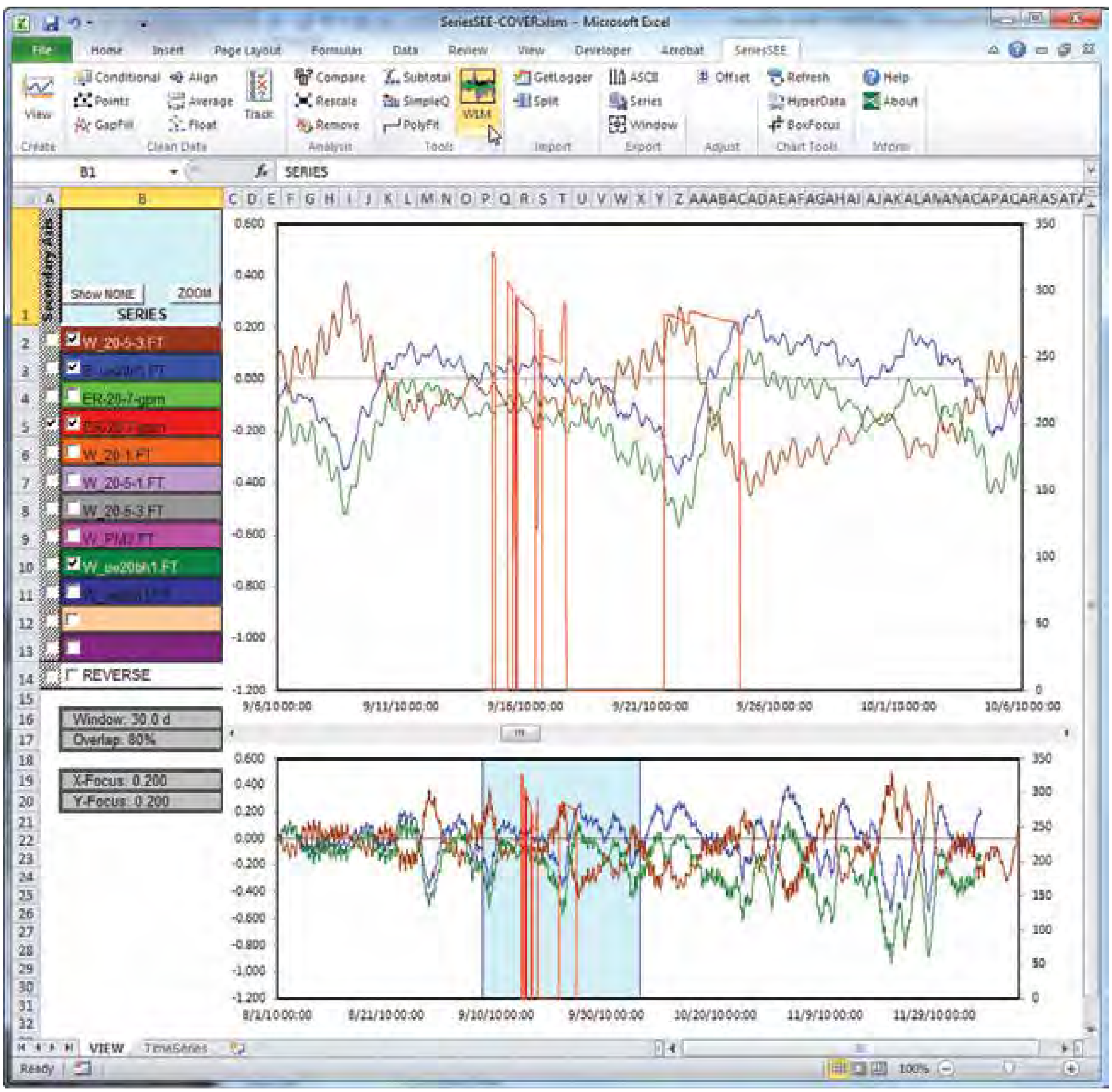

Figure 11. SeriesSEE toolbar and example workbook that was created with SeriesSEE.

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PEST exists in the SeriesSEE installation files, but also can be downloaded independently from *http://www.pesthomepage.org/*. The VBA utility WLM writes the PEST control file, ***.pst**, as multiple, commented input files, which are concatenated and stripped of comments with the FORTRAN program ***NoComment***. Source codes and documentation of ***WLmodel*** and ***NoComment*** are in the FORTRAN folder of appendix B.

Data Requirements

Data must be arranged as a continuous series of headers and values where all headers are in a single row (fig. 12). Multiple time columns can be specified, which allows for specification of series with different or irregular sampling intervals. All series are independent, so time columns need not be synchronous. Multiple data series can share a common time column (fig. 12, See columns C, D, and E), but the shared time column must be the first time column to the left of the data series.

A Viewer file is created by selecting a cell in the block of data to be analyzed and pressing the View button (fig. 11). The entire data block is copied from the user's original file into the viewer file by default. All equations within the block of data are converted to values in the viewer file, which breaks all linkages to the user's original workbook. Original data and formulas are not altered in the user's original file because all SeriesSEE operations act on a copy of the data in the viewer file.

Supporting Utilities

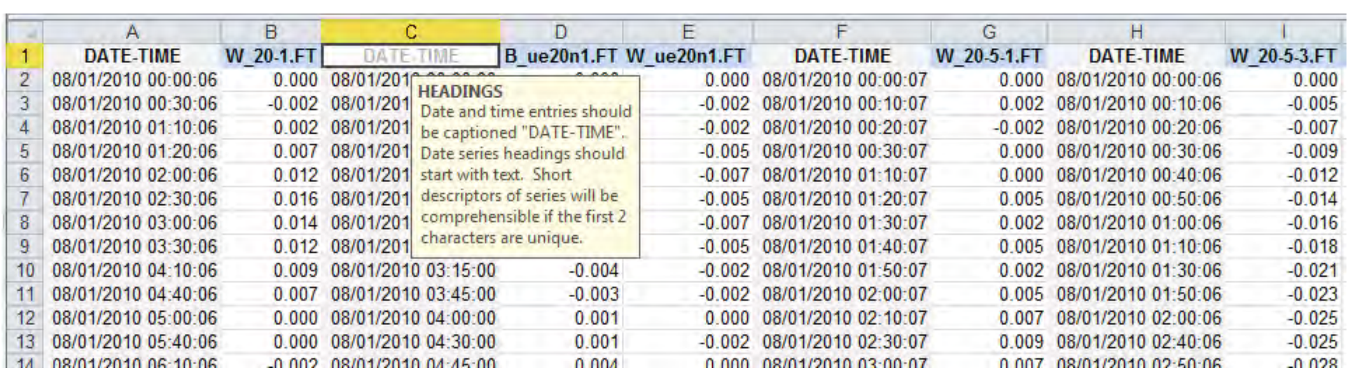
SeriesSEE features more than 20 supporting utilities in addition to the viewer creation and water-level modeling utilities already discussed (table 4). Many utilities exist to provide data-handling capabilities that can be used prior to water-level modeling. Related utilities are grouped and labeled as Clean Data, Analysis, Tools, Import, Export, Adjust, and Chart Tools (table 4).

Time-series data generally must be cleaned before analyzing. Cleaning removes erroneous measurements, converts units, reconciles continuous and periodic measurements, and removes step changes from transducer disturbances. All changes between the original and cleaned series can be recorded with explanations for each data change if the track utility is active. Changes and explanations are recorded to an auxiliary workbook that also contains the original and revised series. Utilities in the clean data and analysis groups perform these tasks (table 4).

