Mifflin & Associates, Inc.

Summary of Order 1169 Testing Impacts, per Order 1169A

A Report Prepared in Cooperation with the Moapa Band of Paiutes

Cady Johnson and Martin Mifflin

June 28, 2013

Fossil spring mound in west-central Moapa Indian Reservation

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Introduction

The Order 1169 test, prescribed by State Engineer Order 1169A, offers Study participants the opportunity to file reports addressing impacts of pumping and availability of water pursuant to the pending applications. Mifflin and Associates, Inc. (MAI), most recently on behalf of the Moapa Band of Paiute Indians (MBOP) has been collecting and analyzing hydrologic data from the Reservation and surrounding areas (Figure 1) for over two decades. We have developed groundwater models, reviewed those of others (notably "Exhibit 54" of 2001 and the TetraTech models of 2012), estimated hydrologic parameters from aquifer tests, reviewed geochemical and isotopic data, estimated ephemeral recharge from runoff measurements, and accounted for the effects of tributary groundwater diversions and climate on streamflow in the Muddy River system. Numerous MAI analysis reports have been distributed to the Hydrologic Review Team (HRT) for consideration. Base-flow reductions in the Muddy River system in response to pumping in Coyote Spring Valley were predicted by MAI (2010), and those predictions were refined by Johnson and Mifflin (2011, 2012a, 2012b) and are supplemented by analyses reported herein.

Tributary groundwater diversions are responsible for historic and ongoing flow reductions in the Muddy River, though natural discharge variations may mask pumping effects. The following discussions and analyses provide several lines of quantitative evidence that up-gradient groundwater diversions

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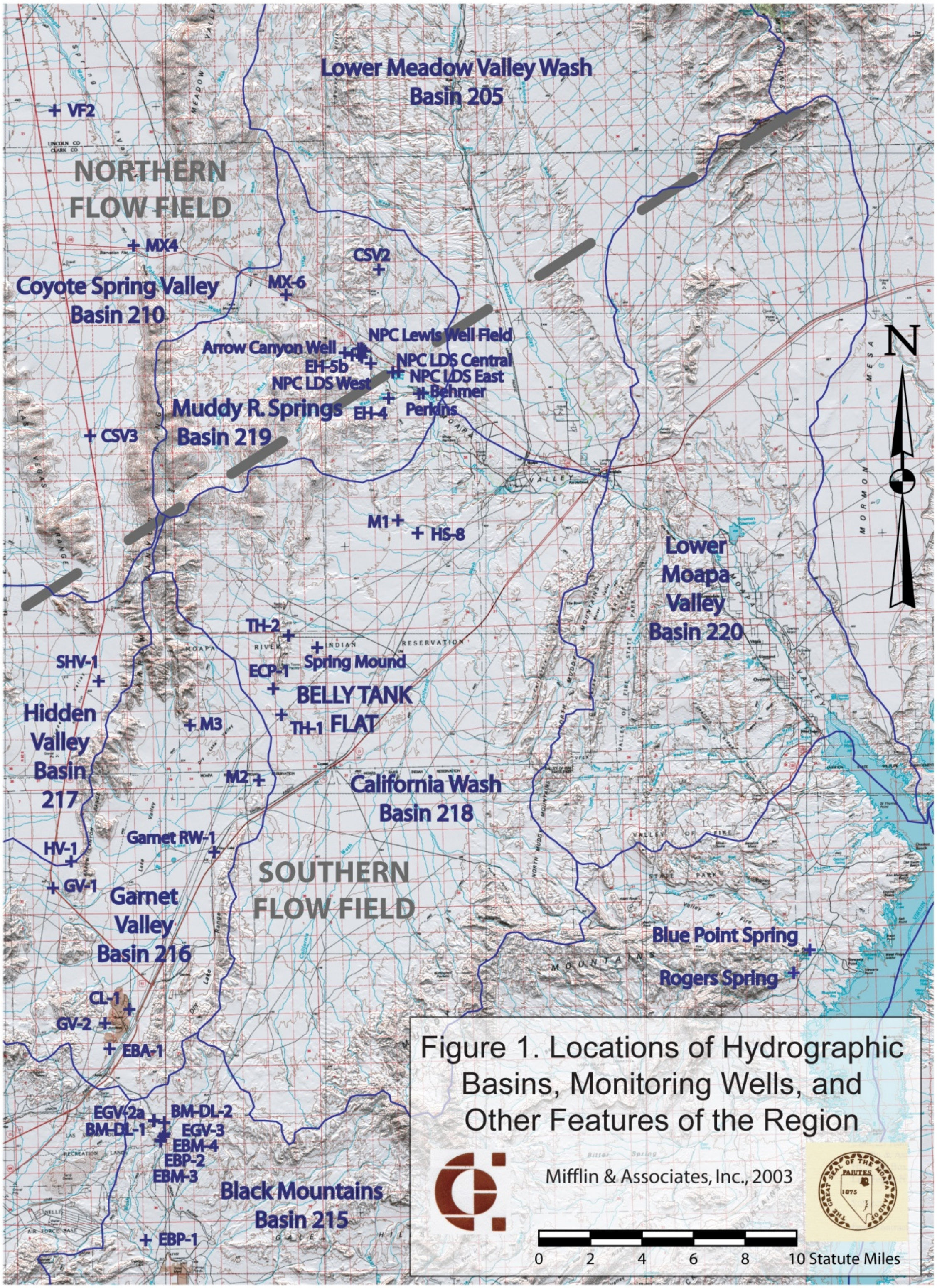

[file CalpineFigure1A.jpg]

have and will continue to impact the Muddy River in direct proportion to their magnitudes, and that discharge reductions are partitioned unequally between large springs and seepage from the alluvial aquifer. Water-balance accounting reconstitutes the natural groundwater flux sustaining the Muddy River to variable rates that lag multi-year climate cycles. Removal of water from the alluvial aquifer in the headwaters area captures water in transit from the underlying Carbonate-Rock Aquifer, which passes through the Muddy Creek Formation via conduits and into the alluvial aquifer, to form the base flows of the Muddy River. Decreased supply from the Carbonate-Rock Aquifer to the alluvial aquifer is equivalent to removal of water directly from the alluvial aquifer, though the time scales over which remote diversions are expressed as River discharge reductions may be prolonged and depend on where groundwater in the up-gradient flow system is diverted (Bredehoeft, 2011).

<u>Background</u>

There has been a long and continuing history of claims and actions that anticipated the regional carbonate aquifer in and up-gradient of the Muddy River Springs area contains a separate (available for appropriation) groundwater resource. The primary water-management questions from past groundwater development proposals in the Muddy River Springs area were related to uncertain relationships between the alluvial aquifer, the underlying carbonate aquifer, and the springs and seepage that give rise to the Muddy River. Now these basic questions have expanded to address more distant up-gradient areas in Coyote Spring Valley and Kane Springs Valley, where fluid-potential relationships, highly-transmissive carbonate-aquifer characteristics, similar water chemistry, and isotopic trends indicate close hydraulic continuity within a groundwater flow system extending to the Springs area and discharging to establish the Muddy River base flows. The earlier questions related to groundwater development in the Muddy River Springs area have been answered by the subsequent history of decline in Muddy River discharge, and water-balance analyses that show the declines are proportional to diversions of tributary groundwater from above the Moapa gage in the Springs area. Now the Order 1169-related groundwater applications in Coyote Spring Valley raise a similar question: is this region of the carbonate aquifer flow field tributary to the Muddy River and in close hydraulic continuity?

The massive and unprecedented water-rights applications of 1989 affect a region where quantitative hydrologic information is sparse and expensive to acquire, and where decades could elapse before pumping effects propagated from up-gradient areas are recognized by monitoring, if indeed they can be recognized at all (Bredehoeft, 2011). Impacts of Order 1169 testing are overprinted on two historic cycles of evaluation, debate, and decision-making that led to large increments of groundwater export from the headwaters area and impacts on the Muddy River system. The first cycle was initiated by the 1963 Nevada Power Company (NPC) purchase of the Lewis Well Field (Figure 2) and NPC's subsequent change applications to increase the associated water rights and export the water for industrial purposes. In testimony before the State Engineer on June 29, 1966, Dr. George B. Maxey explained his report (Maxey and others, 1966) and stated his conviction that it would be impossible for pumping from the Lewis Well Field to decrease springflow in the headwaters area. Significantly, Maxey did not mention the findings of Eakin (1964) and Eakin and Moore (1964) that show seepage from the

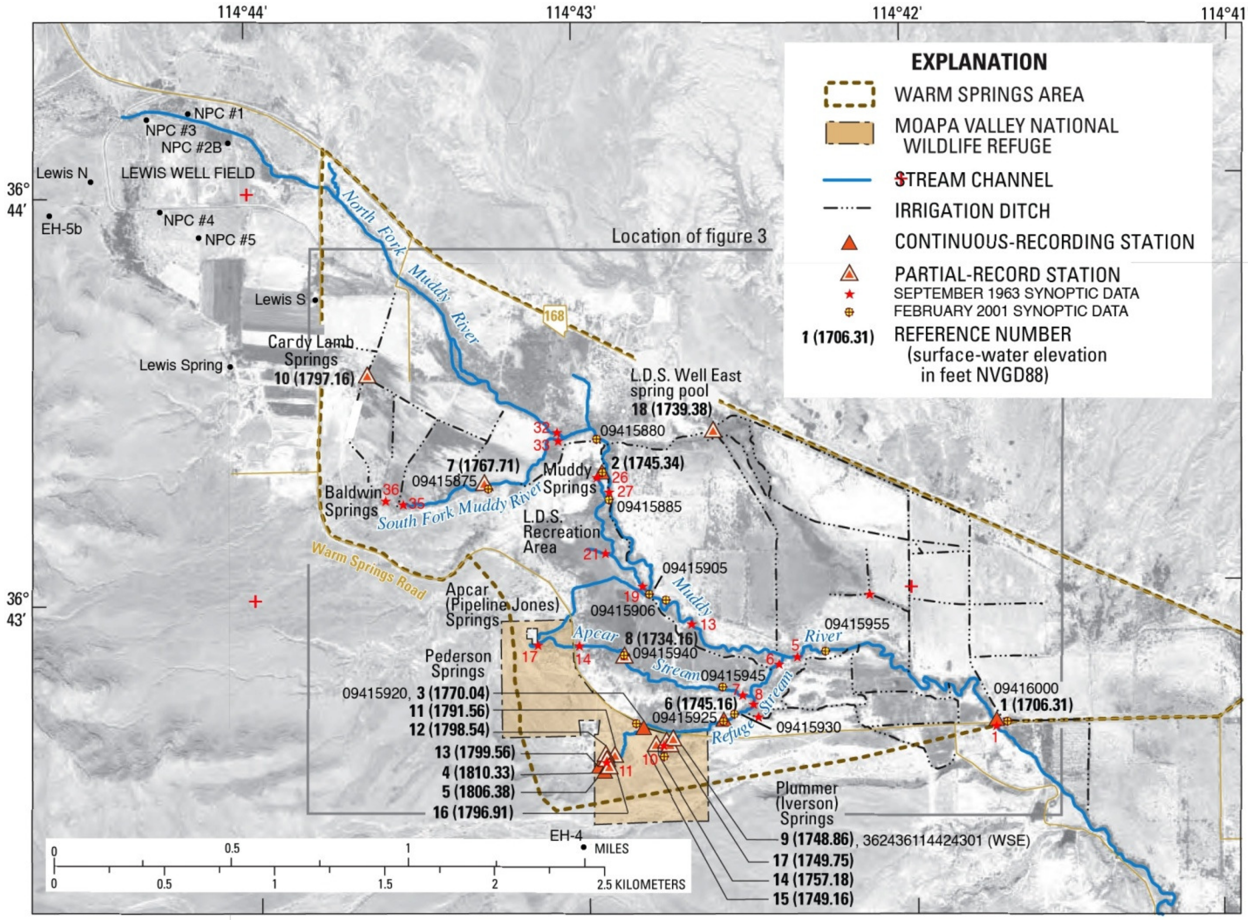

Figure 2. Muddy River headwaters area, selected monitoring and measurement sites, and area of Eakin (1964) Figure 3. The Arrow Canyon wells are 485 meters ((0.3 mile) west of Lewis N, near the west margin of the map area. [file HeadwatersMapGR83c.jpg, modified after Beck and others, 2006, Figure 2]

alluvial aquifer contributes as much or more water to the base flow of the Muddy River as does tributary flow originating directly from large springs. In Ruling 957, the State Engineer overruled protests to the change applications on the grounds that "their granting will not impair the value of existing water rights or be otherwise detrimental to the public welfare". A citation of Eakin and Moore (1964) in Ruling 957 relates to a 15-20-year time lag between regional precipitation and spring discharge response proposed by Eakin (1964). Eakin (1964, p. 14) also states: "Although some recharge to the ground-water reservoir in the valley fill is derived from local precipitation, most is derived from surface and sub-surface discharge of the Muddy River Springs." Water temperatures in the Lewis Well Field (Appendix D) demonstrate that Eakin was correct, and that export of Lewis Well Field water diminishes seepage into the headwater channels of the Muddy River and therefore impacted base flows measured at the Moapa Gage.

The second cycle of groundwater development for export began in 1990, when Moapa Valley Water District (MVWD) filed Application 55450 to appropriate 3.0 cubic feet per second (cfs) from an underground source (the Carbonate-Rock Aquifer) for municipal purposes. In 1992, MVWD filed Application 58269 to appropriate an additional 5.0 cfs from the same underground source for municipal purposes. The Arrow Canyon #1 well was the proposed point of diversion for both applications. On Page 10 of Ruling 4243 of October, 1995, the State Engineer recognized the need to address the issue of whether additional diversions from the Carbonate-Rock Aquifer at the Arrow Canyon Well would reduce the inflow to the alluvial aquifer to a point where the water available in the basin would not satisfy the existing rights within the basin. On Page 9 of Ruling 4243 the State Engineer accepted evidence (testimony) from hearings held during January and February of 1995 that unappropriated water from California Wash, Lower Meadow Valley Wash, and surface inflows was available for appropriation. The Applications were approved by Ruling 4243, contingent upon approval of a comprehensive monitoring plan and review of monitoring records that would continue through 2004. This may be the first instance of the State Engineer justifying appropriations in one water-management basin because there was judged to be unappropriated, related water in adjacent basins. Ruling 4243 hints at recognition of the inter-basin relationships of the Carbonate-Rock Aquifer, but seems to ignore the Muddy River Decree of 1920 which established senior water rights for all Muddy River flow and protected all tributary sources from subsequent appropriations.

The diverse body of evidence currently available is inconsistent with the notion that “new” water is available in up-gradient extents of the Carbonate-Rock Aquifer, which is definitively in close hydraulic continuity with the Springs-area discharge. We have reviewed and analyzed varying lines of evidence in the attached appendices, beginning with classical hydrogeology and then treating water mass balance, climate effects, base flow separation, water demand for power generation, selected water temperature records, mixing and mass balance calculations, EC response to pumping at NPC #2A, and temperature profiles in the Lewis Well Field. We conclude that the hydrogeological evidence is internally consistent with ~1:1 impacts on Muddy River flows resulting from the production of groundwater from the Carbonate-Rock and alluvial aquifers in the Springs area and the up-gradient flow regime in Coyote Spring Valley and Kane Springs Valley.

<u>Reconstitution of Groundwater Discharge and Natural Flux</u>

SNWA and MAI have adopted fundamentally different approaches to evaluating the impact of diversions on the discharge of the Muddy River, and obtain substantially different results. SNWA *subtracts* measured and estimated annual diversions from average 1946 base flow derived by the “Median + 20” method of Johnson (1999), and compares the result to the Median + 20 impacted base flow separated from the observed Muddy River hydrograph as a measure of validity. The underlying assumption by SNWA is that 1946 base flow is representative of the natural (non-impacted) discharge rate and is invariant. MAI begins with the premise that groundwater flux to the headwaters area varies as a function of regional climate, and after separating impacted base flow from the observed hydrograph by the method of Wahl and Wahl (2007) *adds* measured and estimated diversion rates to obtain a “reconstituted hydrograph” that represents total groundwater *flux*, as contrasted with discharge. Temporal variations in this derived natural flux are expected, and the MAI measure of validity is the absence of an overall trend of reconstituted flux for the 7 continuous decades of discharge recordkeeping at the Moapa Gage on the main stem of the Muddy River.

An observation has been put forth by the Southern Nevada Water Authority (SNWA) that pumping from the Carbonate-Rock Aquifer in the headwaters area does not affect Muddy River discharge, supported by Slide 21 (SNWA PowerPoint presentation, HRT meeting of November 15, 2012), and reproduced here as Figure 3. The slide updates Figure 5-11 of Exhibit 54 (LVVWD, 2001), but differs substantially from 1996-2000, the period of overlap. Figure 5-11 (the 2001 version of Slide 21) highlights "a better correlation is achieved by subtracting only the valley-fill pumpage" for 1995-2000. In contrast, Slide 21 shows better correlation until 2006 with "1946 flow less all pumpage/diversions". To our knowledge SNWA has made no explicit finding or acknowledgment that Arrow Canyon Well pumpage is impacting the River, but that is the implication in the evolution of Slide 21.

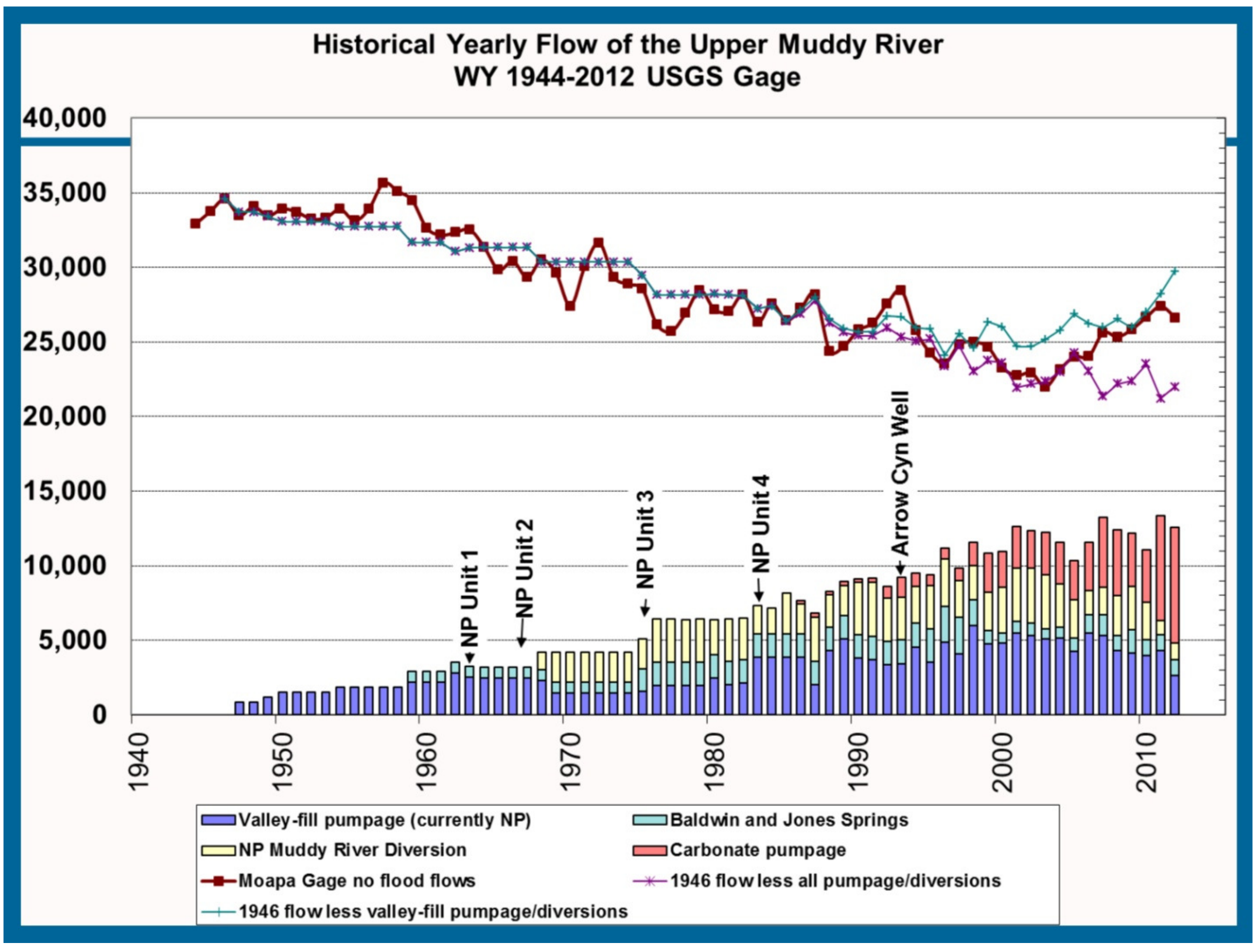

Figure 3. Slide 21 from the HRT presentation by Jeff Johnson, November 15, 2012. The differences (negative in 1957-1959, positive in 1976-1978, for example) argue against the assumption that natural flux (and therefore non-impacted base flow) has remained constant at 1946 levels [file SNWAoriginalReconst.jpg, rasterized from "SNWA Monitoring update 11-01-12.pdf"]

To illustrate the differences between SNWA and MAI analyses of diversion impacts on the Muddy River, we overlay the Slide 21 data with equivalent MAI reconstitution results (Figure 4). The hazed graphics on Figure 4 are the SNWA content of Figure 3, supplied for reference; the bold overlay is the result of our analyses, registered to the x-y grid of Figure 3. The salient differences and their explanations are as follows:

1. The annualized natural-flux hydrograph at the top of the chart is the result of MAI's reconstitution effort. It is consistently above the constant base flow assumed by SNWA for two reasons: surface-water diversions equivalent to the post-2007 Intentionally-Created Surplus (ICS) and evapotranspiration (ET) have been restored to improve the resolution of other seasonal impacts and permit the resolution of lag times. SNWA does not explicitly consider either of these factors in their water-balance model.
2. Impacted base flow, based on observed discharge and represented by the bold purple trace labeled "Reconst (VF+BJ+RI+Carb+ET+ICS)" on Figure 4, is the starting point for the MAI reconstitution and close to the SNWA target hydrograph labeled "Moapa Gage no flood flows" in Figure 3. Small differences arise from different methods of base flow separation from flood flows (Appendix B).
3. SNWA assumes that the Behmer and Perkins wells, which are located down-river from the Moapa Gage, in an area where the alluvial aquifer is confined (Mifflin and others, 1991), participate in reducing discharge at the Moapa Gage, whereas MAI assumes they do not.
4. SNWA does not account for the time lags associated with groundwater exports from the headwaters area, documented by Mifflin and others (1991) as pumping cones that migrate seasonally in the alluvial aquifer to eventually capture flows that nourish the Muddy River by the end of the summer pumping season. SNWA apparently assumes that effects from pumping in Coyote Spring Valley are also expressed instantaneously, rather than building with time as storage in the up-gradient aquifer system is depleted and the decrease in regional flow is propagated to the Springs area; this creates mass-imbalance after 2006 in their model.
5. SNWA utilizes a model of total NPC water demand based on generating capacity; MAI uses measured demand for Reid Gardner Unit 1 and Units 1+2+3 to interpolate Unit 2 demand from 1968-1976 (Appendix B).