Simple analysis and inspection of series are supported by utilities in the analysis group (table 4). New series can be created by adding, subtracting, multiplying, or dividing one series by another with the Compare utility. Measurement frequencies of the two series can differ because of interpolation. Smoother series can be created from noisy series with moving averages or LOWESS (LOcally Weighted Scatterplot Smoothing), which is a nonparametric method of fitting a curved line to data (Helsel and Hirsch, 1992, p. 288–291). Potential correlations among multiple series of disparate scales can be inspected by normalizing these series to a common scale with the Rescale utility.

Water-level modeling and other analyses can be expedited and improved by data reduction where there has been oversampling. Data can be reduced by averaging within periods such that 1-minute data are reduced to 1-hour averages with the Subtotal utility. Continuous records of flow rates with many thousands of measurements can be reduced accurately to a few dozen step changes with the SimpleQ utility. Simplified pumping schedules increase the efficiency and speed at which drawdowns can be simulated in WLMs. Geophysical logs are approximated with a simple polyline using the PolyFit utility, PolyFit, which can eliminate extraneous fluctuations and constrain the polyline to monotonic increases. Utilities in the tools group perform these tasks (table 4).

Time series can be imported from ASCII files and database tables to a SeriesSEE data table with utilities in the import group (table 4). Multiple data-logger files are read interactively with the GetLogger utility to create a single SeriesSEE data table. Database tables with site identifiers, times, and water levels grouped into three columns can be reformatted to a SeriesSEE data table with the Split utility.



	A	B	C	D	E	F	G	H	I
1	DATE-TIME	W_20-1.FT	DATE-TIME	B_ue20n1.FT	W_ue20n1.FT	DATE-TIME	W_20-5-1.FT	DATE-TIME	W_20-5-3.FT
2	08/01/2010 00:00:06	0.000	08/01/201		0.000	08/01/2010 00:00:07	0.000	08/01/2010 00:00:06	0.000
3	08/01/2010 00:30:06	-0.002	08/01/201		-0.002	08/01/2010 00:10:07	0.002	08/01/2010 00:10:06	-0.005
4	08/01/2010 01:10:06	0.002	08/01/201		-0.002	08/01/2010 00:20:07	-0.002	08/01/2010 00:20:06	-0.007
5	08/01/2010 01:20:06	0.007	08/01/201		-0.005	08/01/2010 00:30:07	0.000	08/01/2010 00:30:06	-0.009
6	08/01/2010 02:00:06	0.012	08/01/201		-0.007	08/01/2010 01:10:07	0.000	08/01/2010 00:40:06	-0.012
7	08/01/2010 02:30:06	0.016	08/01/201		-0.005	08/01/2010 01:20:07	0.005	08/01/2010 00:50:06	-0.014
8	08/01/2010 03:00:06	0.014	08/01/201		-0.007	08/01/2010 01:30:07	0.002	08/01/2010 01:00:06	-0.016
9	08/01/2010 03:30:06	0.012	08/01/201		-0.005	08/01/2010 01:40:07	0.005	08/01/2010 01:10:06	-0.018
10	08/01/2010 04:10:06	0.009	08/01/2010 03:15:00	-0.004	-0.002	08/01/2010 01:50:07	0.002	08/01/2010 01:30:06	-0.021
11	08/01/2010 04:40:06	0.007	08/01/2010 03:45:00	-0.003	-0.002	08/01/2010 02:00:07	0.005	08/01/2010 01:50:06	-0.023
12	08/01/2010 05:00:06	0.000	08/01/2010 04:00:00	0.001	0.000	08/01/2010 02:10:07	0.007	08/01/2010 02:00:06	-0.025
13	08/01/2010 05:40:06	0.000	08/01/2010 04:30:00	0.001	-0.002	08/01/2010 02:30:07	0.009	08/01/2010 02:40:06	-0.025
14	08/01/2010 06:10:06	-0.002	08/01/2010 04:45:00	0.004	0.000	08/01/2010 03:00:07	0.007	08/01/2010 02:50:06	-0.028

Figure 12. Format of headers and values for creating a viewer file with SeriesSEE.

Table 4. Summary of available tools in SeriesSEE.

Group	Utility	Description	Name
Create	View	Create Viewer file by selecting a cell in a block of data in an original source file, which is copied to the viewer file. All equations are converted to values in the Viewer file.	View
Clean Data	Conditional	Bad data conditionally can be commented and/or eliminated.	Conditional
	Points	Bad data in a single series can be commented and/or eliminated graphically.	Points
	GapFill	Data gaps from the cleaning process can be filled by linear interpolation, loaded with a dummy value, eliminated altogether, or gaps can be created for alignment.	GapFill
	Align	Shift data segments. Estimate shift with simple water-level models that use a few guide series. Alternatively, shifts can be assigned from other estimates.	Align
	Average	Data reduction by averaging where oversampled.	Average
	Float	Float series to tape downs without changing slope of transducer data.	Float
	Track	Force an explanation to be appended to each data change in an auxillary workbook that also contains the original and revised series.	Track
Analysis	Compare	Create new series by addition, subtraction, multiplication, and division of existing series. Second series interpolated to times in the first series. Series can also be smoothed with a moving average or LOWESS curve.	Compare
	Rescale	Series can be normalized to common scales.	Rescale
	Remove	Removes derived series that are created by Compare or Rescale.	Remove
Tools	Subtotal	Data reduction tool where selected series are binned by time periods or depth intervals to compute statistics.	Subtotal
	SimpleQ	Reduces pumping rates to a simple schedule.	SimpleQ
	PolyFit	Geophysical logs are approximated with a simple polyline.	PolyFit
	WLM	Model water levels interactively in a new workbook, where water levels are simulated with a FORTRAN program and differences are minimized with PEST.	WLM
Import	GetLogger	Series from data-logger files are read interactively and concatenated in a SeriesSEE format.	GetLogger
	Split	Split 3 columns of site identifiers, time, and water levels into SeriesSEE input where a new series is identified at each change in site identifier.	Split
Export	ASCII	Output from tracking workbooks to selected ASCII formats.	ASCII
	Series	Export individual series with options to create drawdown observations. Drawdown observations require shifting, binning, and truncating to a time window.	Series
	Window	Data are copied to a new workbook and reduced to a user-specified period.	Window
Adjust	Offset	Individual, selected, or all series can be shifted such that the average, minimum, maximum, or first value will equal zero.	Offset
Chart Tools	Refresh	Refresh the list of available series after manually adding or deleting series on the data page.	Refresh
	HyperData	Create temporary hyperlinks between visible series and charted data in the Viewer file.	HyperData
	BoxFocus	Magnify subareas of plot. First click adds a rectangle. Second click re-scales both axes to rectangle area. Third click restores plot.	BoxFocus
Inform	Help	Controls and usage of SeriesSEE are explained.	Help
	About	Display ad copy about SeriesSEE.	About

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Series can be viewed and inspected at scales as fine as discrete measurements with utilities in the "adjust" and "chart tools" groups (table 4). Series can be shifted so that all measurements fluctuate about a common reference with the Offset utility, which eases comparisons among series (fig. 13). Subareas of charts in SeriesSEE viewer and auxiliary files can be magnified interactively with the BoxFocus utility. Discrete measurements can be selected graphically and connected to the cell with the numerical value in the Viewer file with the HyperData utility, which creates temporary hyperlinks between charted points and the cell with the plotted value.

Each SeriesSEE utility is fully documented in the help system, which can be called with the Help utility or from context sensitive help calls in each utility (appendix A). Each group, utility, form, and auxiliary workbook is explained briefly, and step-by-step instructions (fig. 14). Complex utilities such as water-level modeling are documented with multiple pages that explain each form and action.