The MAI analysis of system responses depicted in Figure 4 accounts for all of the factors itemized above. The most important conclusion to be drawn from the comparison with Figure 3 is that when the natural groundwater flux sustaining the Muddy River is reconstituted rather than prescribed, an entirely different picture of impacts emerges. The divergence of "1946 flow less all pumping/diversions" (Figure 3) from the measurement record is largely an artifact of 1) the assumption that annualized base flow is constant, and 2) the expectation that pumping in Coyote Spring Valley (CSV) would be expressed instantaneously in the Moapa Gage discharge record, which Bredehoeft (2011) demonstrates to be highly unlikely. When CSV pumping is represented as a backward-looking 3-year average, reconstituted natural groundwater flux ("Reconst MR" on Figure 4) remains well within the historic range. Appendix B provides a step-by-step explanation of the reconstitution process.

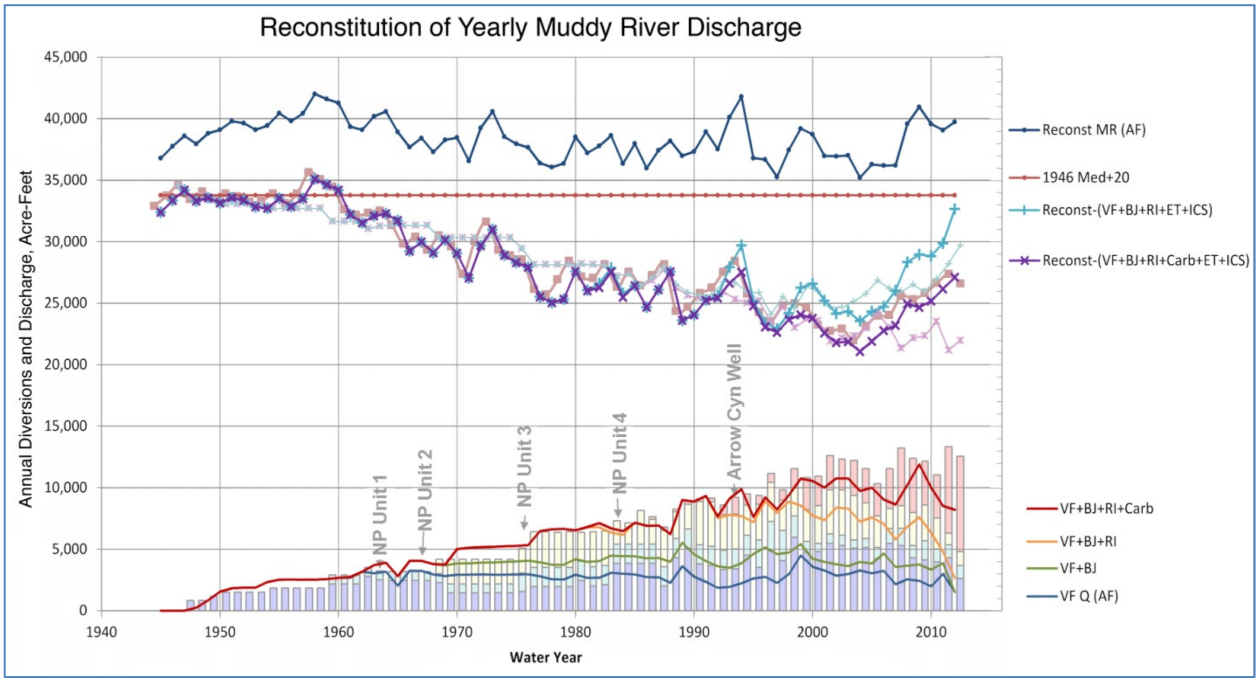

Figure 4. Comparison of *effective* annual diversion rates accounting for lag, ICS, and base flow variations with the SNWA model of Figure 2. The data curves at the bottom of the chart are designed to drape the corresponding SNWA column chart segments for ease of comparison. Mis-alignment of bold and hazed content along the x (time) axis is likely the result of MAI plotting water-year data at the exact x-value of the water year (e.g., data from Water Year 1980 plot directly above "1980" on the horizontal axis), whereas SNWA appears to use Excel dates with the year-value corresponding to the start of the year or water year. Reconstitution of flows provides an exact match to the "Reconst MR" curve at the top of the chart, which is historical yearly natural flux according to our analysis. The flat-line base flow and other assumptions by SNWA (particularly the expectation of instantaneous impacts from Coyote Spring Valley pumping) result in the divergence of "1946 flow less all pumpage/diversions" of Figure 3 from "Reconst-(VF+BJ+RI+Carb+ET+ICS)" of Figure 4, which represents observations, after 2006. [file SNWAcomparisonChart.jpg, derived from file ReconstSimple4.xlsx, sheet 'WYsummary']

Predicting Future Effects

"Climate" refers to variable weather patterns that have produced multi-year droughts and exceptionally wet periods in the general region, resulting in variations in natural groundwater flux to the headwaters area. These climate variations, which cause flux to vary by ±9% about the long-term average (Figure 4), are likely complex and potentially involve both differing response (lag) times and magnitudes due to multiple recharge zones of the regional Carbonate-Rock Aquifer, and variations in magnitude and distribution of weather-related events. There are also occasional, direct surface-water runoff events from local storms that produce shorter periods of increased flow and local recharge along ephemeral streams. Complicating the timing of impacts on natural flux to the headwaters area are the effects of aquifer storage capacity and flow-path lengths, which delay the arrival of flux components in the Muddy River headwaters area. Expressions of these climate-derived signals in Muddy River base flows are varied in timing and magnitude due to variable location and intensity of their origins. While it appears that some distant source area dominates the pattern of variable natural groundwater flux (Appendix C), the effect of combining numerous climate-signal components of non-stationary frequency, variable intensity, and multiple travel paths results in net amplification at some times, and cancellation at others as combinations of wet+wet, dry+dry, or wet+dry signals reach the headwaters area to determine instantaneous flux.

The observations of Eakin (1964) and Eakin and Moore (1964) have been extended to provide a refined estimate of the time required for the natural flux from which the Muddy River is derived to be influenced by climate (Figure 5). A composite climate index was developed for this study using the same monthly precipitation record from Adaven used by Eakin and referenced by Maxey and others (1966), which continued until 1980, combined with monthly infiltration estimates from Lower Meadow Valley Wash (based on losses between Caliente and Rox) and storm runoff measured at the Glendale gage (Appendix C). The sum of squared differences between the climate index and the Muddy River hydrograph reaches a minimum when the climate signal is lagged 248 months (about 21 years) with a secondary minimum at 183 months (about 15 years), validating Eakin's 15-20-year lag-time estimate (Figure C-3). Particularly noteworthy is the deep, historic minimum in the climate index associated with the 2000-2004 drought, which will be impacting the Muddy River in about 10 years.

We emphasize the distinction between the "correspondence" illustrated in Figure 5 and "correlation". The climate and discharge signals are statistically uncorrelated, but correspond best with a response-lag time of 248 months (Appendix C). Attempts to apply linear regression models to relate a climate index to discharge from a regional flow system (e.g., Avon and Durbin, 1994) have failed for reasons discussed by Harrill and Bedinger (2005). In essence, a regional-scale groundwater flow system contains multiple recharge areas, and precipitation on each of the recharge areas will differ as will geologic conditions affecting infiltration and recharge. The recharge areas are at different distances from the common discharge area, and consequently recharge or pressure changes will have different lag times before arriving at the discharge area. The correspondence relations depicted in Figure C-3 are the result of several climate signals, with different intensities and lag times, combining to determine the natural flux arriving at the headwaters of the Muddy River. As identification of recharge areas progresses and monitoring of factors affecting recharge becomes more comprehensive, the reliability of climate indices as predictors of Muddy River discharge may improve.

<u>Muddy River Tributary Groundwater Components</u>

The complex discharge environment in the Springs area, which receives groundwater flux from multiple fracture and porous-media flow paths, integrates flux components with a range of origins and residence histories into the mixture that constitutes the Muddy River. Trigger levels incorporated in the Memorandum of Agreement (MOA) were based on speculation in the Biological Opinion (USFWS, 2006) that the highest-elevation springs would be impacted first by pumping in CSV, and to a limited degree this idea has been validated by discharge reductions in the Pederson Springs area (Figure 6).

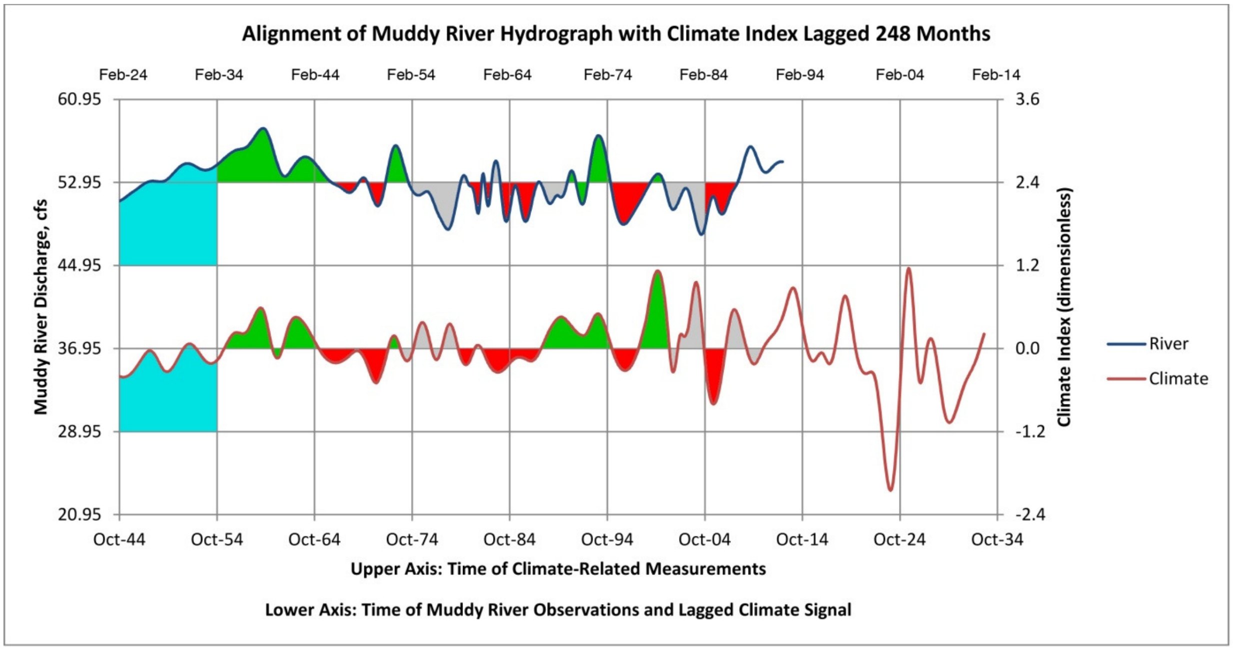

Figure 5. Correspondence of lagged climate index and natural groundwater flux represented as a reconstituted Muddy River hydrograph. The composite climate index is projected 248 months forward in time as an indicator of model-forecasted River response. This revises and extends Figure 4 of Eakin (1964). Aqua tint highlights the early trend, green and red highlight times of relatively good correspondence, and gray indicates generally poor correspondence. According to this predictive model the Muddy River is in for a wild ride over the next two decades due to the increasing frequency and strength of extreme weather events (Hansen and others, 2012) [file ClimateLag5.jpg, enhanced from file 3climateIndicesV5.xlsx, sheet 'ProjectIndex']

Recognition that seepage flux, as contrasted to conduit discharge from the major springs, is a major contributor to the overall water budget of the Muddy River invites analysis of where the seepage occurs across the headwaters area and how different tributary reaches have been impacted by Order 1169 pumping. In principle, this can be accomplished by mixing and mass-balance calculations, where sufficiently comprehensive monitoring records exist. Underlying this approach is the idea that mixing of end-member waters produces a mixture that is intermediate with respect to temperature and those dissolved constituents that do not react or otherwise enter or leave the mixing system. Such constituents are referred to as *conservative*, meaning they are conserved in the mixing process. Conservative natural tracers include the stable isotopes of oxygen and hydrogen, generally non-reactive ions such as chloride and fluoride, electrical conductivity (EC), and temperature (subject to open-channel heat exchange uncertainties).

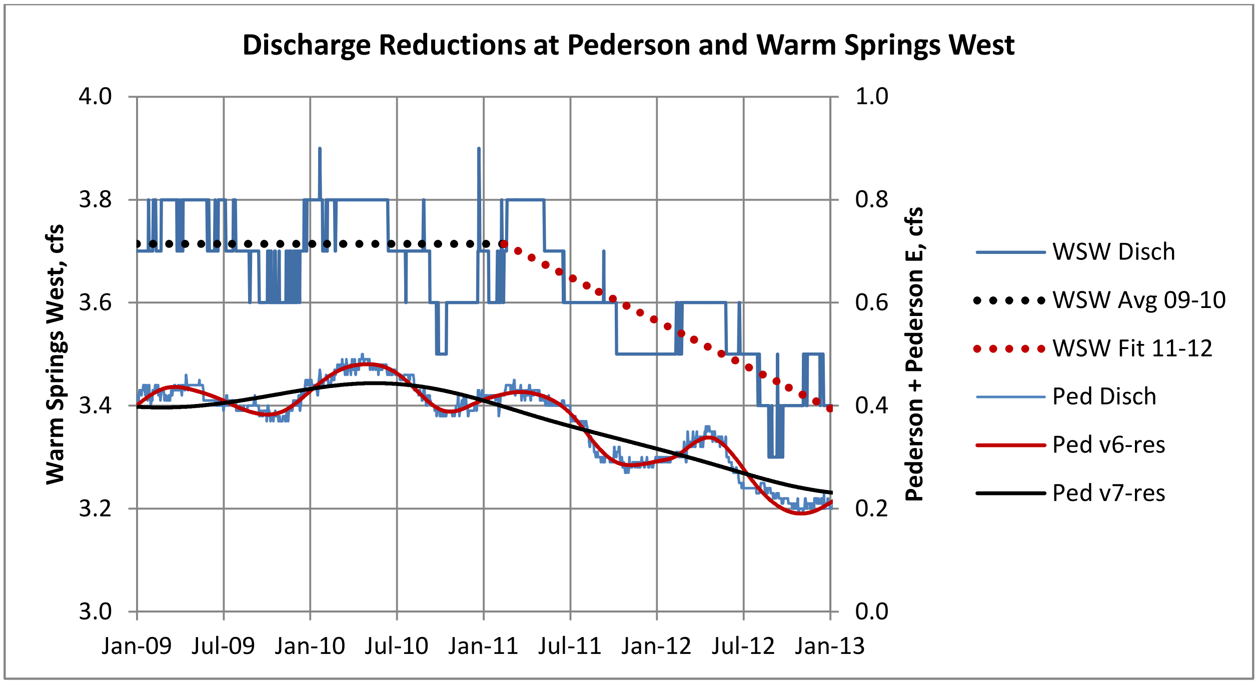

Figure 6. Reduction of discharge at the combined Pederson and Pederson East springs appears to have stabilized at a rate of 0.09 cfs/year, which would result in extinction of the Springs in ~2.5 years if this rate of reduction continues. At Warm Springs West the reduction rate is 0.17 cfs/year, and ~20 years would be required for elimination of flow at that location at the present rate. These relations indicate that seepage gains along headwaters channels dominate the flows measured at Warm Springs West. [file CompareSpringsRiver.xlsx, sheet 'ComparePedWSW']

In the headwaters area of the Muddy River, which contains the largest thermal spring in Nevada, Big Muddy Spring (Garside and Schilling, 1979), numerous springs discharge water very close to 32°C into a closely-interconnected alluvial-aquifer and stream system that maintains the flux sustaining the Muddy River within about ±9% of its historic average (Figure 4, curve "Reconst MR"). There are four major, recognized areas of tributary groundwater inflow to the Muddy River: North Fork (Pahranagat Wash), South Fork (Baldwin and Jones Springs), Refuge Stream (confluence of Plummer and Pederson flows), and Muddy Springs Tributary (Figure 2). Large springs characterize the latter three areas, and based on synoptic sampling by ERTEC (1981) the water quality in the large springs is virtually identical. During 1963 and 1964, Eakin and Moore (1964) monitored discharge from the largest spring groups at several localities (Figure 7) and found minimal seasonal variation in spring discharge, in contrast to the discharge of the Muddy River, which is influenced by the annual ET cycle (Figure 8).

When seepage gains along a tributary reach are documented by simultaneous discharge measurements and accompanied by electrical conductivity (EC) measurements, the EC of the seepage flux can be established by a simple mixing calculation using EC as a conservative tracer. Eakin's (1964) study provides the baseline data needed to evaluate pre-development mixing kinematics in the headwaters area, and from which to evaluate the evolution of water quality in the area in terms of diminished seepage gains along specific tributary reaches.

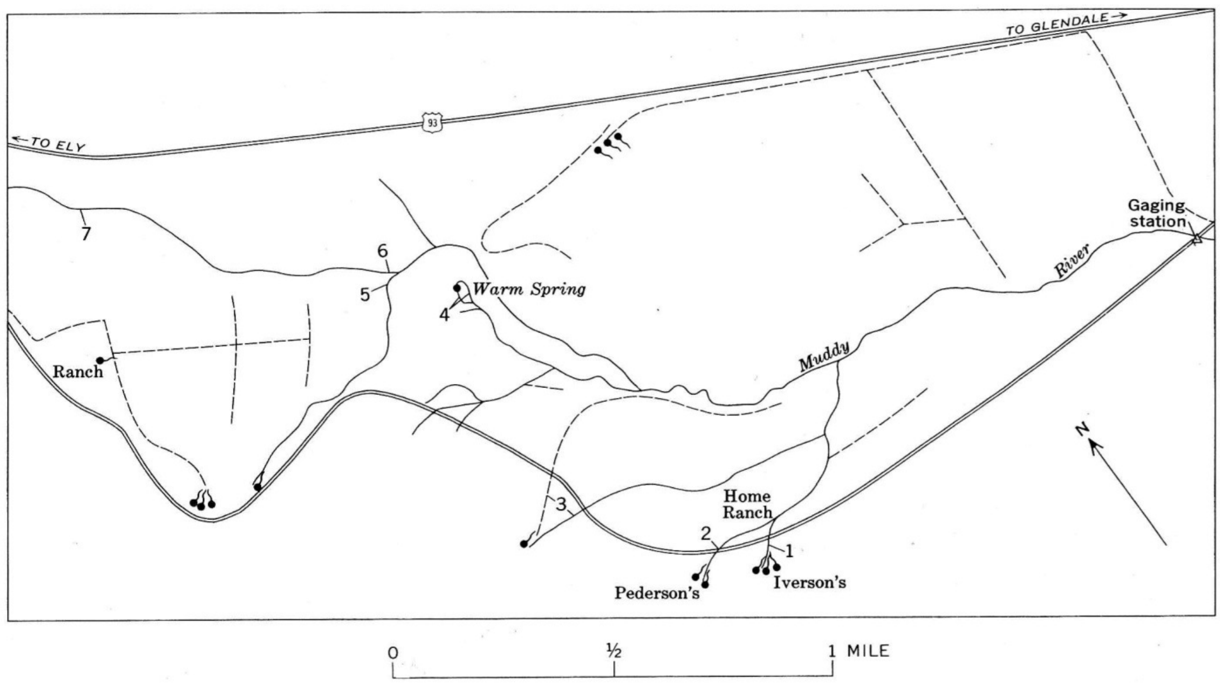

Figure 7. Numbering scheme for selected monitoring stations on the Muddy River and tributaries used by Eakin and Moore (1964); locations correspond with measurements reported by Eakin (1964), as shown in Figure 2, but numbering differs. [file EakinMoorePP501Dfig2.jpg]

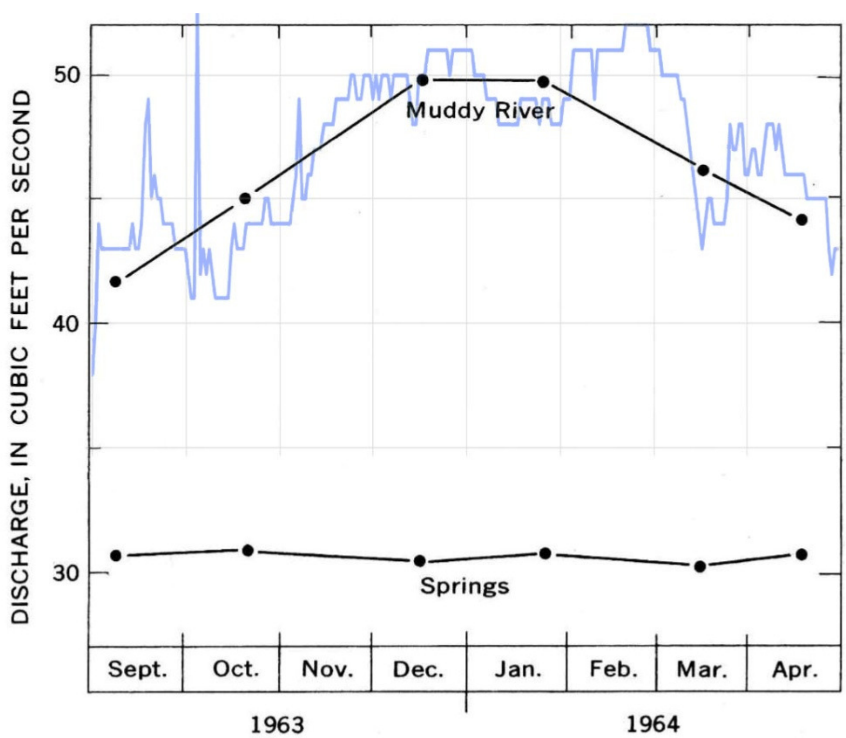

Figure 8. Field measurements reported by Eakin and Moore (1964) with daily discharge (blue haze) from the Moapa Gage, USGS ID 09416000. "Springs" refers to the total discharge at stations 1-6 in Figure 5, apparently adjusted upward by ~1 cfs to account for MVWD diversions from Apcar (Pipeline Jones) Spring. [file EakinMoorePP501Dfig3b.jpg]

No subsequent survey of discharge, temperature, and EC of the Muddy River and its tributaries was as comprehensive as that of Eakin (1964) in terms of spatial coverage. Numerous entities have contributed measurement data, but EC records are particularly problematic because of variable relations between field measurements and laboratory-determined values. We assume that instrument calibration and therefore quality control of laboratory measurements is sufficient to allow direct comparison of laboratory EC data from different laboratories, but field measurements must be adjusted to equivalent laboratory values for inter-comparison of field data from the various sources. We further assume that when laboratory EC measurements are not available, *differences* between close-in-time field measurements are reliable but their absolute values are not. These assumptions allow us to use less-frequent laboratory measurements to normalize field EC data to, hopefully, a measure of internal consistency (Appendix E).