Water-Level Modeling

Water levels are modeled interactively with the WLM utility in SeriesSEE. Water levels to be modeled, input series, period of analysis, and WLM components are defined through the use of data-entry forms. A new workbook for modeling water levels is created with user-specified information from these forms. Fitting periods and WLM components can be modified in the WLM workbook.

Analytical models that transform WLM components in the FORTRAN program ***WLmodel*** have been verified (table 5). The analytical models for moving average and step transforms were verified against intrinsic functions in Excel. The analytical models for Theis, tide, pneumatic lag, and gamma transforms were verified against solutions that were computed with published programs. Source problems, programs, and comparisons between ***WLmodel*** output and published programs are documented fully in appendix C.

Differences between synthetic and measured water levels are minimized with PEST. Parameter estimates, transformed WLM components, synthetic water levels, and differences are imported automatically into the WLM workbook after PEST finishes. Model fit is defined by RMS error and evaluated graphically. Parameters are estimated and WLM results are evaluated iteratively until the user deems the fit to be adequate.

Table 5. Summary of verification tests for analytical models in the FORTRAN program WLmodel.

WLM Component	SeriesSEE Label	Verification Source
Moving Average	SERIES	Excel function
Theis Transform	THEIS	Barlow and Moench, 1999
Tide	TIDE	Harrison, 1971
Step	STEP	Excel function
Pneumatic Lag	AIR-LAG	Barlow and Moench, 1998
Gamma	GAMMA	O'Reilly, 2004

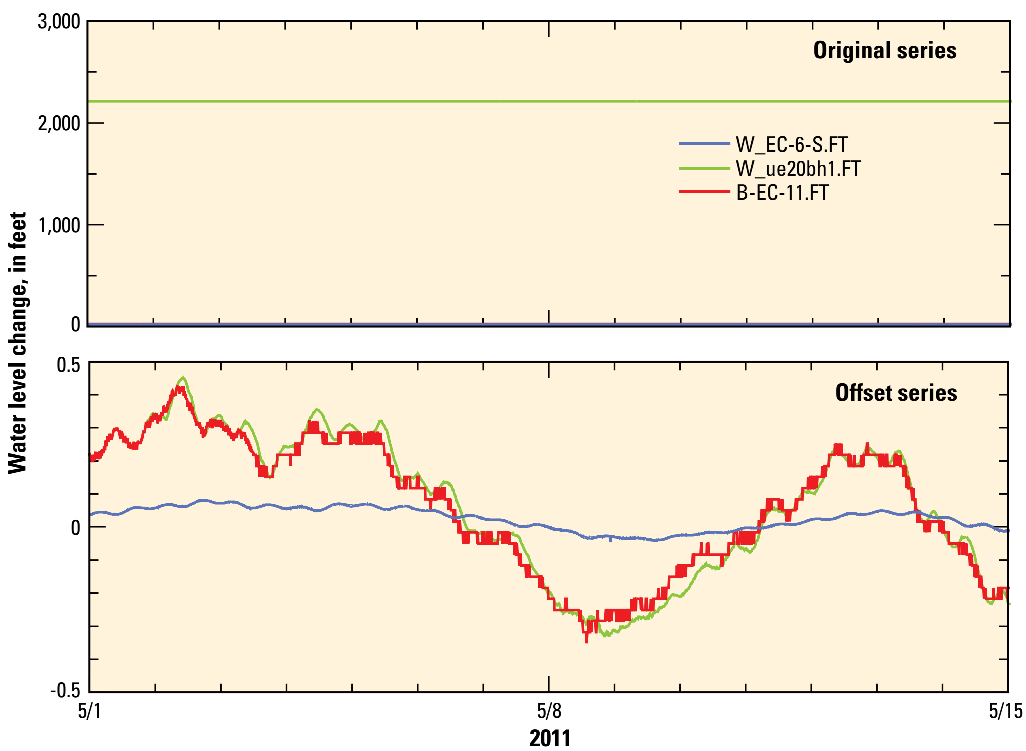

Figure 13. Shifting series to a common reference with the offset utility.

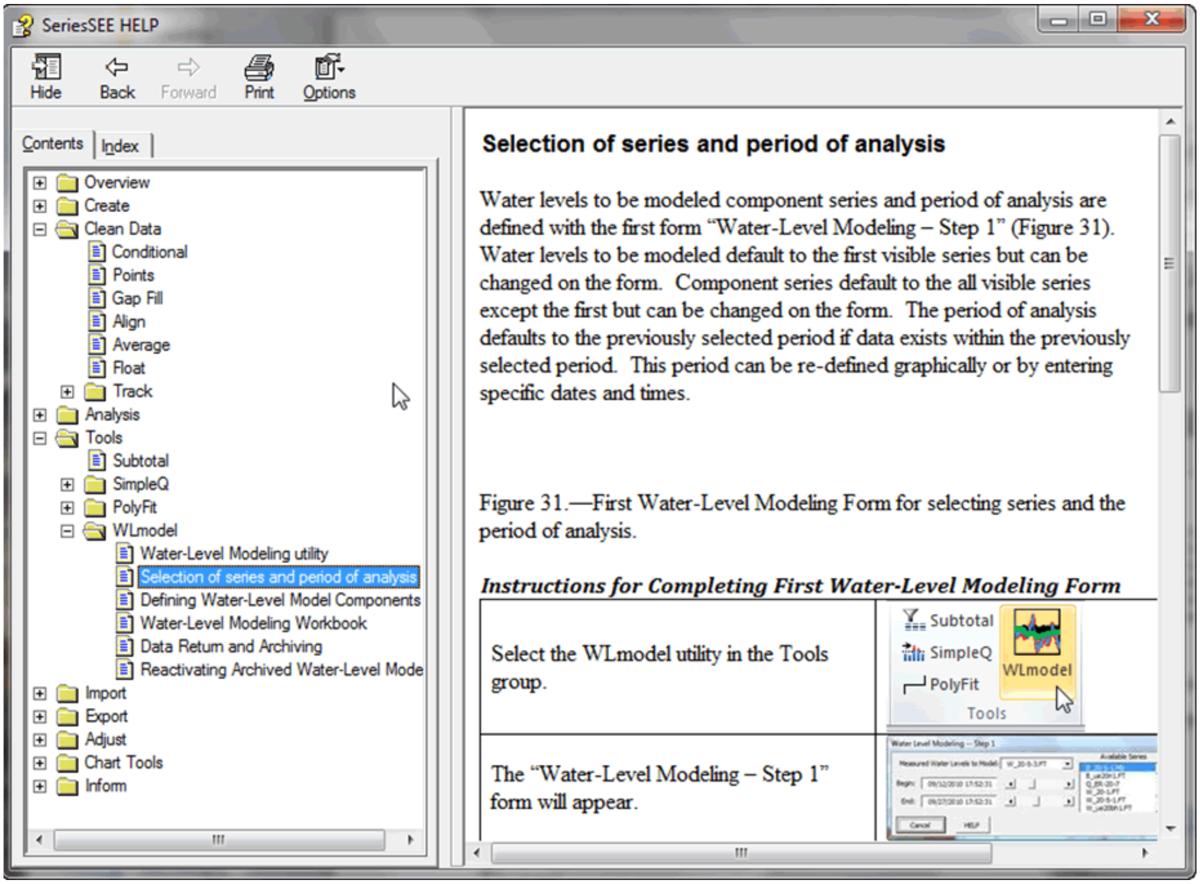

Figure 14. Table of contents and an explanation page in the help system for SeriesSEE.

Drawdowns and transformed WLM components are returned to the SeriesSEE viewer once the user accepts a WLM, where drawdowns are the sum of all Theis transforms minus differences between synthetic and measured water levels. Drawdowns and transformed WLM components are selected individually, so the number of returned series can range from 0 to all WLM components. The WLM workbook can be archived as a macro-free workbook with re-activation capabilities.

Applications of Water-Level Modeling

Water-level modeling applications of SeriesSEE are demonstrated with a hypothetical example and a field investigation at Pahute Mesa, Nevada National Security Site (NNSS). The hypothetical example emulated the complex hydrogeology beneath Pahute Mesa so that known drawdowns could be simulated in a complex aquifer system. Limitations of the Theis-transform approach were investigated with these known drawdowns. Environmental noise, which was the record of water levels in background well ER EC-6 shallow (table 6), was added to known drawdowns. The field investigation demonstrated that drawdowns much smaller than environmental fluctuations can be detected across a major fault structure more than 1 mile from the pumping well. Explanations, data sets, and ancillary software for the hypothetical example and field investigation are in appendixes D and E, respectively.

Water-level modeling was developed and tested with data from Pahute Mesa, NNSS, (fig. 15) because detection of distant drawdowns is imperative and complicated by more than 2,000 ft of unsaturated zone. Migration of radionuclides from underground testing of nuclear devices drives the need to quantify groundwater flow and transport beneath Pahute Mesa (Laczniak and others, 1996). The great depth to water and accessibility limit the number of wells, which typically penetrate a mile of volcanic rock and are more than 1-mi apart (Fenelon and others, 2010). Environmental water-level fluctuations are substantial beneath Pahute Mesa because of the thick unsaturated zone and high hydraulic diffusivity of the volcanic rocks.

The aquifer system beneath Pahute Mesa comprises layered sequences of volcanic rocks that have been faulted into distinct structural blocks (Warren and others, 2000). Rhyolitic lavas or welded ash-flow tuffs such as in the Benham and Topopah Springs aquifers, respectively, comprise aquifers. Bedded and non-welded, zeolitized tuffs typically comprise confining units (Blankennagel and Weir, 1973; Prothro and Drellack, 1997; Bechtel Nevada, 2002). More than a half

Table 6. Site information and completion depths for wells at Pahute Mesa, Nevada National Security Site that were used in hypothetical example and field investigation.

Well name: Names are listed in alphabetical order. Bold part of name is well site as shown on Figure 15.
U.S. Geological Survey site identification number: Unique 15-digit number identifying well.
Latitude/Longitude: Latitude and longitude coordinates, referenced to North American Datum of 1927.
Land-surface altitude: Altitude, referenced to National Geodetic Vertical Datum of 1929.
Open intervals: Depth, in feet below land surface, of the top and bottom of open annulus.

Well Name	U.S. Geological Survey site identification number	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Land-surface altitude (feet)	Open intervals
ER-20-5 #1	371312116283801	37°13'12.2"	116°28'37.8"	6,242	2,249–2,655
ER-20-6 #3	371533116251801	37°15'33.1"	116°25'17.5"	6,466	2,436–2,807
ER-EC-6 shallow	371120116294805	37°11'19.6"	116°29'48.1"	5,604	1,606–1,948
ER-EC-11 main	371151116294102	37°11'51.2"	116°29'41.1"	5,656	3,196–3,385 3,590–4,148
PM-3-1	371421116333703	37°14'20.7"	116°33'36.6"	5,823	1,872–2,192
UE-20n 1	371425116251902	37°14'25.1"	116°25'19.0"	6,461	2,308–2,834
ER-20-7	371247116284502	37°12'47.0"	116°28'44.8"	6,209	2,292–2,924
ER-20-8 main	371135116282601	37°11'35.1"	116°28'26.3"	5,848	2,440–2,940 3,070–3,442

dozen faults with offsets in excess of 500 ft have been mapped previously in Pahute Mesa (McKee and others, 2001), and additional faults are mapped with each new well (for example, National Security Technologies, LLC, 2010).

Hypothetical Example

The reliability of differentiating environmental fluctuations and pumping responses with water-level models was tested with a hypothetical aquifer system. Drawdown from a hypothetical aquifer test was simulated where the hydrogeologic complexity and distribution of hydraulic properties were assigned. The hypothetical aquifer system is comprised of ash-fall tuff, bedded tuff, welded tuff, and lava units that are flat-lying, laterally isotropic, and homogeneous (fig. 16). A fault 1,500 ft east of the pumping well, P1, bisects the aquifer system, vertically displaces hydrogeologic units 1,000 ft, and alters hydraulic properties around the structure.

The hypothetical aquifer system was simulated with a three-dimensional MODFLOW model (Harbaugh, 2005). The model domain was discretized laterally into 135 columns of 135 rows with a variably spaced grid (fig. 16). Cell sizes ranged in width from 10 ft by the pumping well to 40,000 ft at the model edges. Model edges were about 200,000 ft away from the pumping well, P1, and were simulated as no-flow boundaries. The model grid extended vertically from an impervious base at sea level to the water table at 4,200 ft above sea level. Vertical discretization was uniform, with 200-ft thick layers except for a 1-ft thick layer at the water table. The thickness differed so that the storage coefficient and specific storage were equivalent, and it allowed specific yield to be assigned directly in a layer. Changes in saturated thickness of the aquifer were not simulated because maximum drawdown at the water table was small relative to the total thickness.

Hydraulic properties typical of volcanic units were assigned to the hypothetical aquifer system. Ash-fall tuff, bedded tuff, welded tuff, and lava were assigned hydraulic conductivities of 0.001, 0.1, 3, and 50 ft/d, respectively. Horizontal-to-vertical anisotropy of one was assigned to all units. A uniform value of 0.02 was assigned for specific yield. The specific storage of all hydrogeologic units was 2×10^{-6} 1/ft.

Hypothetical aquifer-test results were simulated and analyzed during a 3-month period that was divided into five stress periods. The antecedent, pumping, recovery, pumping, and recovery periods were 21, 10, 10, 10, and 40 days, respectively. Pumping rates were 500 gpm during the second and fourth stress periods. Flow and drawdown in pumping and observation wells were simulated and sampled with the Multi-Node Well (MNW) package (Harbaugh, 2005). Flow to the pumping well was distributed proportionally to cell transmissivities by the MNW package.

Water levels with a “known” pumping signal and environmental fluctuations (noise) shown in figure 17 for well O3 were created by adding simulated drawdowns from MODFLOW to measured water levels in well EREC-6 shallow (fig. 17). Simulated drawdowns from MODFLOW in well O3, which is 7,800 ft from well P1, were interpolated in time to match measured water levels in well EREC-6 shallow. Simulated drawdowns from MODFLOW and simulated drawdowns with environmental noise added are in appendix D in the file .\WLMs\00_Hypo+Meas2SeriesSEE.xlsx.

Drawdowns were estimated by modeling “measured” water levels in well O3. Environmental fluctuations were simulated with computed tides, barometric pressure and background water levels in wells PM-3 and UE-20n 1 (fig. 17). Pumping effects were simulated with a Theis transform of the hypothetical pumping schedule. The water-level model was calibrated during the period from November 18, 2010, to March 6, 2011.