Has a reduction of perennial flow in North Fork gone unnoticed? Flow in North Fork abruptly decreased in 1992-93, coinciding with increases in water exports from the headwaters area (Figure 9). In September of 1963 D.O. Moore (as reported by Eakin, 1964) measured 4.23 cfs and a field EC of 1,330 µS/cm above the confluence with South Fork (point 32 on Figure 2 and point 6 on Figure 7), and in March of 1987 the average of 2 USGS measurements was 4.81 cfs without supporting EC data. MAI measured a field EC of 1,018 µS/cm in April of 1987 at the historical "Big Wash Flume" (NDWR) site in lower North Fork (Figure 2, near Eakin point 32), slightly greater than the median of 938 µS/cm from profiles in the Lewis Well Field during the same month with the same instrument.

Median groundwater temperatures were 31.0°C in the Lewis Well Field in April of 1987, 11°C greater than the mean annual air temperature at Nellis Air Force Base (Appendix E), and surface flow passing the remnant of the Big Wash Flume was 29.3°C. ***These temperatures could not be sustained without constant throughput of deeply-circulated (Carbonate-Rock Aquifer) water***. In 2001, when a synoptic streamflow and water-quality survey was conducted by the USGS and affiliated agencies (Beck and Wilson, 2006), no measurement of flow or EC in North Fork was made and there is no mention of any such flow (or absence of flow) in their report. Where the 2001 measurement locations do coincide with those of Eakin, however, changes in the discharge regime can be quantified.

Eakin (1964) recognized that waters associated with the alluvial aquifer and entering the Muddy River as seepage flow were of slightly poorer quality than those discharging directly to surface streams from the larger springs. Deterioration of water quality is attributable to a small contribution of discharge from the Muddy Creek Formation, which separates the Carbonate-rock Aquifer and alluvial aquifer in the headwaters area, and to evaporative concentration of solutes near the surface as natural recharge and irrigation return flows infiltrate into the permeable gravels. Eakin's relatively high (1,330 µS/cm) EC in North Fork compared to the 1,170 µS/cm he reports in South Fork allows the EC of a discharge-weighted mixture below the confluence to be calculated, and mixing-cell models to be developed for discrete reaches of the Muddy River and its tributaries between points where synoptic data exist. Calculations of seepage flux along discrete reaches of the Muddy River are presented in Appendix E.

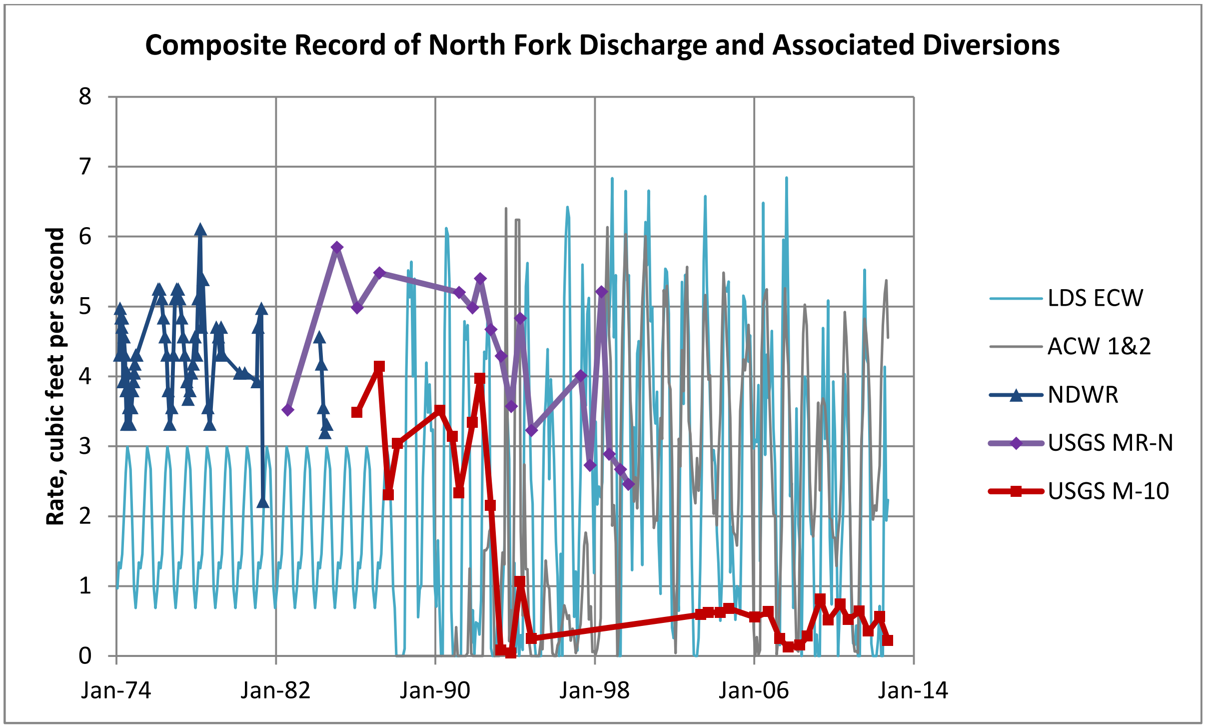

Figure 9. Exports of groundwater to meet demand by Reid Gardner Unit 4 ("LDS ECW") and MVWD's municipal service area ("ACW 1&2") are temporally associated with an almost complete elimination of surface flow in the North Fork of the Muddy River. Consumptive use prior to 1987 is based on estimated irrigation demand at the Taylor wells, later known as LDS East and LDS West. Data from Tables B2 and B47 of Beck and others (2006), who mis-located M-10 as documented by Mifflin & Associates (2010), and the USGS data archive for site 364316114431901. [file NorthForkBigWashM10v2.xlsx]

Stable isotopes, particularly deuterium, are the most reliable tracers known, and Thomas and others (2001) provide a useful compilation of hydrochemical and isotopic data from the region. Limited sampling reported by SNWA and DRI complements the Thomas dataset. Unfortunately no stable-isotope samples from the main-stem Muddy River, Arrow Canyon Well #1 or #2, the Lewis Well Field, or Pahranagat Wash are known to have been analyzed. Still, the Carbonate-rock Aquifer is reasonably well-characterized in terms of the chemical and isotopic composition of its waters, as represented by samples from wells in Coyote Spring Valley, large springs in the Muddy River headwaters area, and two wells on the Moapa Indian Reservation.

The isotopic evolution of groundwater as it moves from Coyote Spring Valley to the headwaters of the Muddy River can be characterized as reflecting admixture of small proportions of isotopically-heavier waters along generally southeasterly flow paths, with the most likely sources including infiltration in Pahranagat Wash and Lower Meadow Valley Wash, and recharge in the Sheep Range. Deuterium concentrations (δD) decreasing from -99.8‰ at CSI-3, to -99.4‰ at MX-5, to about -97.7‰ in large springs of the headwaters area (Thomas, 2001) indicates that Coyote Spring Valley provides the conduit for most, but not all, water discharging in the headwaters area. The δD from Reservation wells is -99.0‰; Johnson and others (2001a, pp. 24-31) and Mifflin and Johnson (2005, pp. 30-32) concluded that available isotopic and geochemical data support groundwater upwelling in the Reservation area.

Regional Water Levels

Well hydrographs from Coyote Springs Valley, through the Springs area and Moapa Indian Reservation, to the Apex area share a pattern of seasonality that cannot be explained by localized pumping with any realistic choice of aquifer parameters. There is no discernible lag or attenuation of the yearly water-level fluctuations with distance from Apex, where pumping is concentrated and seasonal (Figure 10) or from the Muddy River Springs area, where there are seasonal pumping cones developed within the alluvial aquifer that are approximately synchronous in recovery with the annual water-level cycle in the Carbonate-Rock Aquifer. Many have, and continue to, interpret the seasonal water-level cycle as resulting from seasonal pumping or recharge, but the widespread and synchronous nature, as well as the similar and widespread amplitudes between the pumping centers do not support the notions of seasonal recharge or localized pumping signals as forcing agents. Therefore an annual loading phenomenon potentially qualifies based on available evidence.

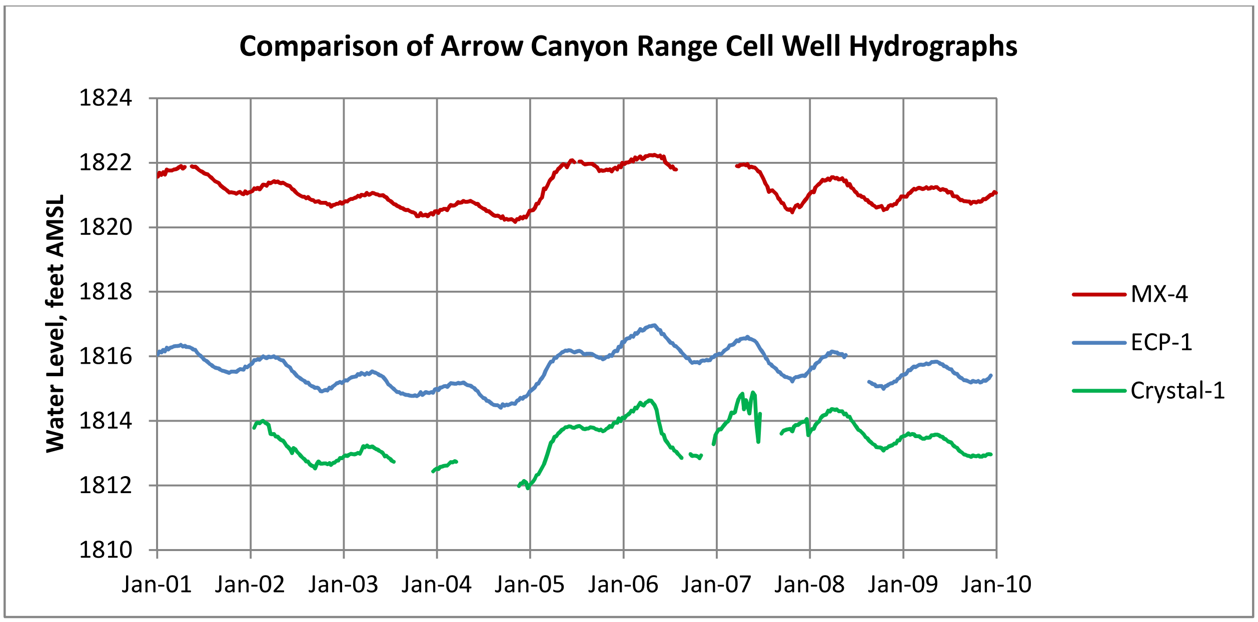

Figure 10. Hydrographs from 3 widely-separated monitoring wells share the same overall trend and seasonality, regardless of distance from pumping centers. [file Compare10yrWL.xlsx]

Smith and others (2004) suggested that the annual cycle might be the result of barometric-pressure fluctuations, but this seems impossible (Figure 11). The seasonal water-level fluctuations are much larger than the corresponding barometric-pressure fluctuations, unlike the pattern at Devils Hole (Harrill and Bedinger, 2005, p. 34). When detrended, however, the inverse relationship between atmospheric pressure and water level is evident (Figure 12). When plotted in terms of detrended total head a barometric efficiency (B.E.=76%) is resolved with high confidence (R^2=0.92; Figure 13). Since atmospheric pressure does not explain the annual cycle in the well hydrographs, it is also apparently not responsible for the seasonality in discharge at Pederson Springs discussed by Smith and others (2004). Barometric effects on water level are nonetheless systematic and important, particularly as the first step in noise reduction procedures that are essential to resolving very small pumping responses (Johnson and Mifflin, 2012b).

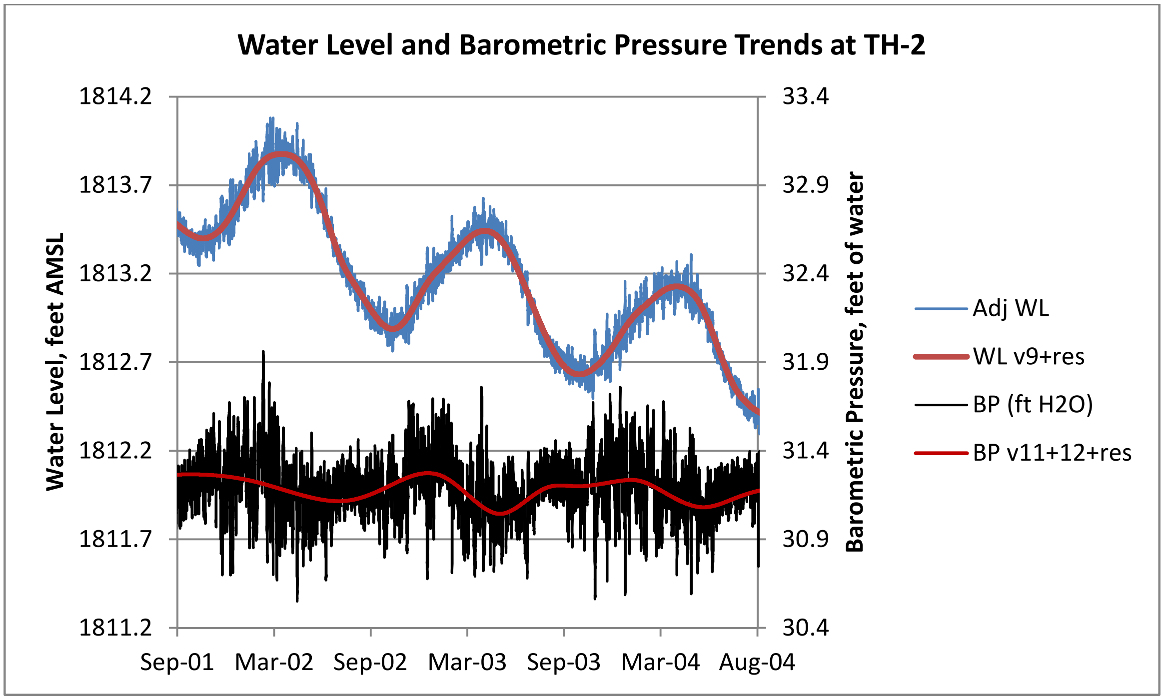

Figure 11. Comparison of daily water-level and barometric-pressure data from monitoring well TH-2 on the Moapa Indian Reservation, with annual trends derived by empirical mode decomposition. [file xTH2wlCumulative2.xlsx, sheet ComparisonPlots]

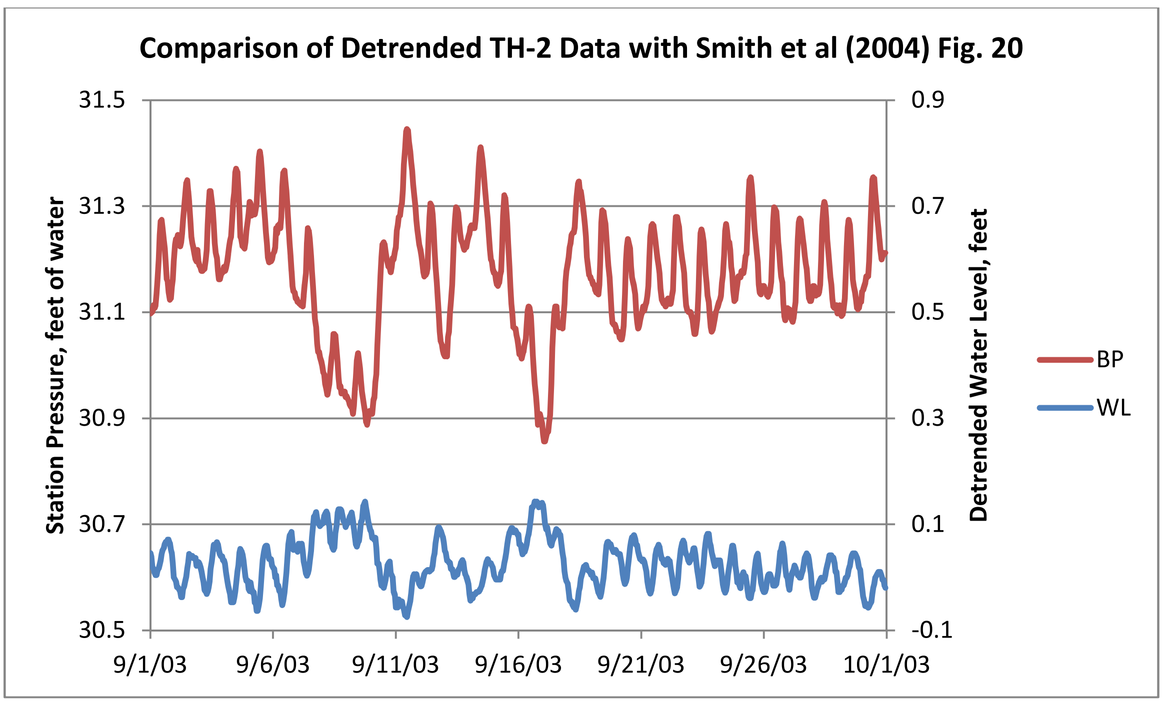

Figure 12. Inverse relationship between detrended water level and barometric pressure illustrated by September 2003 records from TH-2. [file xTH2wlCumulative2.xlsx, sheet ComparisonPlots]

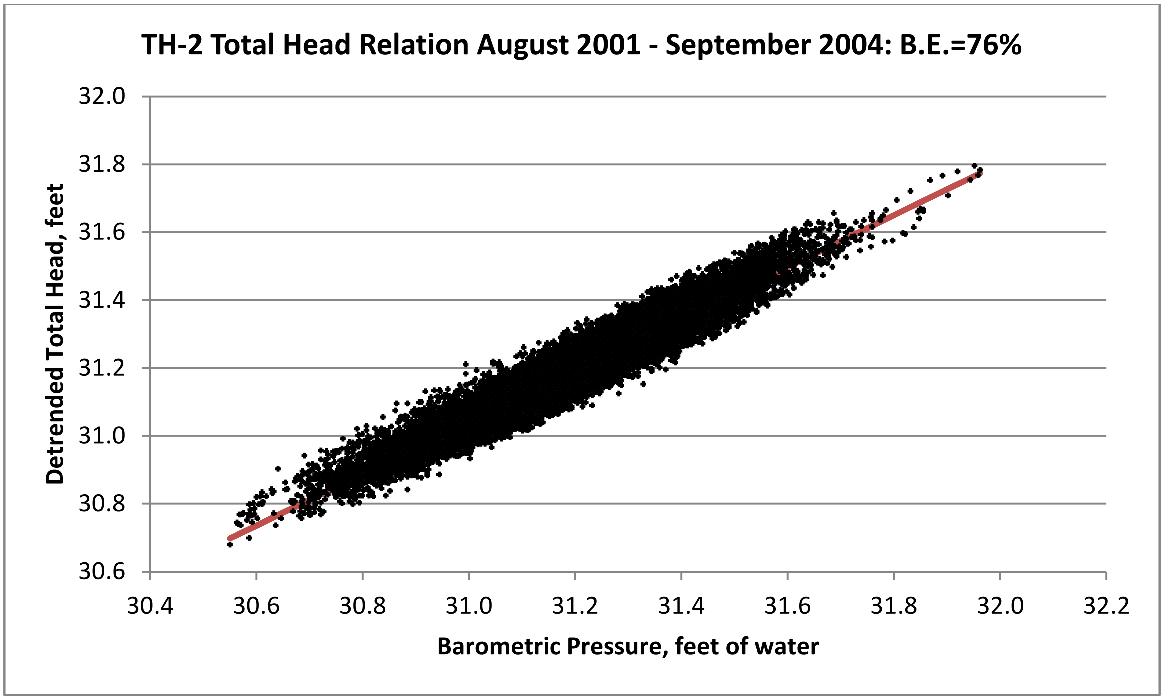

Figure 13. Total head is superior to water level for deriving barometric efficiency relations (Mackley and others, 2010; Rasmussen and Crawford, 1997; Spane, 2002; Toll and Rasmussen, 2007). Compare Figure 19 of Smith and others (2004). [file xTH2wlCumulative2.xlsx, sheet ComparisonPlots]

There is no direct evidence of a discharge area other than the Muddy River Springs for groundwater flux passing through Coyote Spring Valley in the Carbonate-Rock Aquifer, but upwelling beneath the Moapa Indian Reservation does occur based on groundwater temperatures, the presence of paleo-discharge features (cover photo), the fluid-potential gradient toward the south and east beneath the Reservation, and hydrochemical mass balance. The chemical evolution of groundwater moving from the Reservation area toward the east and southeast requires an upwelling source distinct from that feeding the Muddy River Springs (Johnson and others, 2001a, pp. 26-27). These multiple lines of internally-consistent evidence of upwelling and lateral groundwater flux were dismissed by the State Engineer as “speculative” on Page 22 of Ruling 5115, without the benefit of data and discussions in Johnson and others (2001a). At the hearings of July 16-24, 2001, only Johnson and others (2001b), an abstracted version of modeling results, was submitted as evidence (Exhibit 66). Groundwater flux of several thousand AFY toward the Lake Mead area clearly occurs, though no major springs along the lower Virgin River were documented prior to filling of the Lake (Carpenter, 1915; Longwell, 1936).