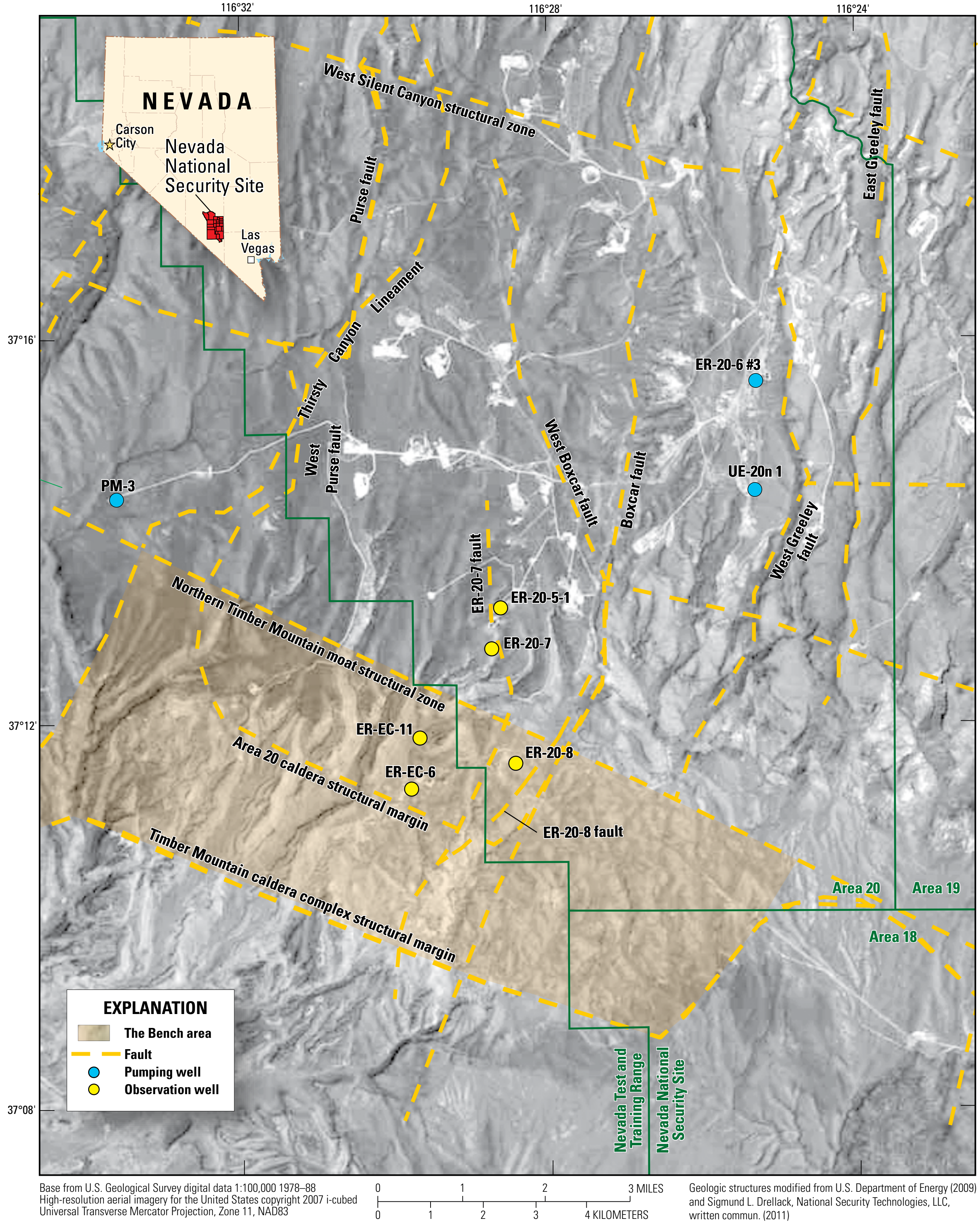

Figure 15. Background wells, observation wells, pumping well, and selected fault structures at Pahute Mesa Nevada National Security Site.

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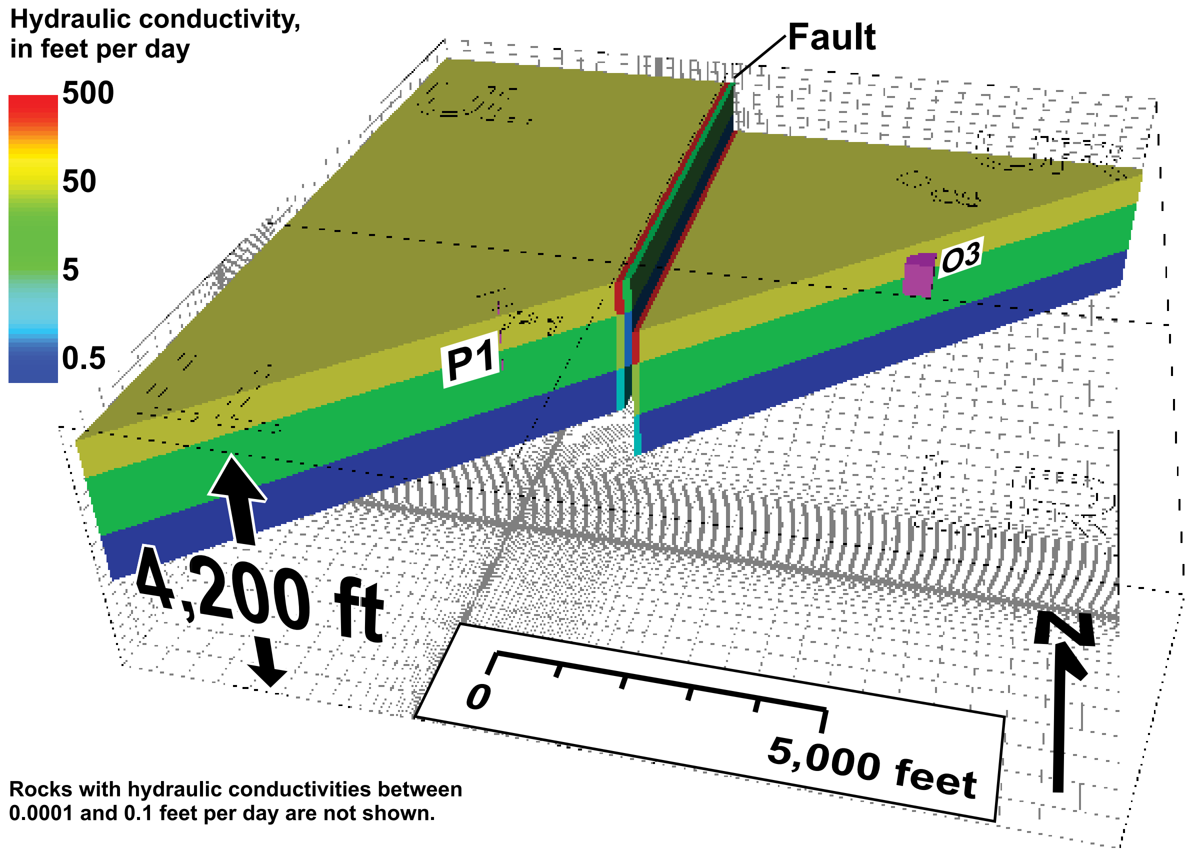

Figure 16. Hydraulic conductivity distribution of a subset of a hypothetical aquifer system that has been bisected by a fault, showing well locations and labeled quadrants (upper left, UL; upper right, UR; lower right, LR; lower left, LL).

Drawdowns that were estimated from "measured" water levels in well O3 agreed with known drawdowns within the noise of the data set (fig. 18). A maximum drawdown of 0.18 ft was estimated which was identical to the known maximum. The RMS error of differences between synthetic and measured water levels was 0.013 ft. The RMS error of differences between synthetic and known drawdowns was 0.015 ft.