After using empirical mode decomposition (EMD) to extract the annually-fluctuating components of Lake Mead water levels and comparing them with the annual cycle observed in MBOP monitoring wells, a lag between Lake Mead fluctuations and those in the monitoring wells is evident as recognized by Buqo (2004) (Figure 14). This relationship may help explain the widespread seasonality of groundwater levels as resulting from some combination of loading-related pore pressure changes and pore volume reductions or, as Buqo (2004) suggested, propagation of head changes at the outflow boundary up-gradient into a confined-aquifer system. With no outflow boundary in evidence, however, the Buqo thesis of hydraulic continuity with Lake Mead is problematic.

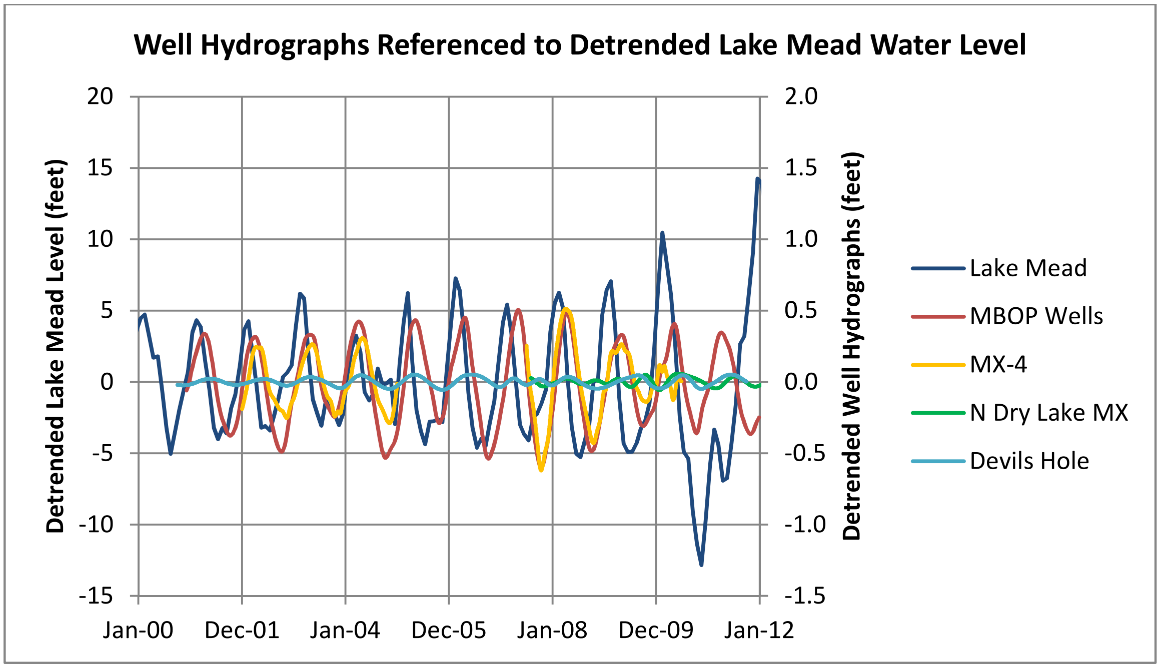

Figure 14. Detrended MBOP water levels lag detrended Lake Mead stage, with annual variability that is about 10% that of Lake Mead. There is a slight lag and attenuation of MX-4 levels with respect to the synthetic MBOP hydrograph. Only weak annual cycles attributable to barometric and earth-tide effects are resolvable in the Carbonate-Rock Aquifer 100 miles (160 km) north of Moapa in the North Dry Lake Valley MX well (Log #22450, USGS Site ID 380531114534201) and at Devils Hole (USGS Site ID 362532116172700) 100 miles to the west. [file LakeMeadMonthly.xlsx, sheet 'LakeMeadEMD']

Between the Moapa Indian Reservation and Lake Mead there are multiple potential lithologic and structural barriers to eastward groundwater flow, accompanied by a large hydraulic gradient (Figure 15). Rogers and Blue Point Springs discharge a combined total of only about 2.2 cfs at near 30°C and 4,200 µS/cm along the Rogers Spring Fault (Pohlmann and others, 1998) at an elevation of ~ 1,550 feet AMSL. Discharge from Rogers Spring appears to reflect the effects of long-term climate seen in the overall trend of regional well hydrographs shown in Figure 10, but not the seasonality (Figure 16). If Buqo's (2004) conceptual model were correct, Rogers Spring would be very sensitive to Lake-stage changes due to its proximity.

Comparison of hydrographs from MBOP monitoring wells M2 and M3 reveal a systematic lag and attenuation of the annual cycle from southeast (M2) to northwest (M3) (Figure 17). These wells are nominally 30 miles northwest of Lake Mead, a possible forcing agent for the seasonal cycles in well hydrographs (Figure 18). Lake Mead declined in a stepwise fashion from an average level of 1185.09 feet AMSL in 2001 to 1162.19 feet in 2002, and just as the departures from declining trends are illustrated in Figure 14, departures from the declining trends of groundwater levels at M2 and M3 are shown in Figure 17. According to Tighi and Callejo (2011) the decrease in lake storage associated with the 22.9-foot drop was 2.914 million acre-feet, or 127,249 acre-ft per foot; the seasonal component of variability, roughly 10 feet (Figure 14), represents cyclic loading by the order of 1.2 million acre-feet (1.6

gigatons) of water in the Lake Mead Basin in 2001-2002. Less-well-documented seasonal sedimentation adds to the loading cycle.

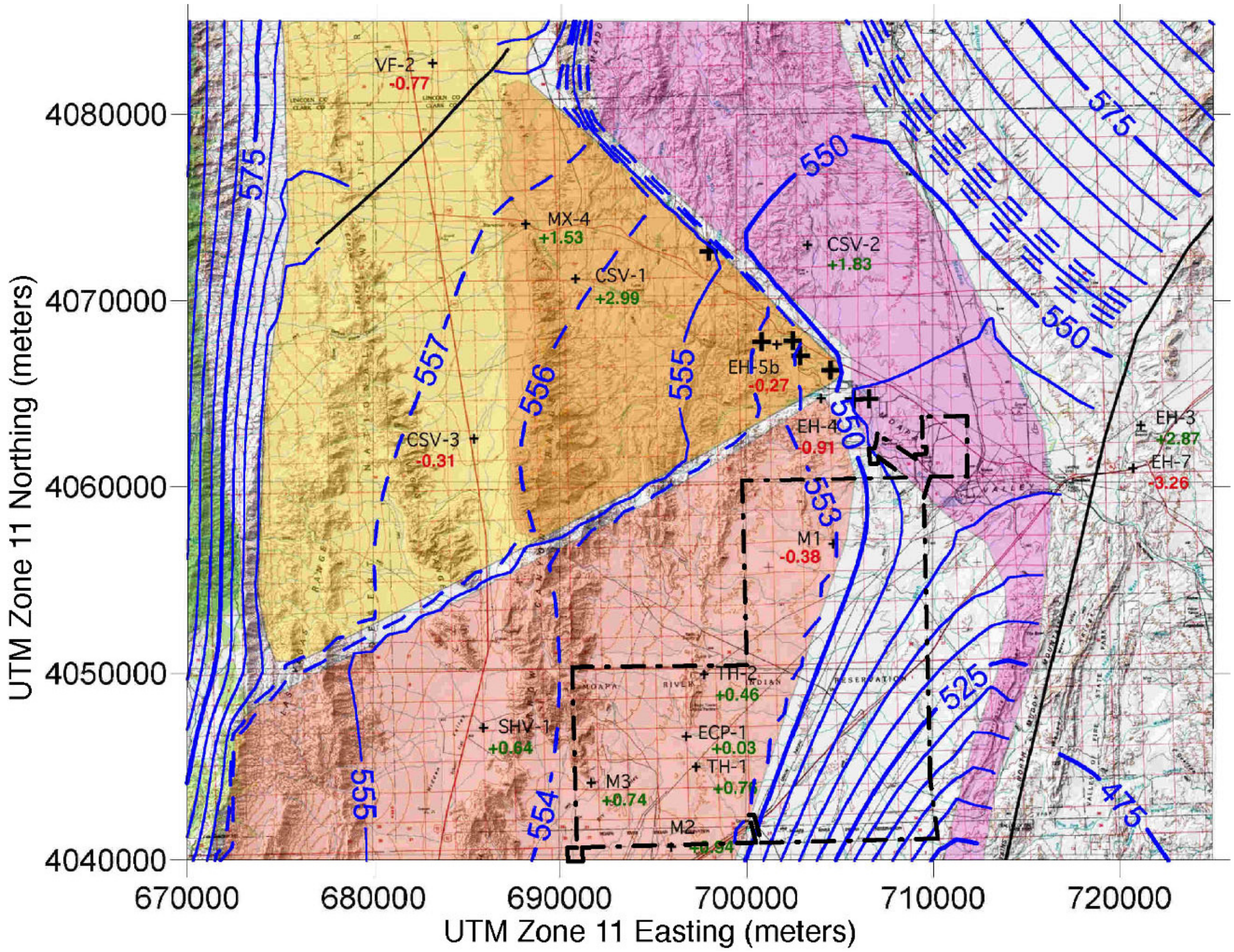

Figure 15. Model-derived water levels (meters AMSL) and calibration residuals in the vicinity of Moapa Indian Reservation. Contour interval 5 meters, 1 meter where dashed [file AshGroveFig3topGR27.jpg]

Crustal loading by large water (and ice) loads results in both elastic and viscous responses (Walcott, 1970), but the annual cycle in crustal loading resulting from water-level changes in Lake Mead is less studied or understood. The area of crustal deformation produced by the filling of Lake Mead clearly extended throughout the Arrow Canyon Range Cell (Figure 18). Paleozoic carbonate rocks extend at depth to the Lake Mead area (Tetra Tech 2012a, Figure 4.2-1) and are widely exposed east of the Lake. Isostatic equilibrium with the water load was reached ~1980 as the viscous substratum was displaced (Kaufmann and Amelung, 2000); subsequent elastic responses in confined portions of the Carbonate-Rock Aquifer to short-term cyclic changes in water load are likely reflected as equal changes in pore water pressure (Mifflin, 1970; Hoffmann and others, 2001).

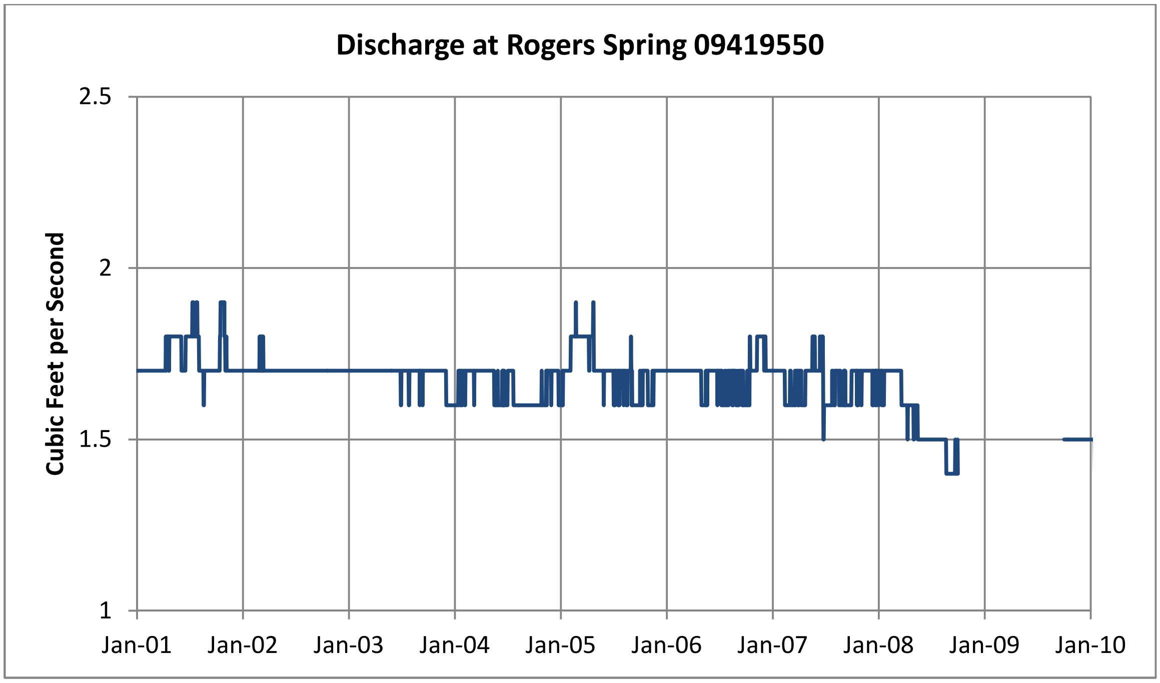

Figure 16. Though relatively coarse in terms of precision, the record of discharge from Rogers Spring appears to show decline from 2001-2004, recovery in 2005, and marked decline beginning in 2008 without the seasonality that Buqo's (2004) thesis suggests. [file RogersSpring85-11.xlsx]

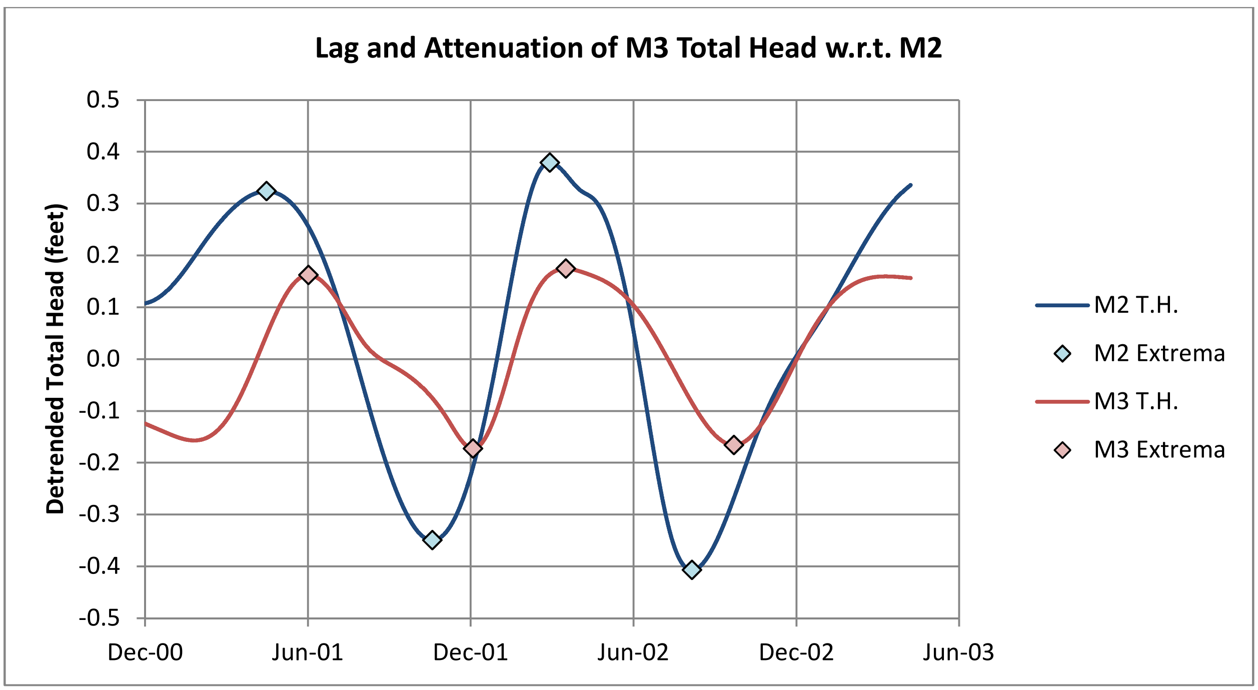

Figure 17. The M3 hydrograph lags the M2 hydrograph by 46 days and is attenuated by 54%, strongly suggesting signal propagation from southeast to northwest, consistent with forcing by loading of the Lake Mead basin [file CompareM2M3.xlsx, sheet 'Compare']

Smith (1999) provides a methodology to utilize cyclic loading as expressed in the detrended M2 and M3 hydrographs (Figure 17) to estimate aquifer diffusivity. The median lag = $F_\theta - R_\theta$ = 46.4 days, where F_θ is the phase of tidal forcing and R_θ is the phase of tidal response. The average peak-to-peak amplitudes are 0.730 feet at M2 and 0.337 feet at M3. M3 is 18,038 feet northwest of M2. If we treat M2 as a tidal boundary, the tidal efficiency TE = R_a/F_a = 0.337/0.730 = 0.462, where F_a is the forcing amplitude at the tidal boundary (M2) and R_a is the response amplitude at a point in the aquifer (M3). The period P of the tidal signal is 365.25 days, so the angular frequency $\omega=2\pi/P$ is 0.0172/day. Smith (1999) gives efficiency-based and lag-based expressions for hydraulic diffusivity (T/S) in terms of tidal efficiency and lag:

$$T/S = \pi x^2/(\ln TE)^2 P = \pi(18{,}038\ \text{ft})^2/(\ln(0.462))^2(365.25\ \text{days}) = 4.69 \times 10^6\ \text{ft}^2/\text{day}$$

$$T/S = x^2 P/4\pi(\text{lag})^2 = (18{,}038\ \text{feet})^2(365.25\ \text{days})/4\pi(46.4\ \text{days})^2 = 4.39 \times 10^6\ \text{ft}^2/\text{day}$$

With these results we can evaluate the aquifer-test interpretation of Mifflin and Johnson (2005) and conversely, the present approach. Johnson and Mifflin (2005) obtained unconfined and confined hydraulic diffusivities of 1.02×10^6 and 4.74×10^6 ft^2/day, respectively, from aquifer tests at ECP-1, bracketing the above results obtained by Smith's tidal method. If unconfined conditions and a specific yield of 0.03 apply, the required transmissivity would be 1.36×10^5 ft^2/day, a factor of four higher than derived from our aquifer-test data. If the transmissivity measured in the aquifer test is representative of the larger area, a storage coefficient of 6.72×10^{-3} is indicated; this is an order of magnitude greater than we derived from re-analyzing aquifer-test data in 2005. If the storage coefficient of 0.0006437 from the aquifer test applies to the tidal forcing, a regional transmissivity of 2,922 ft^2/day is indicated. These results are not inconsistent, since the loading signal is being propagated transverse to the prominent northerly structural grain of the area, whereas the aquifer test at ECP-1 was conducted at a high-yield supply well that penetrated local permeable zones within a north-trending corridor that contains paleo-discharge features and evidence of upwelling groundwater. The large-scale anisotropy indicated by the geologic setting has not been incorporated into prior modeling analyses, and it has become clear that the system cannot be considered to be purely confined or unconfined. The great thickness of the Carbonate-Rock Aquifer, several thousand feet based on water temperatures, allows ill-defined, confined flow domains to co-exist and interact with thick and well-mixed unconfined domains that to date have sustained most groundwater development in the Arrow Canyon Range Cell of Mifflin (1992).

Down-gradient from the Moapa Indian Reservation, groundwater in the Arrow Canyon Range Cell is bounded by less-transmissive lithologies. If confined portions of the Carbonate-Rock Aquifer system extend to areas affected by elastic crustal responses to Lake Mead, they would respond to loading phenomena and propagate pressure signals. Hydraulic continuity in a confined system between the Reservation and the Lake-loading induced deformation would transmit pressure pulses as responses to rise and fall of the Lake, possibly explaining the annual periodicity and the lag and directional attenuation between M2 and M3 (Figure 15). Cavalié and others (2007) discuss "pore pressure diffusion" below Lake Mead in response to loading, indicating that a poroelastic model could explain the observed deformation pattern. "Important delayed effects" should then be expected, and we suggest

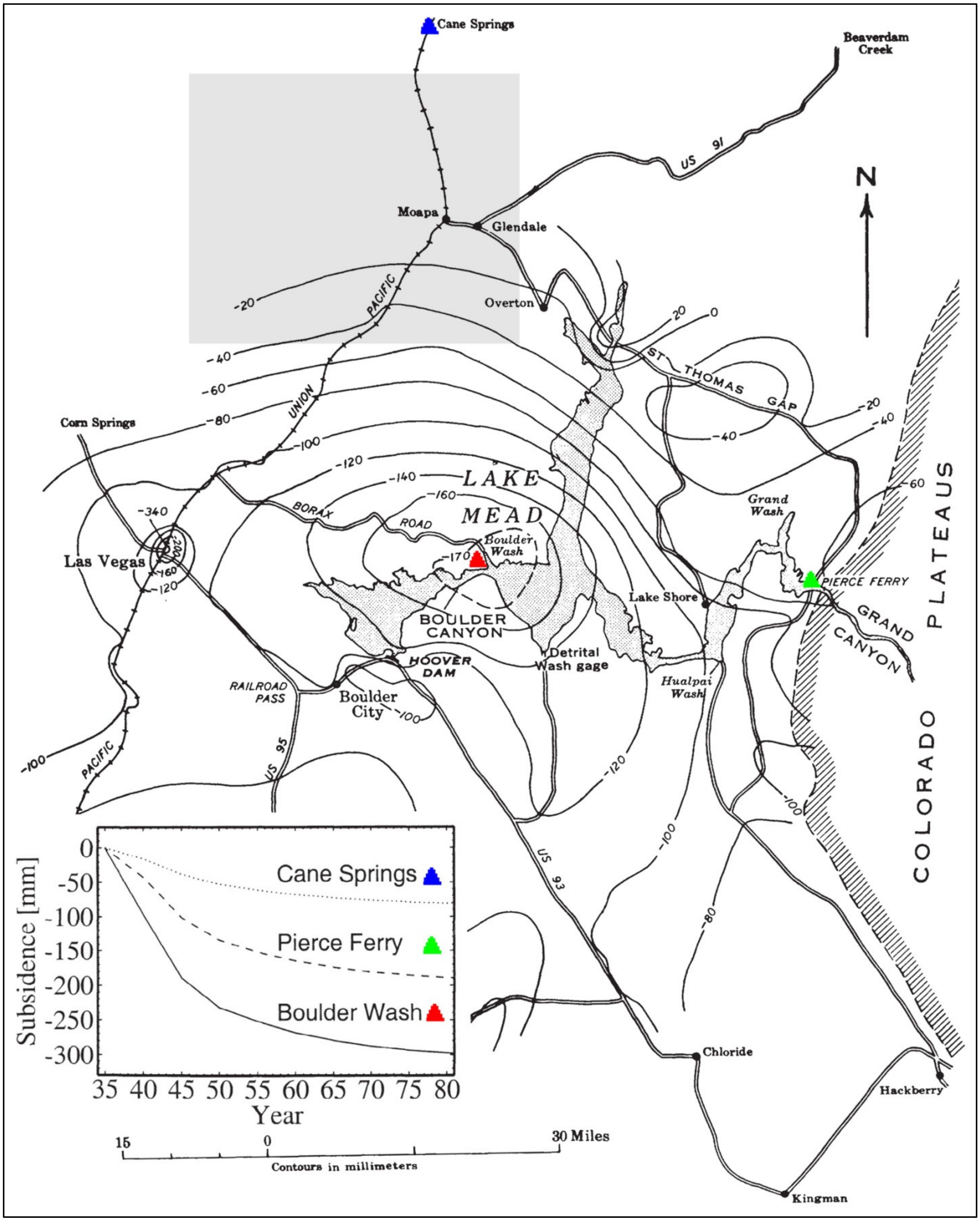

Figure 18. Subsidence in the Lake Mead Region from the 1948-1949 survey and model trends toward isostatic equilibrium from Kaufmann and Amelung (2000). Regional subsidence resulted from the filling of the Lake; superimposed local subsidence near Las Vegas was from groundwater pumping. Shading shows area of Figure 14. [modified after Figure 8 of Longwell (1960); file LakeMeadPP295fig8.jpg]

the anomalous annual periodicity of water levels observed in the Arrow Canyon Range Cell could be one manifestation of such effects. The signal is derived from the pore water carrying the majority of the high-frequency loading changes.

Resolution of Order 1169 Pumping Effects

Available aquifer-test data indicate that pumping responses in the Northern and Southern Flow Fields of Figure 1 are profoundly different with respect to the types of boundary conditions revealed by the well hydraulics (Figure 19). In the Southern Flow Field, the response curve flattens to about half its initial slope within one day, indicating a single recharge boundary was encountered by the spreading pumping cone. In the Northern Flow Field, the response curve increases to about four times its initial slope after about one day, then again after the first week of pumping, indicating multiple hydraulic barriers. The conceptual model for the groundwater flow system in Coyote Spring Valley is therefore that of a well-mixed (based on temperature) and channelized flow system. At least two boundaries of lower transmissiviy were encountered by the spreading pumping cone in the first week.

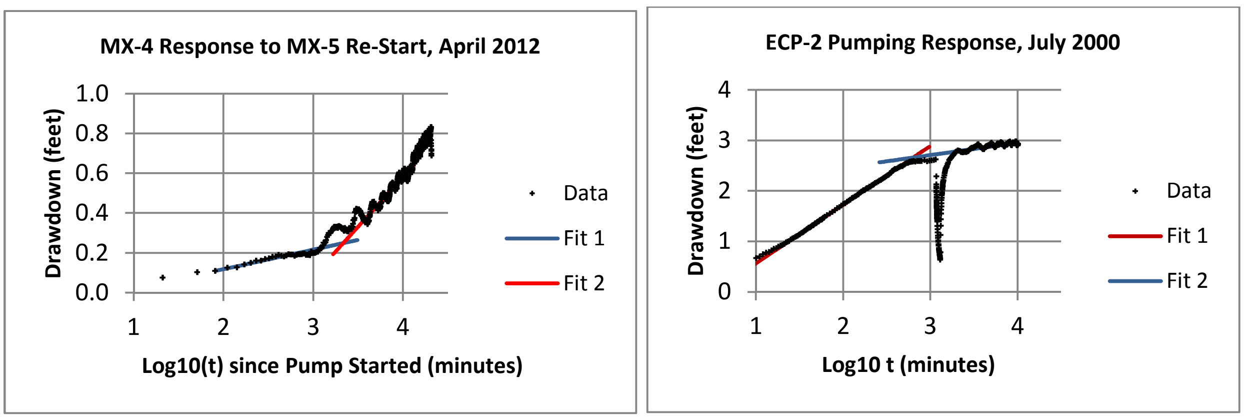

Figure 19. Semi-log plots of time versus drawdown at MX-4 when MX-5 was pumped (left) and at ECP-2 when ECP-1 was pumped (right). Deflections at the end of the test data set (left diagram; Johnson and Mifflin, 2012b) and at about 10^3 minutes (right diagram; Mifflin and Johnson, 2005) reflect pump stoppage. [files MX4_Apr12response.xlsx and ECP2adjustedDD.xlsx]

Reconstitution of net groundwater flux to the Muddy River headwaters area indicates that average flux increased from 50.2 cfs in 2001-2007 to 54.9 cfs in 2008-2012 (Figure 4). During this time interval there is a prominent rise in regional water levels from 2004-2006, general stability in 2007-2009, and decline from 2010 onward (Figure 20). The magnitudes of these multi-year trends as well as seasonal variations are markedly subdued in the CSVM-4 record from the north end of Coyote Spring Valley. Attenuation of an annual loading-related forcing signal from southeast to northwest (Figure 17) and its eventual disappearance within 100 miles north and west of the Moapa Indian Reservation (Figure 14) is a dominant influence on regional water levels in monitoring wells.

Groundwater flux entering the Coyote Spring Valley flow domain is determined by recharge boundary conditions, independent of pumping or loading-related water-level changes in the down-gradient areas. The hydrograph of the Paiutes M1 monitoring well is representative of well hydrographs throughout the Moapa Indian Reservation, which for over a decade have been generally absent any *demonstrated* pumping effects. When the Paiutes M1 hydrograph is aligned with pre-Order-1169 water levels at MX-4 and UMVM-1 the pumping effects at those wells are resolved (Figure 21).

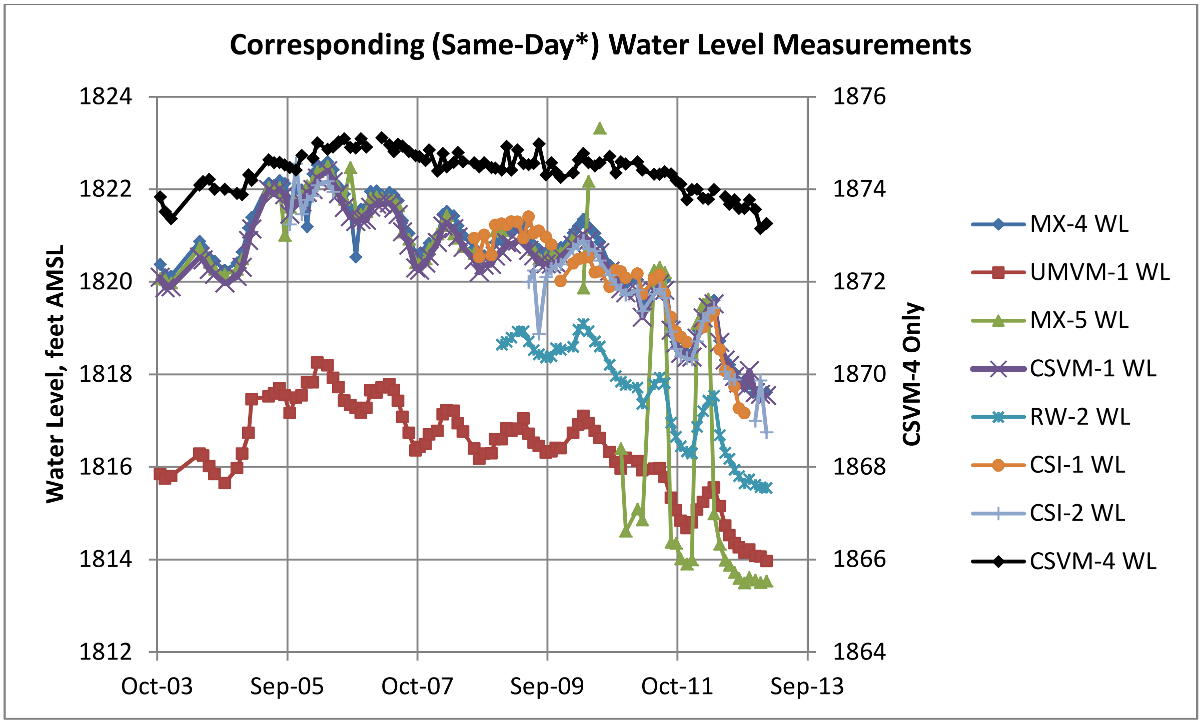

Figure 20. Water level measurements by SNWA in the Coyote Spring Valley area. *With the exception of CSVM-4 after mid-2007, monthly measurements shown here are from the same day each month, with non-corresponding measurements excluded [file MX4-UMVM1gradient.xlsx, sheet 'CorrespondingWLs']

To address the question of how greater groundwater fluxes at the end of the Order 1169 test are consistent with lower water levels in the region, we emphasize changes to the hydraulic gradient rather than declining water levels that have attracted so much attention. Under pre-test (2009) conditions, the hydraulic gradient in Coyote Spring Valley was about 7.69 X 10^{-4}, based on a 3-point solution of water levels at CSVM-4, CSI-1, and UMVM-1. With a transmissivity of 1.26 X 10^{6} ft^{2}/day and porosity of 0.126 (Johnson and Mifflin, 2012b) a flow corridor 0.85 miles (4,480 feet) wide and 4000 feet thick would transmit the requisite 50.2 cfs of pre-2008 groundwater flux under this gradient.

The hydraulic gradient in Coyote Spring Valley had increased to about 8.23 X 10^{-4} by October of 2012 in response to Order 1169 pumping and unloading of the Lake Mead Basin (Figure 22). Under the new (late-test) gradient the calculated flux in Coyote Spring Valley based on Darcy's Law is 53.7 cfs, substantially in agreement with the reconstituted flux of 54.9 cfs for 2008-2012 presented in Figure 4. Note that the 3-point pumping solution presented in Figure 22 (middle) over-predicts water levels at MX-4 by 0.23 m (0.75 ft) so the effective hydraulic gradient is actually larger than represented (compare Figure 22, right), with greater flux than that derived from the uniform flow field obtained from a 3-point solution using wells remote from the center of pumping. The evidence indicates drawdowns from groundwater development in Coyote Spring Valley and regional lowering of water levels in response to unloading of the Lake Mead Basin have allowed a post-2004 recharge pulse to propagate through the system without a corresponding increase in water levels after 2007, as a result of larger hydraulic gradients.

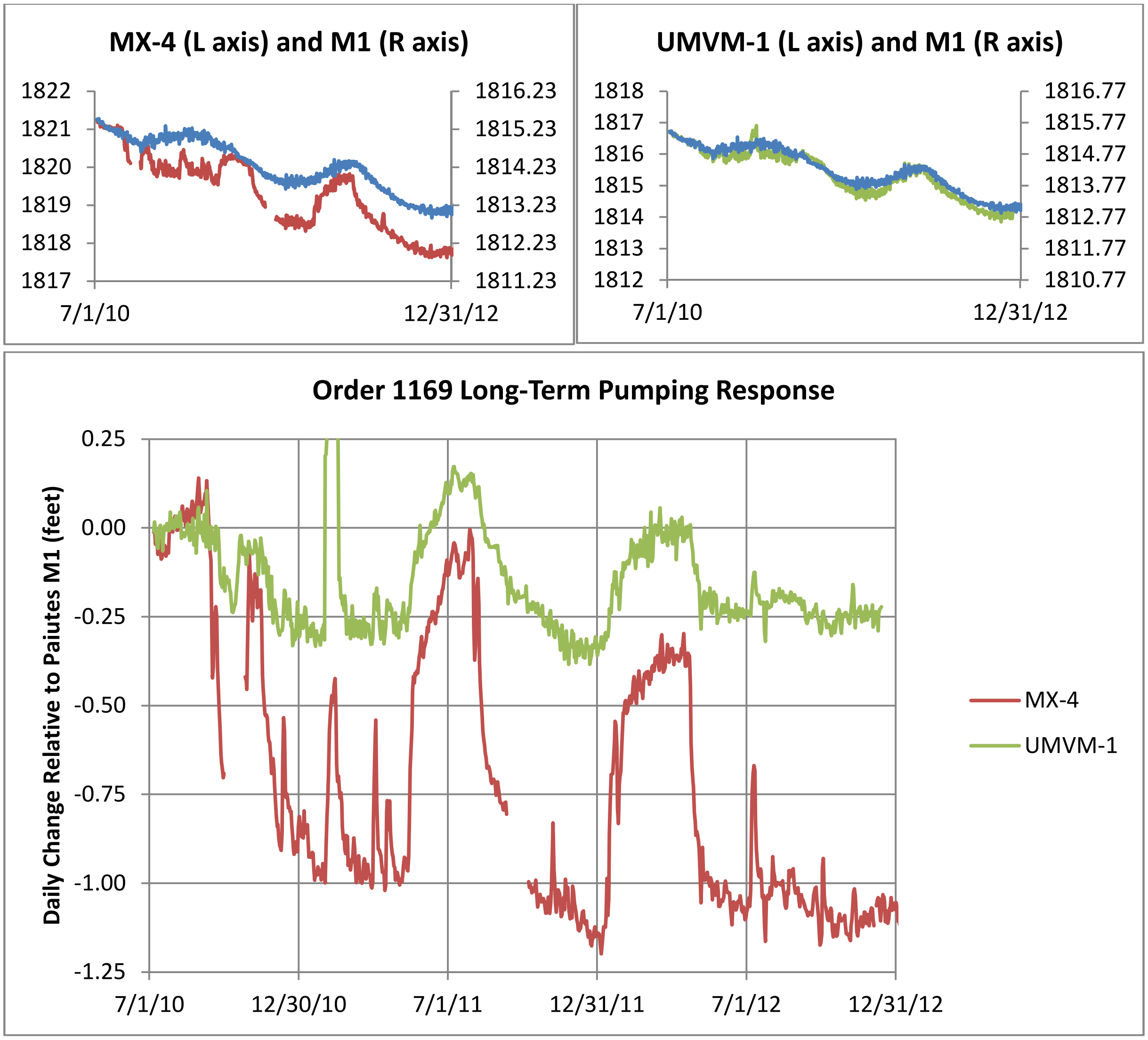

Figure 21. The hydrograph of the Paiutes M1 well (blue) is aligned with the MX-4 hydrograph (top left) and the UMVM-1 hydrograph (top right) by offsets to match pre-test water levels. The differences represent pumping response (bottom). In the fourth quarter of 2012, drawdown at MX-4 stabilized at about 1.09 feet and at UMVM-1 about 0.25 feet. Note that monitoring well UMVM-1 is less than 5 miles from the pumping well MX-5, a distance approaching the practical limit of detection for drawdown effects of the Order 1169 test. [file MX4-UMVM1gradient.xlsx, sheet 'M1vsMX4daily']

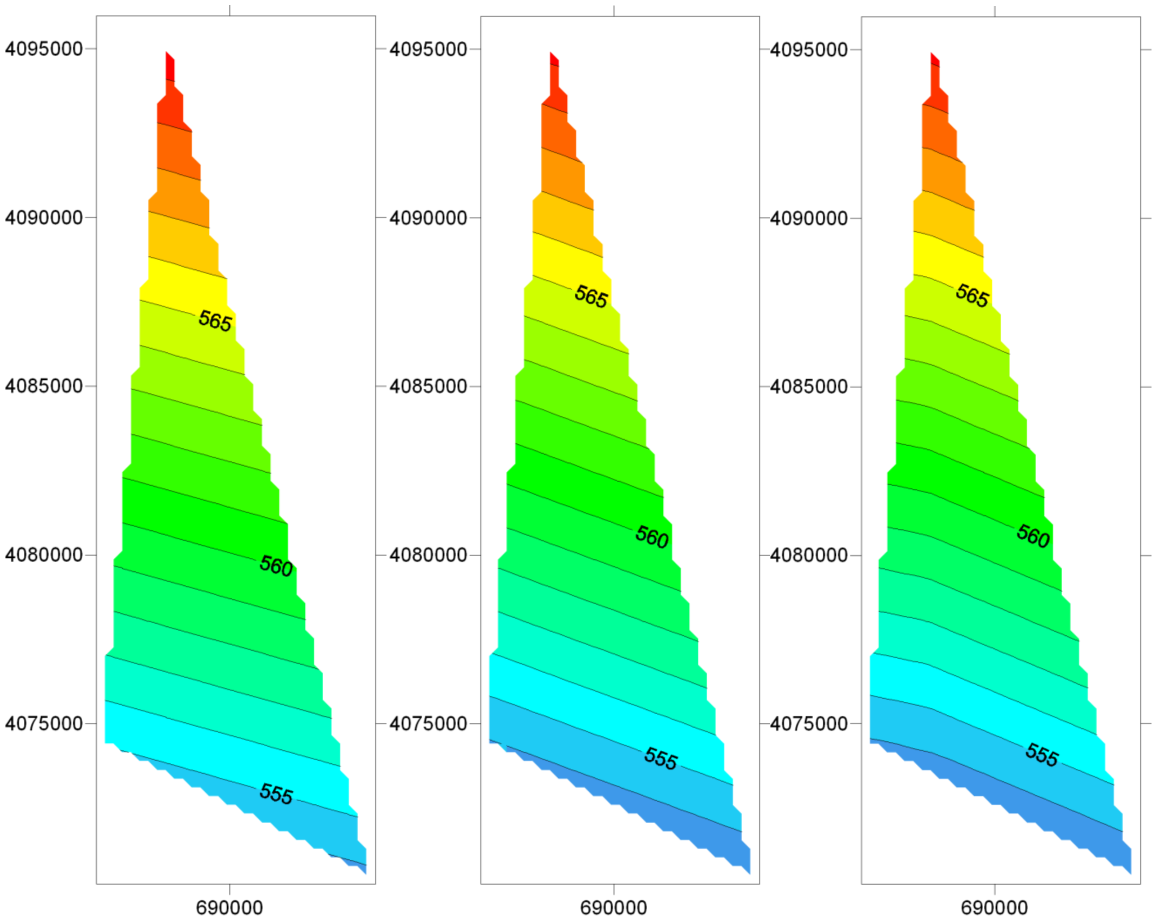

Figure 22. Three-point solutions for water levels and hydraulic gradients in Coyote Spring Valley prior to (left) and at end (middle) of Order 1169 test. Control points for 3-point solutions are CSVM-4 (north), CSI-1 (southwest) and UMVM-1 (southeast). Right-hand diagram illustrates conservatism of 3-point solution by including the pumping water level at MX-4, near center of cone of depression from MX-5 pumping. Map coordinates are NAD83 Zone 11 meters, elevations in meters AMSL based on SNWA reporting [plots exported from file CSVsurface1.srf, basic data in files 3ptCSVM4-CSI1-UMVM1.xls and 3ptCSVM4-CSI1-UMVM1a.xls]

Water-Resource Potential

The water resource potential of the Carbonate-Rock Aquifer of the southern extent of the Arrow Canyon Range Cell is constrained by very few well-controlled tests, associated monitoring, and derived analyses (Mifflin and Associates, 2010). Order 1169 test results and other existing databases define the sustainable water-resource potential of the Carbonate-Rock Aquifer from the Kane Springs Valley area down-gradient to the Springs area, the Northern Flow Field (NFF) of the Carbonate-Rock Aquifer (Figure 1). Basically, the sustainable water-resource potential is the historic base flow plus direct flood runoff flows of the Muddy River at the Moapa Gage. The sustainable water-resource potential remains less certain for the Southern Flow Field (SFF) of the Carbonate-Rock Aquifer in the Arrow Canyon Range Cell (Figure 1). Available databases and analyses (Johnson and others, 2001; Johnson and Mifflin, 2006) suggest regional, unconfined flux to the south and southeast is characteristic of the upper portions of the SFF, potentially up to the order of 15,000 to 20,000 AFY. Water chemistry and isotopic-signature relationships suggest the unconfined flux may originate as upwelling of regional flow that has not evolved directly from the same flow field in the Carbonate-Rock Aquifer that discharges at the Springs area.