Drawdowns alternatively were estimated in well O3 by modeling the original MODFLOW results with Theis transforms. No other WLM components were considered because environmental fluctuations did not exist in the original MODFLOW results. This alternative water-level model also was calibrated during the period from November 18, 2010, to March 6, 2011.

Drawdowns that were estimated directly from MODFLOW results could be replicated almost perfectly with Theis transforms. Differences between MODFLOW results and a single Theis transform could be reduced to a RMS error of less than 0.006 ft. RMS error declined to less than 0.0006 ft with the addition of a second Theis transform (fig. 18). Deviations of less than 0.001 ft approach the accuracy of the numerical solution of the hypothetical aquifer test.

The simplicity of Theis transforms did not introduce error because MODFLOW results could be replicated near perfectly with Theis transforms. Differences between known drawdowns and drawdowns that were estimated from "measured" water levels differed because of noise in the measured input series.

The hypothetical model and SeriesSEE input were created with **HypoFrame**, which is a workbook for simulating hypothetical aquifer tests and creating water levels with known pumping signals and environmental noise. Hypothetical aquifer systems must have flat-lying geologic units of uniform thickness and laterally isotropic, homogeneous hydraulic conductivity. A hypothetical aquifer system can be subdivided into four quadrants by two intersecting faults. Rock sequences in each quadrant can be displaced vertically within each quadrant. The **HypoFrame** workbook and documentation are in appendix D.

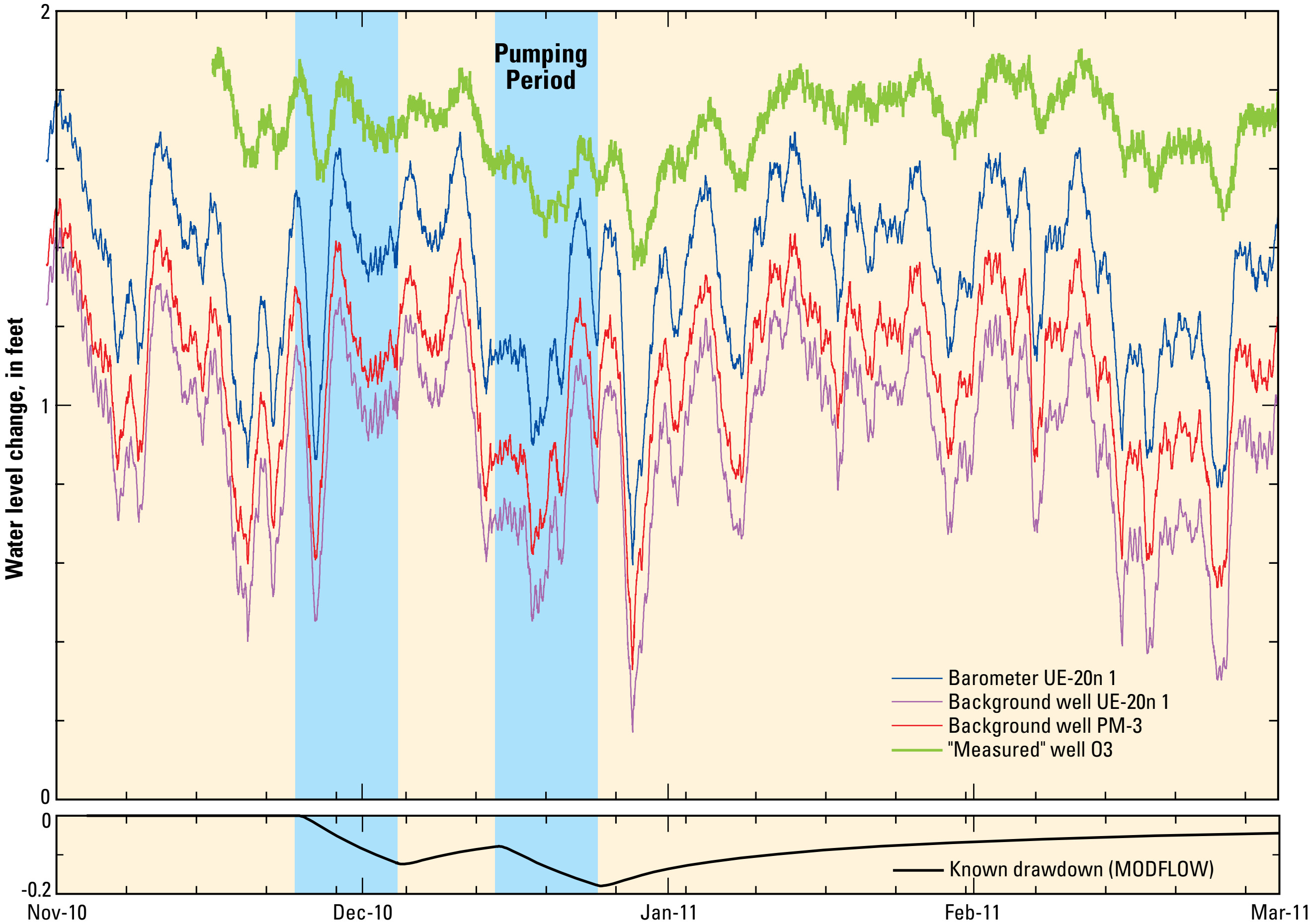

Figure 17. Barometric pressure, background water levels, and water levels with known drawdowns in hypothetical well O3.

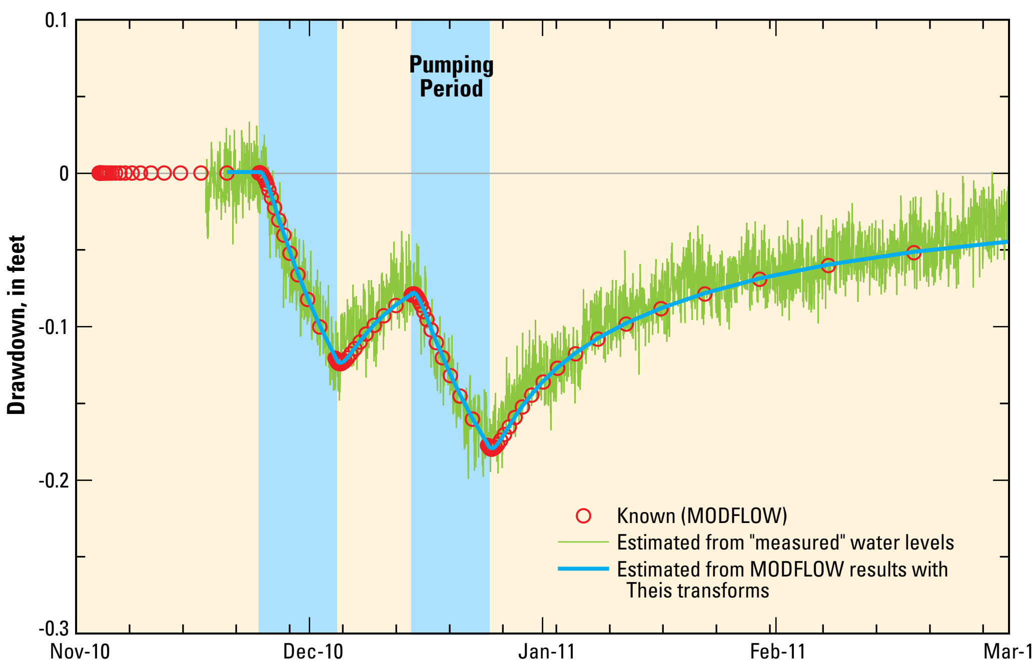

Figure 18. Known drawdowns (MODFLOW), drawdowns estimated from "measured" water levels, and drawdowns estimated directly from MODFLOW results in well O3.

Pahute Mesa Example

Water-level modeling was tested in a complex hydrogeologic system by estimating drawdown from two aquifer tests beneath Pahute Mesa (Halford and others, 2011). The upper and lower zones of well ER-20-8 main produced water from the Tiva Canyon and Topopah Spring aquifers sequentially between June 16, 2011, and August 8, 2011. Each well was pumped a total of 20 d, where pumping periods were evenly divided between well development and a constant-rate test (fig. 19).Drawdown from pumping both zones was estimated in observation well ER-20-7, which is screened in the Topopah Spring aquifer. Pumping and observation wells are 1.4 mi apart and penetrate different structural blocks (fig. 15).

Drawdown in well ER-20-7 was estimated with multiple Theis transforms in the water-level model. Environmental fluctuations were simulated with computed tides, barometric pressure, and background water levels from well UE-20bh-1 (fig. 15). Pumping effects were simulated with two Theis transforms for each of the two pumping schedules (fig. 19). The fitting period was from April 20, 2011, to November 11, 2011. Synthetic water levels matched measured water levels with a RMS error of 0.004 ft.

Drawdown in well ER-20-7 also was estimated with an identical water-level model, except that WLM components with background water levels were negated. Synthetic water levels matched measured water levels with a RMS error of 0.027 ft during the same fitting period from April 20, 2011, to November 11, 2011 (fig. 19). Each drawdown estimate was the difference between a synthetic water level without Theis transforms and a measured water level.

Poor drawdown estimates from the water-level model without background water levels demonstrates the need to simulate as much of the environmental fluctuations as possible. Antecedent conditions were simulated poorly where estimated drawdowns should be zero. Estimated drawdowns unambiguously were wrong during October and November when net water-level rises from pumping were estimated (fig. 19).

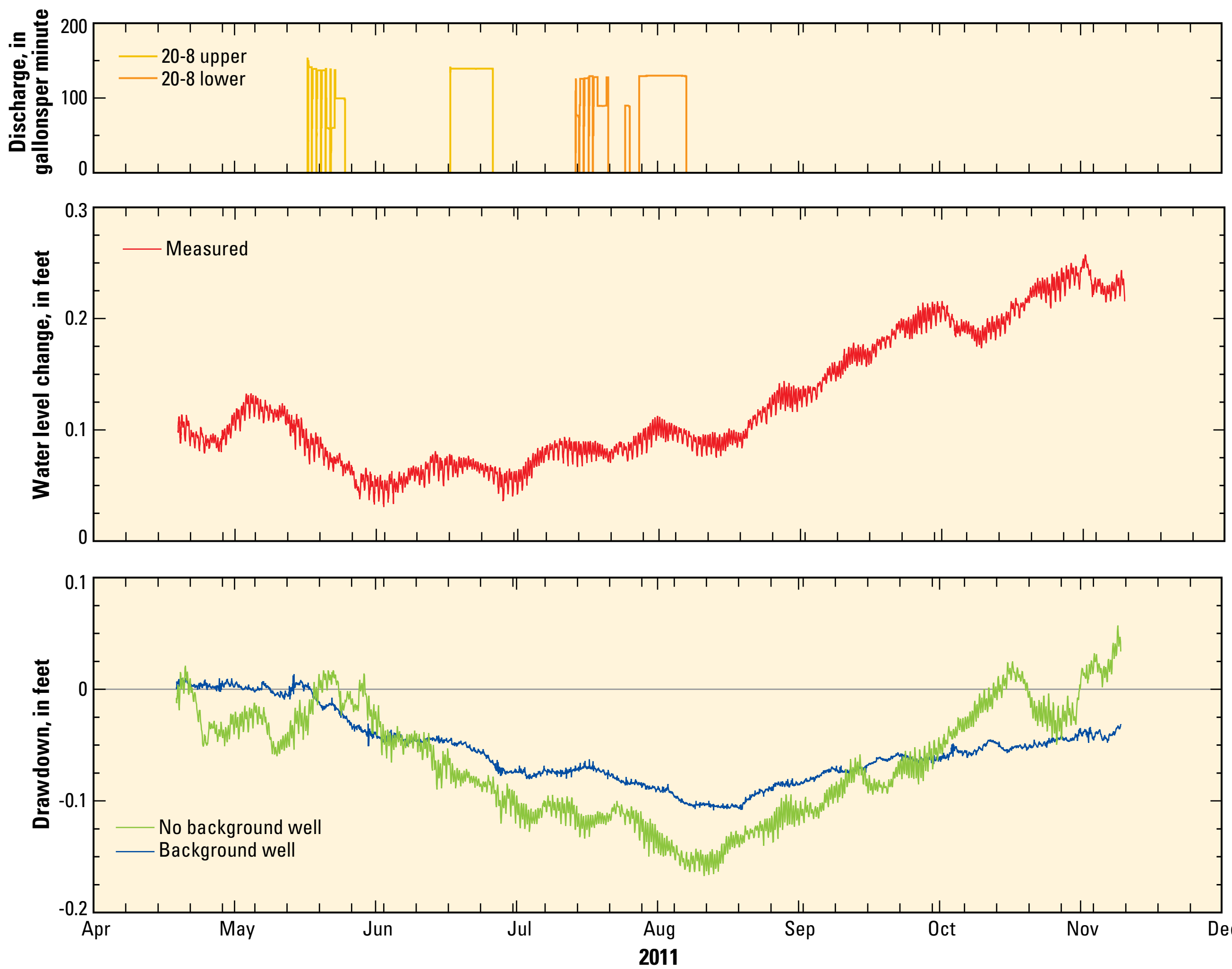

Figure 19. Measured water levels, synthetic water levels, Theis transforms, and estimated drawdowns in well ER-20-7 from pumping ER-20-8 main upper and lower zones, Pahute Mesa, Nevada National Security Site.

Water-Level Modeling Strategies

Estimating drawdowns that have been obscured by environmental fluctuations is the primary goal of the water-level modeling approach. This approach is most effective and efficient where many WLM components are specified and fitting periods are great. This approach has been summarized, sometimes derisively, as the flak-gun, fishing-with-dynamite, and kitchen-sink approaches. All phrases accurately depict testing many WLM components simultaneously. Unique contributions from each WLM component remain unknown, but pumping signals are not correlated with environmental fluctuations. The flak-gun approach was adopted here.

The flak-gun approach uses WLM components that could have been excluded. This is not a problem because mechanisms exist to negate WLM components. Amplitudes tending to zero will negate a WLM component. Multiple WLM components also can negate one another by summing to zero. Likewise, Theis transforms also are negated by a large transmissivity or storage coefficient value where pumping signals are below detection or absent. Negated WLM components aesthetically are lacking, but do not affect results. Systematic investigation of WLM components is possible with SeriesSEE, but has not been automated.

The flak-gun approach has many advantages, especially when estimating drawdowns in dozens of wells. Reporting is easier because the same input series and WLM components were used in all of the water-level models. Water-level models calibrate quickly after analyzing the first or second well because WLM components are defined with fair initial estimates of amplitude and phase. The flak-gun approach can fail when the fitting period decreases and correlation becomes possible between pumping signals and environmental fluctuations.

Correlation between weak pumping signals and environmental fluctuations is possible and requires further investigation. Nebulous drawdown estimates can be investigated with multiple water-level models where water levels initially are simulated without Theis transforms. An alternative water-level model is created by adding a Theis transform to the initial water-level model. The initial transmissivity and storage coefficient should create a small but measureable maximum deflection in the added Theis transform. Drawdowns likely were not detected if the RMS error cannot be reduced by more than 30 percent.