Flow system theory, modeling analyses, and regional observations (Mifflin, 1968) indicate that flow-system bypass configurations may exist in areas where there are deep, transmissive zones which may occur in some areas of thick sequences of Paleozoic carbonates. The elevated fluoride concentrations and isotopic signatures observed in the central and southern Arrow Canyon Range Cell suggest a regional source area (with felsic volcanic terrain) similar to the Muddy River Springs flow system source area, but the gross water chemistry precludes an origin as chemically-evolved Coyote Spring Valley / Muddy River Springs flow field water (i.e. shallow flux that bypasses the Springs discharge area). Some evidence is indicative of compartmentalization and barriers within (Johnson and Mifflin, 2003) and bounding (Johnson and others, 1986) the Arrow Canyon Range Cell, and modeling analyses show that low-permeability boundaries down-gradient of the Springs area are required for discharge to occur (Johnson and others, 2001; Mifflin and Johnson, 2005; Johnson and Mifflin, 2006; Tetra Tech, 2012a, 2012b). To date, the outflow boundaries of the SFF in the Apex area have not been sufficiently well-characterized for outflow locations to be identified or confident quantitative estimates of outflow flux to be made.

There are at least 2 water-management incentives for establishing and maintaining better monitoring records throughout the entire southern extent of the Arrow Canyon Range Cell. It is already clear that hydrologic impacts in the Apex area do not respect the boundary between the Garnet Valley (216) and Black Mountains (215) hydrographic areas, but measurement locations are too sparse and measurement frequency generally too coarse to effectively track pumping effects outward from the major pumping centers.

1. With upgraded monitoring the existing pumping stresses may help to indicate longer-term responses and how pumping cones develop and expand, which in turn may allow a better assessment of regional gradients (which indicate the order of magnitude and pattern of flux).

2. In this down-gradient region of the Arrow Canyon Range Cell it may be possible to heavily exploit (mine) groundwater without measurable impacts on the Springs-area flows or other groundwater resources currently in use. This portion of the Arrow Canyon Range Cell may be a region of the Carbonate-Rock Aquifer where the large volume of water in storage could be mined without impacts on water resources in use.

There is no plan in sight to control global warming, and consequential impacts (longer and more extreme droughts) are predicted by modeling analyses and statistical studies (Hansen and others, 2012). Warming impacts as reduced average annual flows have apparently begun in the Colorado River catchment basins, and signal more of similar impacts on Colorado River flows in the foreseeable future. The Apex area is adjacent to Las Vegas, and potentially a better (more timely) target for emergency water supplies than distant groundwater basins to the north. Its resource potential needs to be better understood, as currently available evidence suggest it might be possible to heavily exploit the groundwater in storage without impacts on other water sources.

Perhaps the most confident approach for evaluation of the resource potential (without impacts on existing supplies) is a large pumping stress developed in the Reservation area, and monitoring the development of the pumping cone development. In Ruling 5115, the State Engineer granted one application (54075) for a reduced quantity (5.0 cfs and 2,500 AFY annual duty) and held the other (54076) in abeyance until the Order 1169 study was completed, reasoning that gradual, staged development, monitoring, and mitigation (if necessary) would best advance scientific understanding of the complex, interbasin, regional flow systems under consideration. Consistent with Ruling 5008 and Order 1169, the State Engineer found in Ruling 5115 that previous analyses of perennial yield of hydrographic basins did not contemplate the carbonate-rock aquifer resource as perhaps changing the analysis of the water available for appropriation, and only by stressing the system can such a determination be made. A pumping stress of similar order of magnitude and duration as the Order 1169 test would refine understanding of the groundwater resource potential of the Moapa Indian Reservation, as well as the resource potential of the SFF. Application 54076 released from abeyance may be necessary for the large pumping stress. The framework of the ICS and Forbearance Agreements may present an opportunity for a testing strategy directed at evaluating the groundwater-resource potential of the SFF. The primary question that needs to be resolved is the degree of hydraulic continuity extending to the Springs area, if any, and a large pumping in the northern portion of the SFF creates the best opportunity to determine impacts, if any.

Conclusions and Recommendations Regarding Availability of Water

Order 1169 was prescribed by the Nevada State Engineer to establish a large (~8,000 AFY) and prolonged pumping stress, based on half of existing groundwater permits in Coyote Spring Valley, to be applied for at least 2 years to better determine potential impacts on the Muddy River system from existing groundwater permits. Exhibit 54, a groundwater modeling analysis presented as evidence by SNWA in 2001, predicted very small incremental impacts on the Muddy River (flow reduction of only ~2.5 cfs by the end of a 60 year period) from adding the pumping stress proposed in LVVWD's 1989 applications (27,512 AFY) to existing undeveloped permitted rights in Coyote Spring Valley (16,100 AFY) and groundwater permits held by MVWD in the Muddy River Springs area (4,981 AFY). The minimal impacts forcasted by the Exhibit 54 model raised sufficient questions to justify Order 1169.

The pumping stress prescribed by Order 1169, ~8000 acre-ft/year (AFY) is equal to about 22% of the long-term average discharge in the Muddy River Springs area (Eakin and Moore, 1964), about 11 cubic feet per second (cfs). Reconstitution of Muddy River base flow (Figure 4) indicates annual variability of ±9% (~4.5 cfs) from the long-term average. Discharge reductions of 11 cfs occurring from two years of testing would be evident from cursory inspection of the Muddy River hydrograph if attenuation (peak spreading) were minimal. However, an annualized pumping stress of less than 7 cfs has been realized, at a time when the Muddy River is experiencing short-term base-flow variability related to the exceptionally wet period in 2010-11 superimposed on longer-term effects of 2004-05 and earlier wet seasons as revealed by the relationship between the long-term climate index and natural-flux hydrograph (Figure 5). Natural variations of base flow are of elevated importance because the two years of Order 1169 pumping stresses in Coyote Spring Valley were of the same order of magnitude as climatically-induced variations in Muddy River base flows based on Moapa Gage records. **If natural-flux variations are ignored in water-balance analyses, the impacts resulting from less-than-anticipated Coyote Spring Valley pumpage (Carbonate-Rock Aquifer production) are effectively masked by climatically-induced variation in Muddy River base flows mixed in with more local pumping impacts**.

In order to evaluate past and current claims that have been made (that the carbonate aquifer is a large, separate water resource in this local region that constitutes the Springs area and extending into and through Coyote Spring Valley/Kane Springs Valley) it is useful to review the evidence that establishes: 1) that Muddy River base flows are largely derived from discharge waters from the underlying carbonate aquifer, and 2) that Muddy River base flows have been impacted by the amount of groundwater production with appropriate lag times in the regions of the aquifers that are tributary sources for the Muddy River flows as measured at the Moapa gage (Appendix B). **Monitoring records developed during Order 1169 continue to support the long-standing lines of evidence (fluid-potential relationships, evidence from well hydraulics of highly transmissive carbonate aquifers, similar hydrogeochemistry, water temperatures universally higher than mean annual air temperature, and stable-isotope trends) that provide internally consistent evidence that groundwater in the Carbonate-Rock Aquifer of Coyote Spring Valley is the primary tributary source to the Muddy River Springs-area groundwater-discharge system that gives rise to the Muddy River base flows.**

Figure 4 reconstitutes the history of a slowly developing "perfect" water-management storm that began in the 1960's as a consequence of Ruling 957. In 1920 the Muddy River flows were adjudicated by the Muddy River Decree, with the point of reference for enforcement of the Decree on the historic Holmes and Knox property near the present-day Glendale gage, with the objective of the Decree to protect tributary flows from additional development that would reduce flows above the control point. Subsequent granting of groundwater rights, all junior to the 1920 Decree, in the Springs headwaters area and export of surface-water diversions for industrial and municipal uses have resulted in decreasing Muddy River flows at the Moapa and Glendale gages. The pattern of groundwater development now targets the Carbonate-Rock Aquifer in up-gradient areas where well-established hydrogeologic databases demonstrate the Carbonate Rock Aquifer is the source for nearly all of the groundwater discharge in the headwaters area. The developing "perfect" water-management storm relates to the total of undeveloped but permitted groundwater rights that have been issued. If also fully developed, the totals are approximately equal to the minimum daily-average flow to date (19 cfs) that was recorded at the Moapa gage in 2003. On an annualized basis 19 cfs equals 13,765 acre-ft. The minimum flow occurred during a multi-year period of below-normal base flows when discharge rates were reflecting a lagging net effect from earlier multi-year droughts affecting source areas of the regional flow system that discharges in the Springs area. Reconstituted Muddy River base flows shown in Figure 4 demonstrate similar "climate" variations have occurred in the period of record shown, as well as variations producing greater than average base flows.

The relationships displayed by Figure 4 and supporting analyses forecast that the existing permitted rights that are as yet to be developed are of the right order of magnitude to allow Muddy River base flows to be totally exhausted by the combination of current surface-water and groundwater diversions and undeveloped but permitted amounts in the Muddy River Springs area, Coyote Spring Valley, and Kane Springs Valley, all of which anticipate additional production from the Carbonate-Rock Aquifer. The recommendations that follow are based on the general intent of Nevada water law to foster sustainable development of the State's water resources, with appropriations governed by the Prior Appropriation Doctrine. The preservation of habitats for ESA-listed or endangered species is consonant with conditions of the 1920 Muddy River Decree.

Recommendation I: Integrate at least four water-management basins that include and extend upgradient from the Muddy River Springs area into a new water-management unit to include the extents of the Carbonate Rock Aquifer where the hydrogeologic evidence indicates the aquifers are in close hydraulic continuity with the Muddy River Springs discharge area and therefore the tributary source region for sustaining the base flow of the Muddy River. Rationale: the sustainable capacity of the water-resources base (at a realistic total) is ~37,500 AFY plus any flood flows that might be captured. Both the surface-water base flow and the groundwater development must be managed on an integrated basis for sustainable development.

Recommendation II: Order 1169 test results indicate that the 1989 LVVWD applications for ~27,000 AFY should be denied. Rationale: these applications equal about 72% of the flux in the Carbonate Rock Aquifer discharging to form the pre-development base flows of the Muddy River. All hydrogeological evidence indicates such production would reduce the flux to the discharge area by a similar amount over a relatively short time. Almost one third of predevelopment Muddy River flows are currently consumed before reaching the Moapa gage, and these applications should be denied on the grounds that they would impact senior rights by the full amount.

Recommendation III: If future periods of eliminated Muddy River base flows in the Springs-area headwater reaches are to be avoided, the currently undeveloped permits within the proposed management unit must be largely revoked, restricted, or otherwise creatively managed because they total up to a similar order of magnitude as remaining minimum base flows resulting from current diversion impacts in the Springs area. Rationale: There is only about 37,500 AFY on average of Carbonate Aquifer derived base flow, with multiyear periods of less than 35,000 AFY (Figure 4), and varying additions of short term flood flows. The sustainable development management objective limits the combined total of surface-water and groundwater rights to the sustainable total. Ideally, valid senior rights should be based on the Prior Appropriation Doctrine, but also be geographically distributed in a manner that maintains sufficient Muddy River flows to satisfy the ESA constraint. A potential management strategy to meet the general objectives of Nevada water law is an integrated approach to surface and groundwater rights that considers senior (both surface and groundwater) to be interchangeable rights. An effective strategy would require temporal and geographic distribution of diversions, to maintain at least current levels of Muddy River base flows, or improve them in the upper reaches of the Muddy River.

<u>Recommendation IV</u>**: The water-resource potential of the Southern flow Field (SFF) of the Arrow Canyon Range Cell should be evaluated with a large interim pumping experiment in the northern portion of the SFF.** Rationale: Available databases indicate a large sustainable yield for the SFF, and perhaps even interim mining (over-exploitation) may be possible without negative impacts on Springs-area flows or other water resources in use. The recommended approach to further determine the resource potential of the SFF is a large interim pumping stress in the Reservation area, since the only apparent exploitation constraints would result from pumping-induced water-level declines propagating from the SFF into the Springs area. The current ICS agreement provides for a testing approach that would route groundwater pumped during the test to the Muddy River. The water-resource potential of the SFF is important to establish because of its close proximity to Las Vegas, favorable boundary conditions, and large reserves of water in storage, particularly if Colorado River flows continue to be reduced by drought.

The hydrogeology of the region, and the naturally-available (reconstituted) base flows of the Muddy River have not changed much since the early work of Eakin (1964, 1966) when the regional hydrogeology was correctly interpreted in terms of required knowledge to allocate the available water resources. **There may be alternative, creative approaches for the State Engineer to maintain Muddy River flows, given the opportunities afforded by SNWA's Forbearance and ICS agreements**.

The Tribe has negotiated in good faith for senior surface-water and groundwater rights, and also supports the preservation of sufficient flows to maintain the natural aquatic habitats required by the Moapa dace. **Flows of 19 cfs or less through the Reservation reach are unacceptable, in that exercise of the full Tribal surface-water rights would result in significant impacts on aquatic habitats from the point of diversion through downstream reaches, and thereby place the Tribe's diversion rights at risk**.

A final observation that cannot be over-emphasized is the distinction between water-level changes and drawdown. Several environmental factors other than drawdown contribute to water-level fluctuations, including local and regional climate, atmospheric pressure, tides, and crustal loading phenomena (Lake Mead?). Throughout HRT interactions, there has been a tendency to equate regional water-level declines since 2010 to drawdown, which is specifically defined as the *component* of water-level decline attributable to pumping. If pumping were responsible for the long-term water-level changes we see (Figure 23) then the prominent rise in 2004-2006 should be associated with a reduction of pumping somewhere, which it is not (Figure 24). Documented pumping response and associated parameter estimates for the Carbonate-Rock Aquifer derived from aquifer tests (Appendix F) provide quantitative evidence against the notion that similar water-level trends across several hydrographic basins constitute pumping response.

The significance the distinction between water-level decline and pumping-induced drawdown is profound. If regional drawdowns were as great as the observed water-level declines since late 2010, affecting several hydrographic basins, groundwater derived from *storage* would have supplied most or all of the groundwater that has been diverted from the headwaters area during the Order 1169 experiment. On the other hand, as we conclude, if groundwater pumped for Order 1169 is being captured and diverted from Springs-area discharge, the next cycle of low River flows will be exacerbated. Our findings indicate that *boundary conditions*, not storage, dominate Order 1169 pumping response.

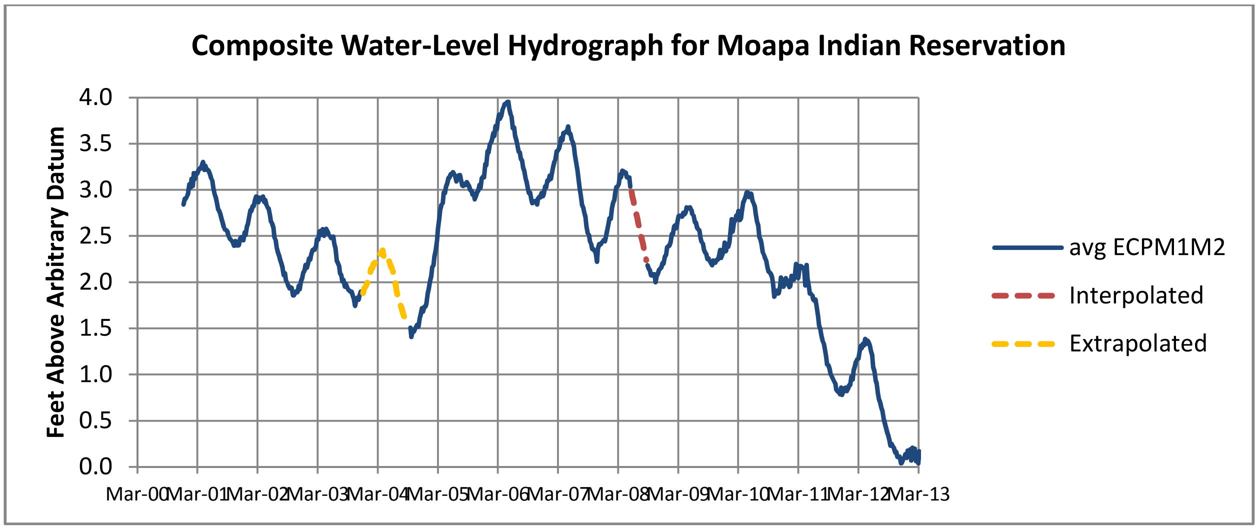

Figure 23. Weekly water levels beneath the Moapa Indian Reservation, offset to a common datum using the average difference between individual wells during overlapping periods of record. [file RefWeeklyHydrograph2.xlsx]

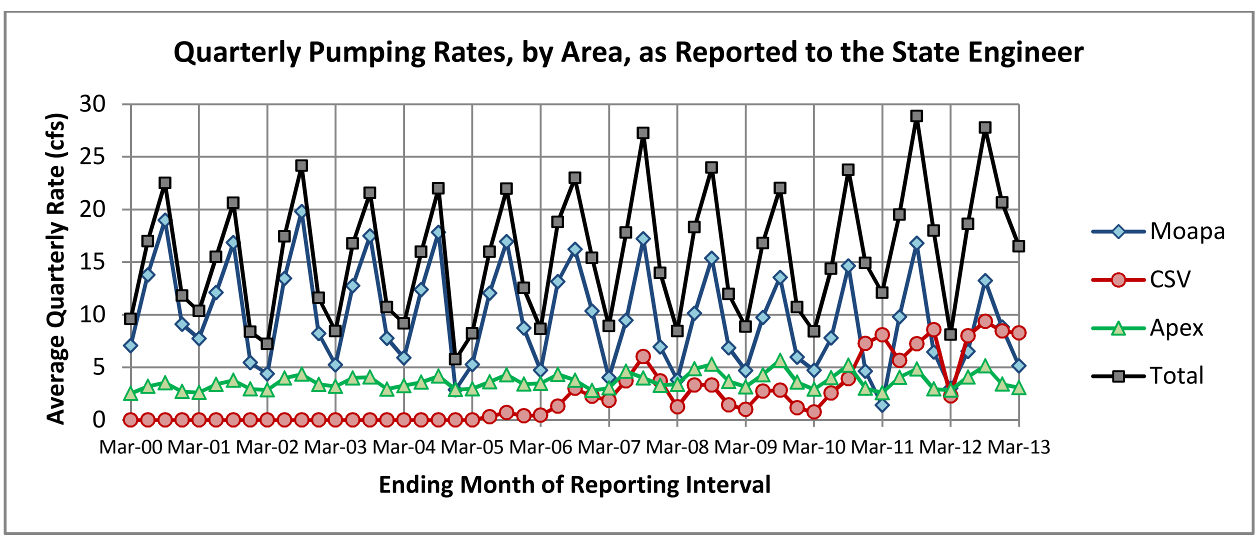

Figure 24. Pumping histories in upper Moapa Valley (Lewis, LDS, Perkins, Behmer, Arrow Canyon, and MX-6 wells), Coyote Spring Valley (CSI, RW-2, and MX-5 wells) and Apex area (Republic Services, Nevada Cogeneration, Chemical Lime, Duke, Mirant and Pinnacle West wells) [file AllAreasQuarterlyQ.xlsx]

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Appendix A . Hydrogeologic Overview

A general consensus has existed during the past ~50 years that the Muddy River Springs and associated Muddy River base flows are largely the result of the discharge from the regionally extensive Carbonate-Rock Aquifer, with evidence of interbasin flows indicated by hydrographic basin water-balance studies, supplemented by other hydrogeological relationships and the general distribution of Paleozoic carbonate rocks. Eakin's (1966) initial delineation of regional interbasin flows (the White River Regional Flow System, "WRRFS") has often been followed in subsequent water -balance studies, as his delineation balanced the regional basin-water budgets with discharge at the headwaters of the Muddy River. However, the fundamental problem with Eakin's water-balance-based delineation of this regional flow system is sparse fluid-potential information in nearly all areas of mountainous terrain, which prevents rigorous evaluation of hydrochemical evidence from large springs that indicates there is likely far more interbasin flow than is generally believed (Mifflin, 1968). There may be no unique delineation solution based solely on basin water-budget evidence in terms of participating sources to any regional flow system, or related discharge areas, typically large springs with water chemistry and discharge characteristics indicating regional sources.

The extent to which adjacent basins are hydraulically connected is not clearly defined by comparison of shallow fluid-potentials between basins. Supplemental evidence developed since Eakin's pioneering work suggest alternative delineations for some "WRRFS" basins. Mifflin and Wheat (1979) in studies of pluvial (glacial state) climates based on catchment basin areas and areas of respective pluvial lakes throughout Nevada, noted that Long Valley and Jakes Valley (the two northern-most basins of Eakin's White River Regional Flow System) apparently leaked to the west (rather than south) to Newark Valley based on an oversized pluvial lake in Newark Valley, and undersized lakes in the other two basins. The three basins, when combined, gave hydrologic indices that matched the regional trend. If the interbasin contributions of Eakin's two northern basins are eliminated in his regional water balance, the White River Regional Flow System water budget balances at Pahranagat Valley. Supporting this alternative delineation is the absence of isotopic or geochemical evidence for a significant amount of Pahranagat Valley-derived water in Coyote Spring Valley. Elevated fluoride (nominally 2 µg/l in Coyote Spring Valley) is absent in the major carbonate-aquifer springs of Pahranagat Valley, and isotopic evidence presented by Thomas and others (2001) requires either a significant component of isotopically heavy water mixing with Pahranagat Valley water to produce compositions observed in Coyote Spring Valley, or an entirely different source.