Input series of greater duration potentially can degrade with time as pressure transducers fail. For example, multiple input series could be good for the first four months, while one input series degrades during the last two months. Degradation likely will be apparent in the WLM residuals as scatter increases. Identifying the onset of failure in a specific input series requires modeling water levels during subsets of the fitting period. Degrading input series can be investigated manually with SeriesSEE, but an automated tool would be a better approach.

Summary and Conclusions

Pumping responses can be differentiated reliably from environmental fluctuations with water-level modeling. Water-level modeling approximates measured water-level fluctuations by summing multiple component fluctuations. Environmental fluctuations primarily are composed of barometric and background water-level input series and computed tide components. Pumping signals are modeled by superimposing multiple Theis transforms, where step-wise pumping records of flow are transformed into water-level changes. The summation of all component fluctuations is a synthetic water-level series.

Water-levels can be modeled robustly with the Theis-transform approach because environmental fluctuations and pumping signals are simulated simultaneously. Long-term trends are well simulated because environmental fluctuations are defined with entire periods of record. Fitting periods are extended greatly where pumping and recovery affect a majority of the record. Multiple Theis responses with different hydraulic diffusivities are summed to approximate lithologic variability.

Water-level modeling with Theis transforms has been implemented in the program SeriesSEE, which is a Microsoft® Excel add-in. Water levels to be modeled, input series, period of analysis, and water-level model components are defined interactively and viewed in workbooks that are created by SeriesSEE. Water levels are modeled with a FORTRAN program that is called from Excel. Differences between synthetic and measured water levels are minimized with PEST.

Water-level model components are transformations of input series. Moving average, Theis, pneumatic-lag, and gamma transforms are available transforms in SeriesSEE. Moving averages most frequently transform input series of barometric pressure and background water levels. Pumping schedules are transformed into water-level fluctuations with Theis transforms. Pneumatic-lag transforms barometric pressure changes at land surface to lagged and attenuated responses at the water table. Water-level rises from infiltration events are simulated with the gamma transform. Earth tides and step transforms are purely computed quantities that do not require input series.

Many utilities exist in SeriesSEE for viewing, cleaning, manipulating, and analyzing time-series data in addition to water-level modeling. Supporting utilities exist because data handling frequently consumes more time and effort than water-level modeling. Each SeriesSEE utility is documented with a brief explanation and step-by-step instructions that are accessed through context sensitive help.

Water-level models must be calibrated to reliably differentiate small pumping responses from environmental fluctuations. Differences between synthetic and measured water levels define goodness-of-fit. Sum-of squares of differences are minimized by PEST where singular value decomposition and Tikhonov regularization are used to assure stable results, not to inform estimated parameter values. Preferred homogeneity within amplitude, phase, and hydraulic property parameters is enforced with Tikhonov regularization.

Drawdown estimates from a water-level model are the summation of all Theis transforms minus residuals. The summation of all Theis transforms is the direct estimate of the pumping signal. Residuals represent all unexplained water-level fluctuations. These fluctuations should be random residuals during non-pumping periods, but can contain unexplained components of the pumping signal during pumping and recovery periods.

The simplicity of Theis transforms did not introduce error because results from a hydrogeologically complex MODFLOW model could be replicated near perfectly with Theis transforms. Differences between known drawdowns and drawdowns that were estimated from “measured” water levels differed because of noise in the measured input series. Estimated drawdowns are affected minimally by the Theis-transform approach relative to the inaccuracies that result from noise in the data sets.

Drawdowns much smaller than environmental fluctuations have been detected across a major fault structure more than 1 mile from the pumping well beneath Pahute Mesa, Nevada National Security Site. A maximum drawdown of 0.1 ft was estimated in well ER-20-7 during an 8-month period of analysis. Drawdown estimates in well ER-20-7 were consistent with a plausible pattern of drawdowns at all observation wells. Drawdowns could not have been detected without water-level modeling as implemented in SeriesSEE.

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Appendix A. SeriesSEE add-in

The SeriesSEE add-in, example data sets, and installation instructions in the zipped file, AppendixA_SeriesSEE.v.1.00.zip, can be accessed and downloaded at *http://pubs.usgs.gov/tm/tm4-F4/*. The SeriesSEE add-in, supporting modules, templates, and compiled FORTRAN codes are in the subfolder AddIN. Examples of geophysical log, data logger input, other time series, and water-level modeling data sets are in the subfolders Example_BOREHOLE, Example_LOGGER, Example_TIME, and Example_WLM, respectively. An Adobe PDF version of the help files, SeriesSEE.V1.00_Explain.pdf, is in the root directory because compressed help files that are on servers can be disabled, *http://support.microsoft.com/kb/896358*. Contents of all subdirectories are reported in README file in the root directory of the unzipped AppendixA_SeriesSEE.v.1.00.zip file.

Appendix B. Source Codes for SeriesSEE

Source code for SeriesSEE exists as FORTRAN, XML, and VBA codes in the zipped file, AppendixB_Codes-SeriesSEE.v1.00.zip, which can be accessed and downloaded at *http://pubs.usgs.gov/tm/tm4-F4/*. The FORTRAN codes NoComment and WLmodel support PEST and solve water-level models, respectively, and are in the FORTRAN subfolder. All VBA code are in the SeriesSee.V*.xlsm and SSmodule_*.xlsm files in the VBA subfolder. The XML that defines SeriesSEE commands and buttons in the Excel ribbon are in the XML subfolder. Contents of all subdirectories are reported in a README file in the root directory of the unzipped AppendixB_Codes-SeriesSEE.v1.00.zip file.

Appendix C. Verification of Analytical Solutions

Analytical solutions that were computed with the FORTRAN program WLmodel and published results of the same solutions in the zipped file, AppendixC_Verification.zip, can be accessed and downloaded at *http://pubs.usgs.gov/tm/tm4-F4/*. The analytical models for pneumatic lag, gamma, moving average, step, Theis, and tide are verified against known solutions in the subfolders AirLAG, Gamma, MovingAverage, Step, Theis, and Tide, respectively. Contents of all subdirectories are reported in a README file in the root directory of the unzipped AppendixC_Verification.zip file.

Appendix D. Hypothetical Test of Theis Transforms

The Excel program, HypoFrame, measured water levels, measured barometric changes, and reported water-level models in the zipped file, AppendixD_HypotheticalAquifer.zip, can be accessed and downloaded at *http://pubs.usgs.gov/tm/tm4-F4/*. HypoFrame is a workbook for simulating hypothetical aquifer tests and creating water levels with known pumping signals and environmental fluctuations. The premise and usage of HypoFrame are documented in the compressed help file 00_HypoFrame-HELP.chm. Measured water levels and barometric changes that serve as environmental fluctuation sources and background water levels are in the file 00_Meas+Back-for-Analysis.xlsx. Reported water-level models and tools for viewing parameter correlation are in the subfolder WLMs.

Appendix E. Pahute Mesa Example

Measured water levels, measured barometric changes, pumping signals, and reported water-level models in the zipped file, AppendixE_PahuteMesaExample.zip, can be downloaded at *http://pubs.usgs.gov/tm/tm4-F4/*. The zip file contains the pumping response in well ER-20-7 from the ER-20-8 main upper and lower aquifer tests.

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SE ROA 50191

Halford and others—**Advanced Methods for Modeling Water-Levels and Estimating Drawdowns with SeriesSEE, an Excel Add-In**—Techniques and Methods 4–F4

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