The large area with relatively high fluoride concentrations in groundwater, likely derived primarily from weathering of peralkaline volcanic rocks overlying or adjacent to carbonate-rock terrain in the Upper Meadow Valley Wash region, underlies Coyote Spring Valley and the Arrow Canyon Range Cell of Mifflin (1992). Regional relationships indicated by water chemistry, stable isotopes, and other evidence, have potential significance in terms of issued groundwater permits in other basins where interbasin flow is evident. Coyote Spring Valley may not be a significant part of Eakin's classical WRRFS, but Muddy River flows are definitely dominated by Coyote Spring Valley waters, and are likely related to interbasin flows from some northern candidate basins displaying fluoride-bearing waters (Kane Springs

Valley, perhaps Dry Lake Valley and Delamar Valley, and Upper Meadow Valley Wash tributary basins). Monitoring activities in the northern candidate source basins, where permits have been issued, need to prioritize the development of databases of conservative tracers (water chemistry and isotopes) as well as fluid-potential relationships indicating presence or absence of close hydraulic continuity with down-gradient basins.

In addition to the regional flow from distant recharge areas, base flow of the Muddy River in the Springs area is influenced by more localized and often ephemeral sources of recharge which include infiltration from storm flows in Pahranagat Wash, Meadow Valley Wash, and recharge in the Sheep Range. Exceptionally wet periods, drought periods, and occasional short-term runoff events influence the base flows in the river with differing lag periods in terms of the timing and magnitude of influences on the Muddy River base flows. Impacts from pumping stresses in the alluvial aquifer and carbonate aquifer also display varied lag times for impacts on flows.

Generally underlying the alluvial gravels of lower Pahranagat Wash and Moapa Valley (Arrow Canyon is the exception) are fine-grained, unconsolidated sediments of the Muddy Creek Formation. Erosionally inset into the fine-grained sediments of the Muddy Creek Formation are highly transmissive gravel lenses of the alluvial aquifer. The alluvial aquifer varies in total thicknesses up to ~100 feet in the Lewis Well Field area. The Muddy River Springs, including some essentially extinct spring areas, are related to localized conduit zones that occur along at least two north-trending, parallel lineaments resulting from extensional faulting. Localized conduit zones pass from the underlying carbonate rocks through the Muddy Creek sediments, which were deposited on a high-relief, carbonate-rock-dominated paleotopography. The conduits, locally bounded by secondary calcium carbonate precipitates within the alluvial aquifer, pass into and through the alluvial gravels at the still active spring areas.

Within the Muddy Creek Formation, generally much higher-TDS (total dissolved solids) groundwater is the result of gypsum dissolution that dominates the chemical evolution of Muddy Creek waters as compared to the carbonate-aquifer waters. The alluvial aquifer waters are a dilute mix due mostly to a small percentage of Muddy Creek Formation water mixing into carbonate aquifer derived water. Only about half of the discharge forming Muddy River base flows at the Moapa gage was derived directly from large springs (via conduits in close hydraulic continuity with the underlying carbonate-rock aquifer) and half originated as seepage from the alluvial aquifer into the headwaters channels. The slightly higher TDS of the alluvial-aquifer waters within the Springs area indicates a small amount of discharge is likely from the Muddy Creek Formation and some concentrated salts related to ET in the local areas of phreatic vegetation and irrigation.

In the lower Meadow Valley Wash area north of Glendale, similar alluvial gravels of Meadow Valley Wash occupy paleovalleys eroded into the Muddy Creek Formation. When high-yield production wells were pumped over a period of several years, water quality in the alluvial gravels was markedly degraded by induced inflow of higher TDS waters from the underlying Muddy Creek Formation. Similar intrusion of poor quality water occurred in the confined portion of the alluvial aquifer below the Moapa Gage when the Perkins replacement well was accidentally over-pumped in 1989. Domestic wells tapping the Muddy Creek Formation throughout the general area yield high TDS water.

Gravel lenses within the alluvial aquifer are highly transmissive, and in both the unconfined aquifer area (between Arrow Canyon and the Springs area) and the confined area (below the Springs area) seasonal pumping cones develop and extend each pumping season to the Springs area, and downstream to White Narrows area (the extent of monitoring wells available to monitor the pumping cone developments). Seasonal pumping cones generally recover fully between September and March both above and below the Springs area.

The primary source of water in the alluvial aquifer in the Springs area, including the Lewis Well Field area, is from the carbonate aquifer as indicated by both water temperature and water quality. Below the Springs area the Muddy River is not in direct hydraulic continuity with the alluvial aquifer, which in turn displays confined aquifer responses to pumping. Below White Narrows there is insufficient monitoring well control to determine the hydraulic characteristics of the alluvial aquifer or if the Muddy River remains hydraulically isolated from it.

Appendix B. Reconstitution of Natural Groundwater Flux to the Headwaters Area

"Reconstitution" refers to the process of computing the natural groundwater flux to the Muddy River headwaters area by restoring (adding) the quantities of water diverted upstream of the Moapa Gage (USGS Station ID 09416000) to discharge measurements made at the Gage. Reconstitution of the Muddy River hydrograph to represent flux was accomplished by a series of steps documented in supplemental dataset ReconstSimple4.xlsx, in which successive diversion-rate adjustments are applied to daily-average discharge measurements from the Moapa Gage. Daily equivalents of monthly diversion rates were derived by empirical mode decomposition (Huang and others, 2008; Kim and Oh, 2009) so category-specific lag times between diversion occurrences and Muddy River discharge reductions could be derived with daily resolution. Beginning with base-flow separation and evapotranspiration (ET) adjustments, which affect even the earliest measurements, diversion effects are cumulatively restored to the hydrograph in the order of when they first appear in the historical record.

The first step in reconstitution is to remove the effects of runoff from intense local storms by the process of base flow separation. The Base Flow Index (BFI) method (Wahl and Wahl, 2007) allows "raw" base flow (unadjusted for ET and diversions) to be isolated (Figure B-1). In contrast, SNWA employs the "Median + 20" technique of Johnson (1999) for separating the Muddy River hydrograph into base flow and storm flow components (Figure B-2). Both methods utilize daily-average discharge records from the USGS as basic data. The base-flow index is the ratio of base flow to total flow; minima

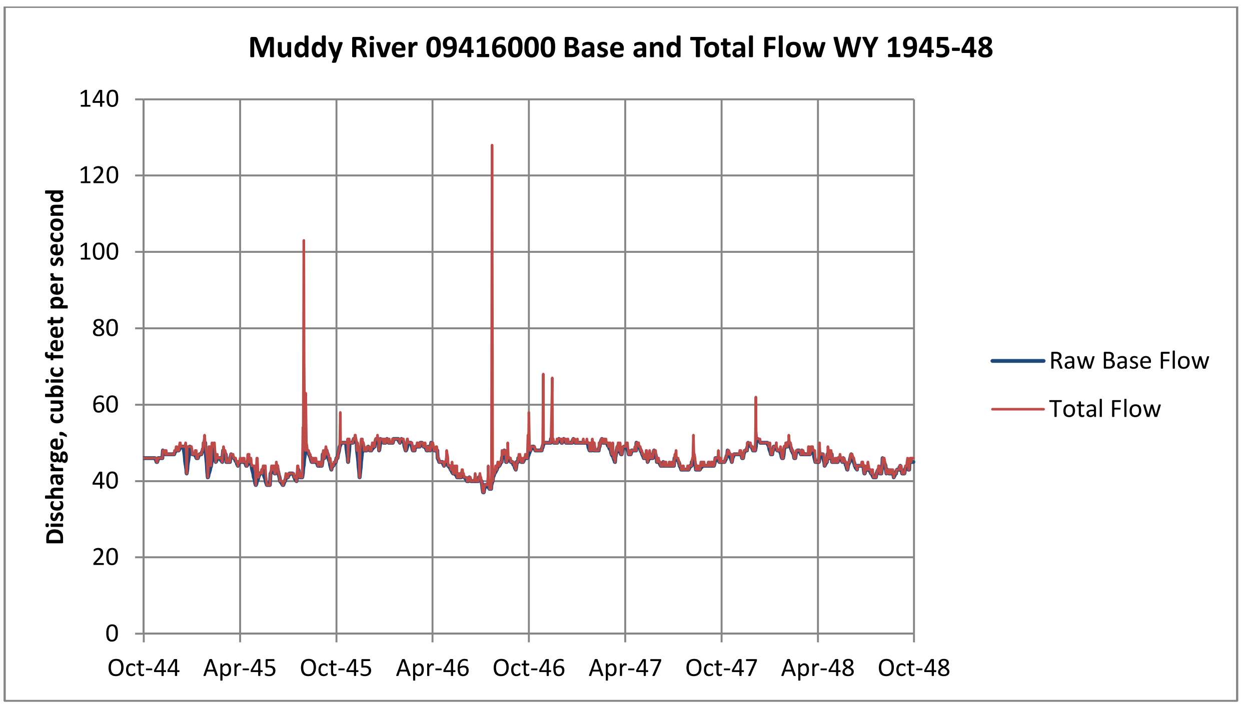


Figure B-1. Local climate typically results in intense summer thunderstorms resulting in flash floods, as shown by the hydrograph in the summers of 1945 and 1946. In contrast, winter storms generally produce soaking rains with less direct runoff and a greater residual contribution to base flow, as in the winter of 1946-47. [file ReconstSimple4.xlsx, sheet 'ETfromEarlyBaseFlow']

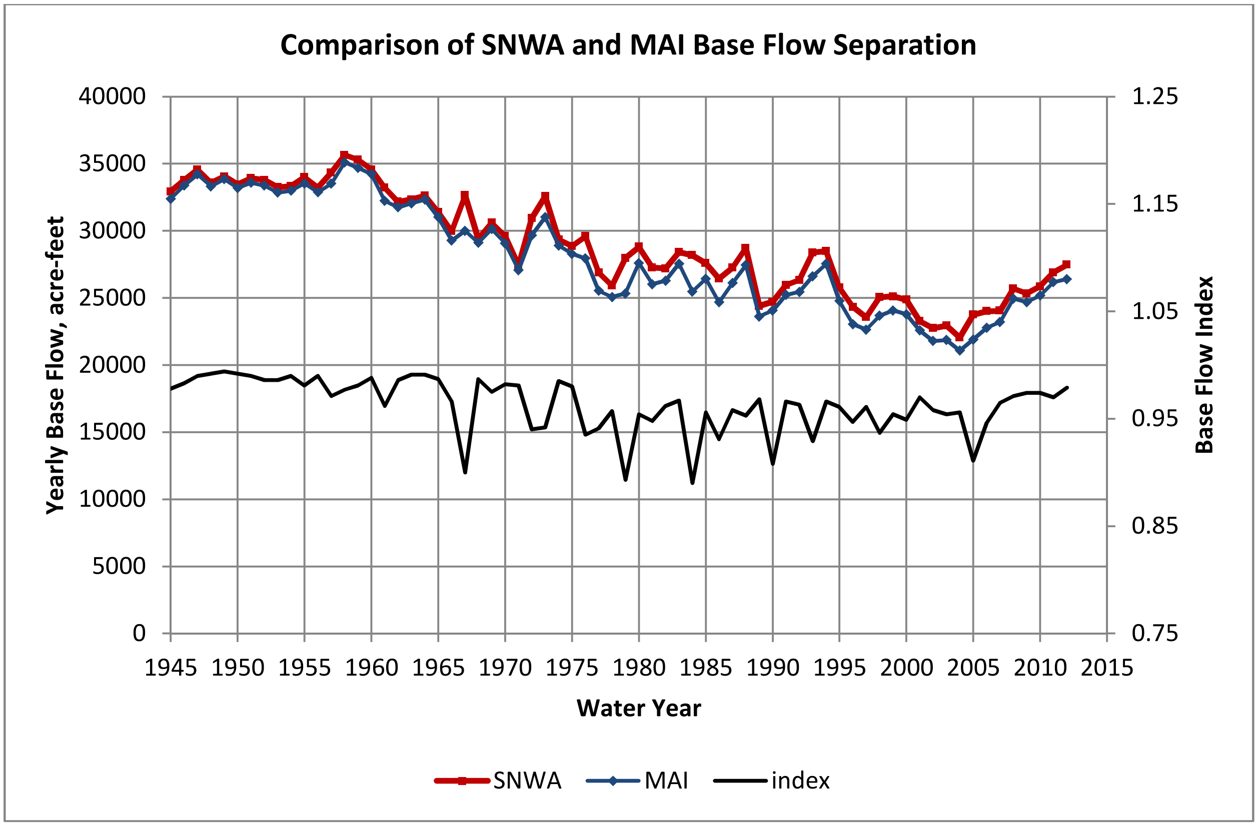


Figure B-2. Annual base-flow separation by SNWA (Median + 20 method) and MAI (BFI method) [file SNWAreconst.xlsx, sheet 'BFI']

in the BFI are indicators of years with a relatively great proportion of storm (surge) runoff. Note that base-flow estimates by the Median + 20 method are significantly greater than those derived by the BFI method in years of above-average storm runoff, as illustrated by low base-flow indices in those years.

The next preliminary step is to add back the losses from evapotranspiration (ET) that produce the seasonal fluctuations in base flow. The relationship between discharge of large springs (nearly constant) and discharge of the Muddy River (seasonally variable; Figure 8) indicates an ET effect on Gage readings (Eakin, 1964; Eakin and Moore, 1964). We fit a sinusoidal function to WY 1945 daily-average discharge data after removing storm surges as described in the previous section, and find ET to vary between 0.45 cfs in winter and 5.90 cfs in summer, a mean annual rate of 3.2 cfs (Figure B-3). These rates correspond to a participating area of 450 acres with average ET varying between 0.002 ft/day (winter) and 0.026 ft/day (summer), consistent with DeMeo and others (2008, Figure 6). The ET signal is 180° (π radians) out of phase with the model hydrograph. Adding the ET loss rate to the raw base flow produces a partially-reconstituted hydrograph that still contains a seasonal component attributable to surface-water diversions for flood irrigation (Figure B-4).

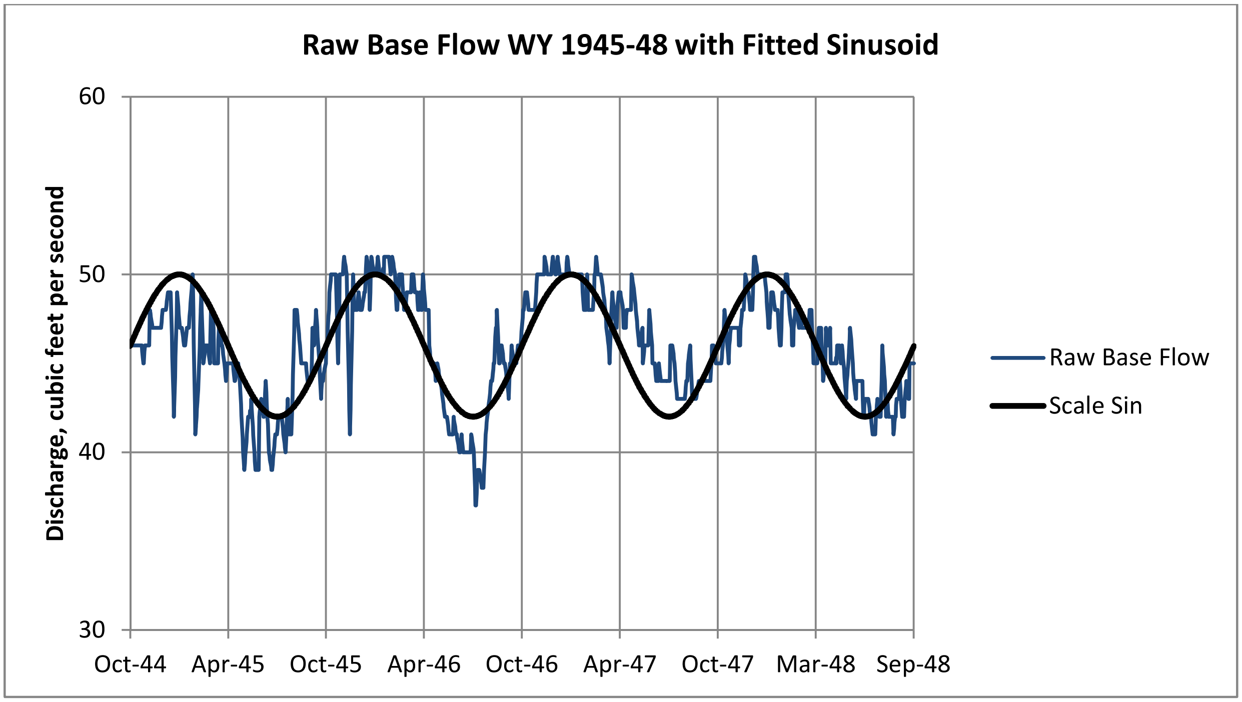


Figure B-3. Approximating the raw base flow of the Muddy River with a sinusoid provides daily estimates of ET losses in the headwaters area. [file ReconstSimple4.xlsx, sheet 'ETfromEarlyBaseFlow']

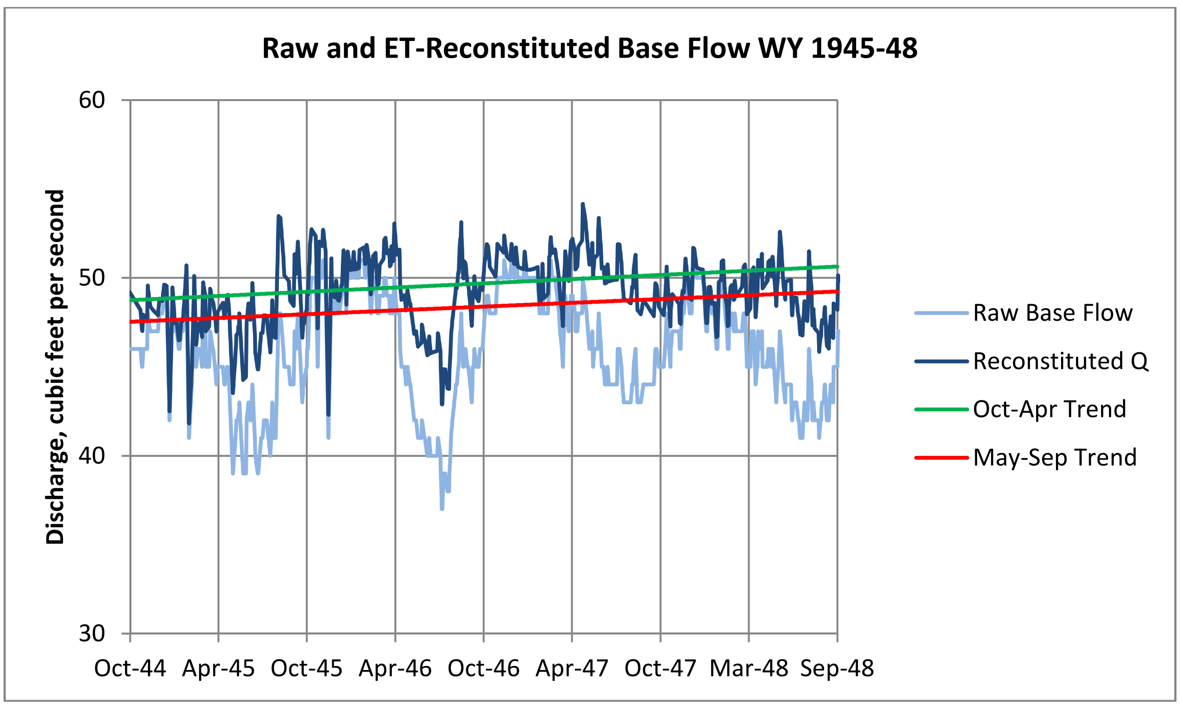


Figure B-4. The wet winter of 1946-47 resulted in significantly higher discharge rates the following summer than in either of the previous two years, which began with relatively dry winters (Figure B-1). There is no reason to believe flood irrigation practices were any different or less intense in 1947 than in 1946, yet compared to the prominent flow reduction in the summer of 1946, the summer deficit was more modest in 1947. [file ReconstSimple4.xlsx, sheet 'ETfromEarlyBaseFlow']

The difference between winter and summer discharge rates shown in Figure B-4 is consistent with SNWA's Intentionally Created Surplus (ICS) that was claimed after retirement of irrigated lands was complete in 2008 (SNWA, 2011). On that basis, a "Reverse ICS" approach restores waters diverted directly from tributary channels for flood irrigation prior to 2008 to the Moapa Gage record, removing most of the residual seasonality in the base-flow hydrograph of Figure B-4 and providing an estimate of minimum natural groundwater flux to the headwaters area before the era of irrigation wells creates the need for additional adjustments beginning in 1948 (Figure B-5).

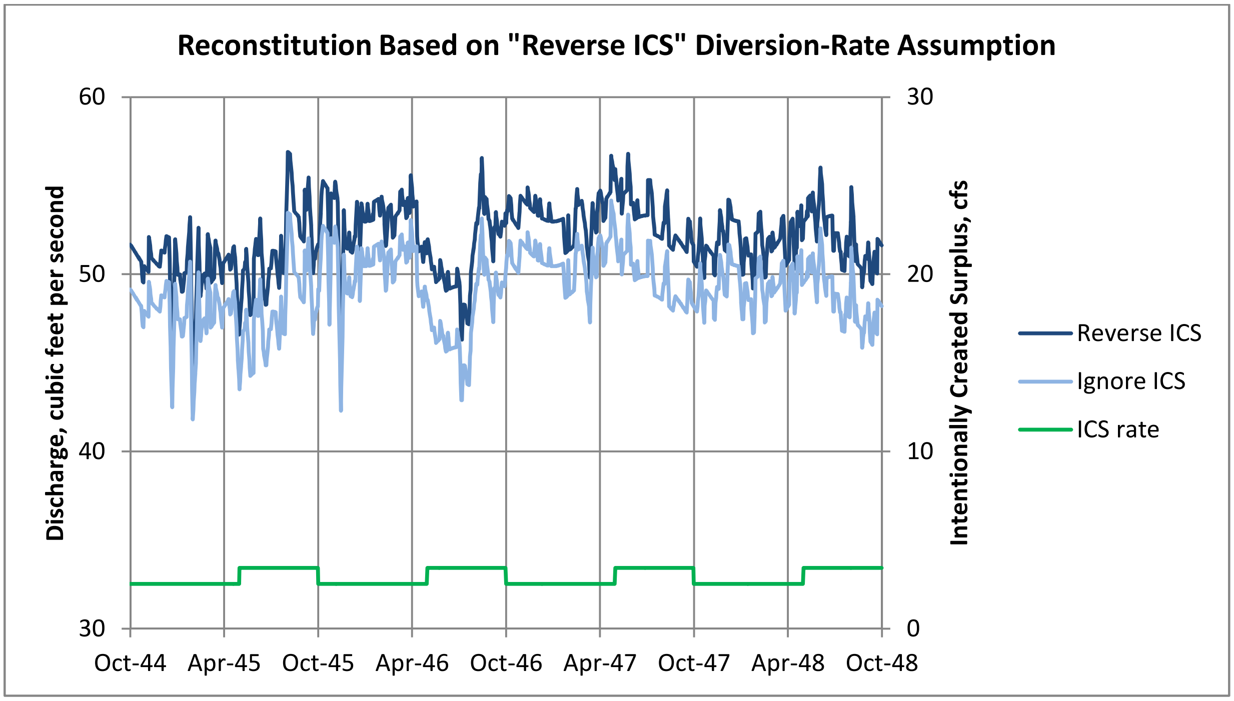


Figure B-5. The Intentionally Created Surplus (ICS) claimed by SNWA after 2007 is applied retroactively to account for seasonal surface-water diversion rates [file ReconstSimple4.xlsx, sheet 'ReverseICS']

The next step is to utilize sparse diversion records from the two decades following 1947, when the first wells were drilled in the headwaters area, to isolate the effects of those wells prior to any exports of groundwater. The data presented by Eakin and Moore (1964) and Maxey and others (1966) are essential in this regard, since together they identify active irrigation wells and pumping records from 1961-1965. If the well inventory is assumed to be complete and the pumping rates representative (over the history of each well), diversion rates from groundwater pumping can be reconstructed.

The Taylor E well, drilled in 1948, was the precursor to LDS E; Eakin (1964) reported a pumping rate of 1,400 gallons/minute (gpm) on September 12, 1963, and James Haworth (oral testimony June 29, 1966) indicated 2.5 second-feet (1,122 gpm) had been pumped each year since 1951. Diversion rates at Taylor E were estimated by scaling measurements at Taylor W provided by Maxey and others (1966) to the greater irrigated acreage serviced by Taylor E (Figure B-6); peak rates by this method are 2.66 cfs, generally consistent with Eakin's observation and Haworth's testimony.

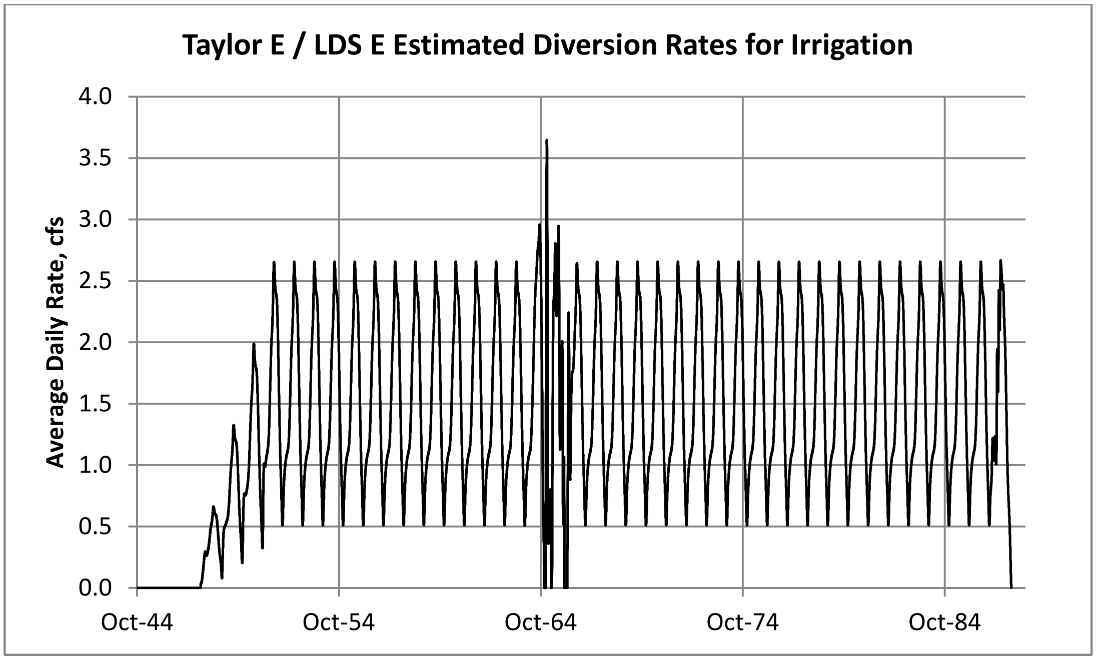


Figure B-6. Daily diversion rates prior to 1988, when monthly reporting began, were estimated by scaling monthly-average rates from 1961-1963 reported by Maxey and others (1966) for the Taylor W well in proportion to irrigated acreage. [file ReconstSimple4.xlsx, sheet 'FloodIrrCU4487']

Moapa Valley Water District (MVWD) spring diversions were estimated based on Eakin's (1964) observation of about a 1 cfs rate, and an exponential growth model with seasonality based on usage patterns from monthly records that began in January of 1988 (Figure B-7).

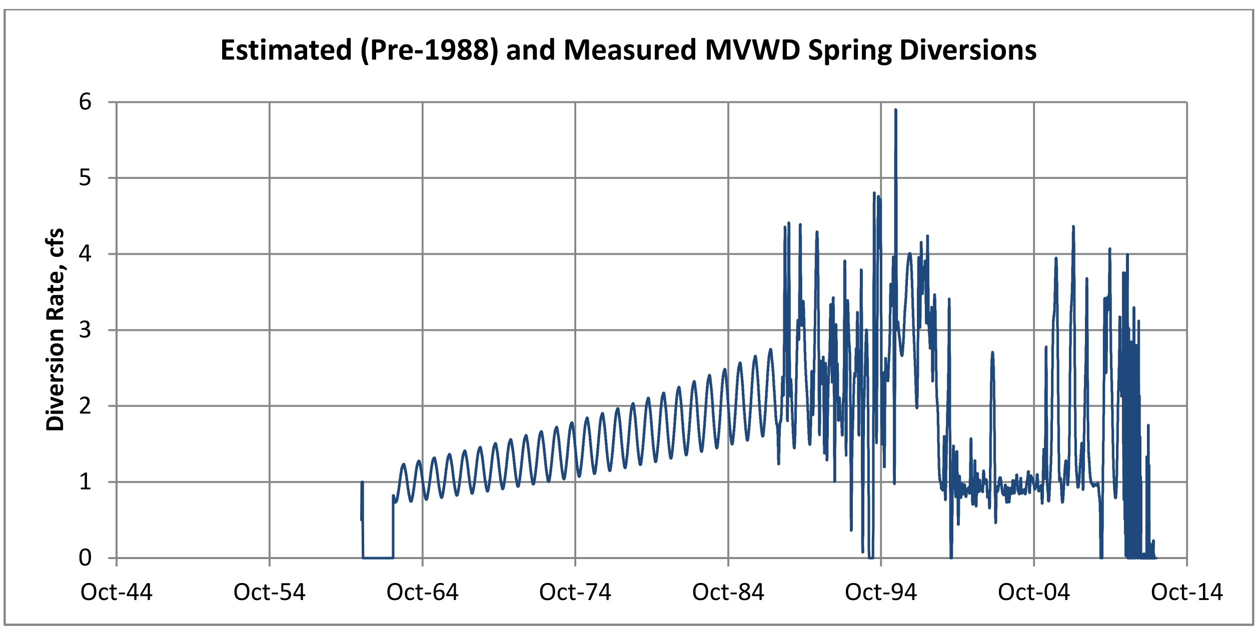


Figure B-7. Exponential growth model for pre-1988 derived from 1 cfs 1963 diversion rate estimated by Eakin (1964), and monthly diversion rates reported by MVWD after 1988 [file ReconstSimple4.xlsx, sheet 'FloodIrrCU4487']

Maxey and others (1966) provide monthly records of production from the 7 active wells in the headwaters area for the period 1961-1965, which overlaps the startup of MVWD diversions from springs feeding South Fork in 1960. These 7 wells (Lewis 1-5, Taylor W, and the Lewis Farm well) were completed in unconfined gravels of the alluvial aquifer in the Lewis Well Field area (Figure 2), from which pumping signals were later shown to propagate down-valley over the course of the summer pumping season (Mifflin and others, 1991). Comparison of monthly pumping records from November, 1961 through October, 1963 and the corresponding, partially-reconstituted Muddy River hydrograph allow the time lag between pumping and River-discharge reductions to be determined.

Diversion records are intermittent and when available were reported as monthly totals, with rare exceptions, from 1988 through 2005. In order to utilize the daily discharge record from the Muddy River to their full advantage, as opposed to degrading the data by averaging to some lower sampling frequency, monthly diversion records are approximated as daily equivalents using empirical mode decomposition (EMD). This allows the lag time between occurrences of the diversions and corresponding responses at the Moapa Gage to be discretized in terms of days instead of months, which are of unequal length and offer too coarse a time interval for effective correlation of impulse (pumping) and response (flow reduction) signals. Application of EMD to the Muddy River hydrograph, after base flow separation (removal of storm surge effects), objectively and systematically isolates underlying trends from day-to-day noise.

To illustrate the application of EMD to the reconstitution effort, Figure B-8 shows the monthly pumping from Lewis 1-5, reported from November of 1961 through October of 1963 by Maxey and others (1966), and the daily approximation of the pumping record derived by EMD (lower curves and right-hand axis). The upper curves and left-hand axis represent a trial reconstitution based on a consumptive use factor of 50%, such that half the EMD-derived daily pumping rate is added to the sum of measured base flow + ET + ICS + Taylor E + MVWD Springs.

EMD is applied to the trial reconstitution of daily discharge to quantify the relationship of residual seasonality in the hydrograph to the pattern of pumping. A prominent maximum in the pumping history occurred on July 15, 1963 (green diamond on Figure B-8), and a prominent minimum in the trial hydrograph followed on October 24 (pink diamond on Figure B-8), suggesting a lag of 101 days between pumping in the Lewis Well Field area and corresponding reductions in the discharge of the Muddy River. Repeating the reconstitution process, this time adding the daily Lewis-area pumping stress to the base flow + ET + ICS + Taylor E + MVWD Springs hydrograph 101 days after the pumping occurs, and at full strength rather than applying the 50% consumptive-use scale factor used for trial purposes, we obtain the reconstituted hydrograph shown in Figure B-9. For the 2-year interval when diversion-rate measurements are available, a rising trend with minimal seasonality characterizes the reconstituted Muddy River hydrograph. Extrapolating the 1961-1963 pumping rates backward according to the time each individual well entered service, and forward until irrigation from individual wells ceased, and applying the 101-day lag universally, the reconstituted hydrograph of Figure B-10 is obtained. Lewis wells 1-5 were converted to industrial use in April of 1965, while Taylor W remained in service as an irrigation well until 1988.

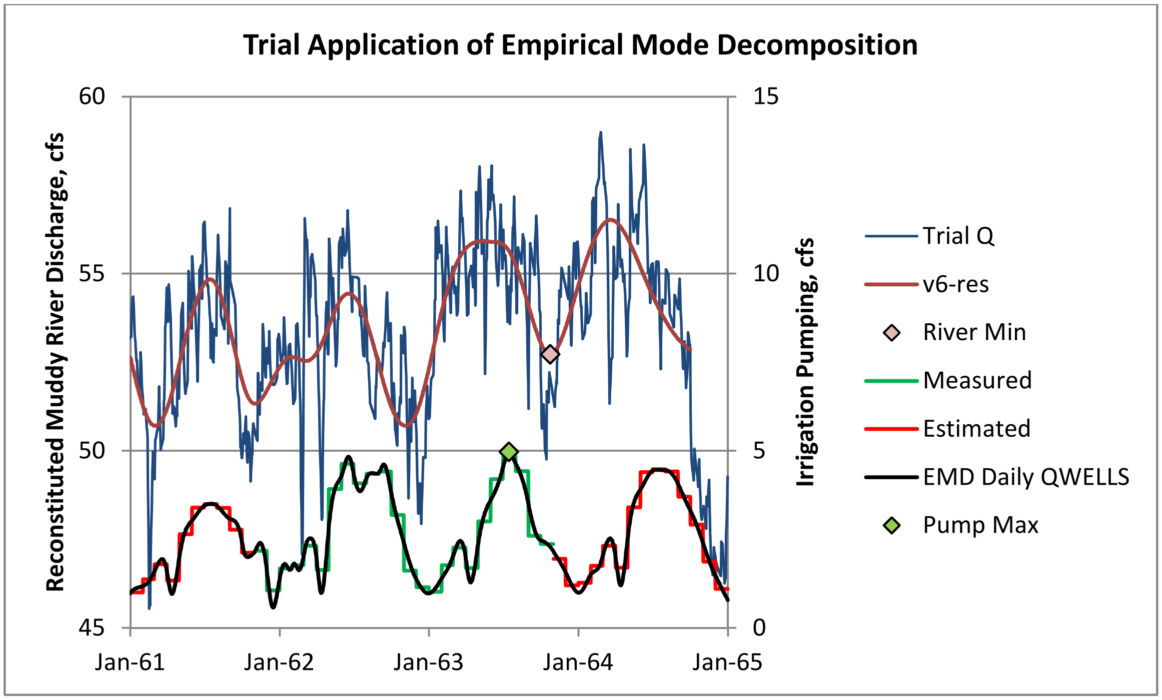


Figure B-8. Trial reconstitution of the Muddy River hydrograph based on an assumed consumptive use factor of 50% and no lag between pumping and River response. Monthly production from the Lewis Well Field area reported by Maxey and others (1966), monthly estimates, and EMD approximation of the monthly rates as daily values are shown for reference. [file IllustrateEMD.xlsx, sheet 'TrialSF.5']

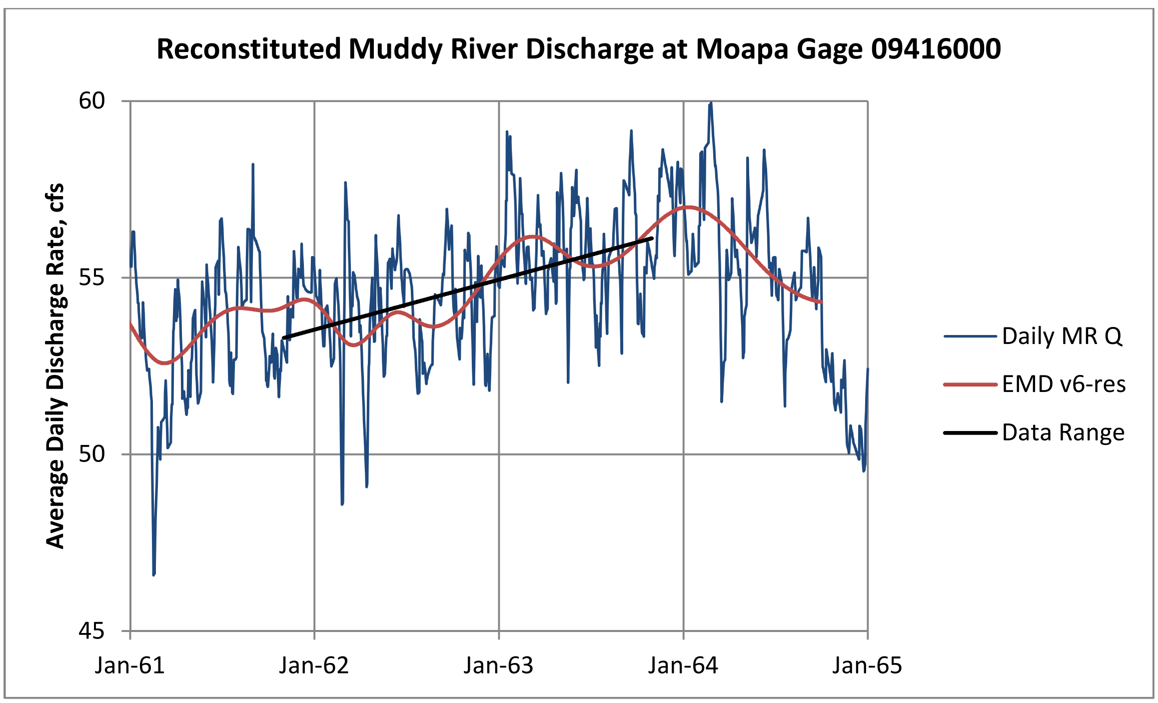


Figure B-9. Accounting for lag indicated by the green (Pump Max) and pink (River Min) symbols in Figure B-8 and 100% consumptive use removes seasonality from the reconstituted record in the 1961-1963 data range and reveals a 2-year rising trend in base flow [file IllustrateEMD.xlsx, sheet Lag101SF1]

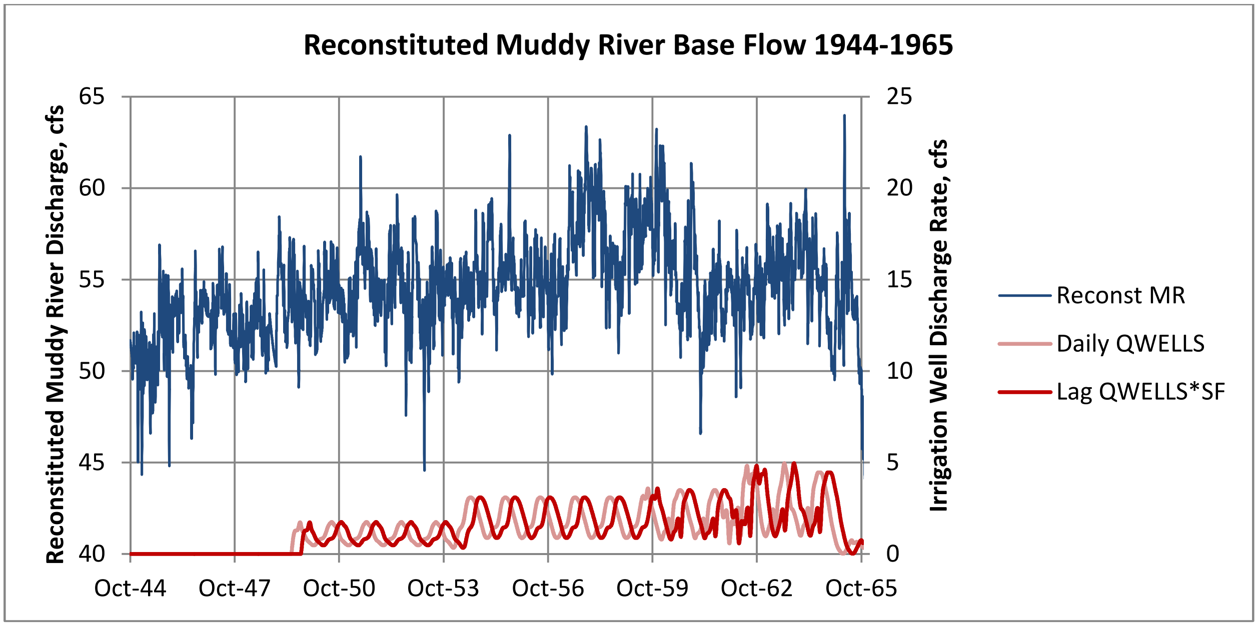


Figure B-10. Aggregate diversion rate of wells monitored by Maxey and others (1966) are lagged to minimize seasonality in the November 1961 – October 1963 interval of the reconstituted hydrograph; the result is generally valid until April of 1965, when groundwater export to Reid Gardner Generating Station began. The scale factor (SF) here is 1.0. [file ReconstSimple4.xlsx, sheet 'FloodIrrCU4487']

Annual energy deliveries from Reid Gardner Station Units 1-3 were reported from 1991 and 2000-2010, years when water consumption was also metered. Diversions from the Lewis and Behmer wells and the River intake are used for Units 1-3; calendar-year totals are given in Table B-1.

Table B-1. Water demand and energy deliveries from Reid Gardner Units 1-3 [file NPCgeneration2.xlsx, sheet 'WaterDemand']

Year	RG 1-3 KWh	RG 1-3 GWh	Acre-ft	Fit	Hours	Avg Rate (Mw)	**acre-ft/Mw**	
		0	0	0				
1991	1,854,444,000	1,854	3,605	3872	8760	211.69	17.03	
2000	2,390,602,000	2,391	5,133	4992	8784	272.15	18.86	
2001	2,164,141,000	2,164	5,005	4519	8760	247.05	20.26	
2002	2,372,245,000	2,372	5,149	4953	8760	270.80	19.01	
2003	2,320,199,000	2,320	4,839	4845	8760	264.86	18.27	
2004	2,292,950,000	2,293	4,388	4788	8784	261.04	16.81	
2005	2,149,283,000	2,149	4,397	4488	8760	245.35	17.92	
2006	2,010,884,000	2,011	4,016	4199	8760	229.55	17.49	
2007	1,954,011,000	1,954	3,094	4080	8760	223.06	13.87	
2008	1,883,622,000	1,884	4,442	3933	8784	214.44	20.72	
2009	1,604,615,000	1,605	3,687	3351	8760	183.18	20.13	
2010	1,724,277,000	1,724	3,928	3600	8760	196.84	19.95	
							18.36	**Average**
							1.93	**Std Dev**

SNWA has used generating capacity of Reid Gardner Station as the basis for estimating water demand for power generation between 1965 and 1986 (LVVWD, 2001, Table B-11). A conversion factor of 12 acre-feet of water per megawatt was used to estimate total annual water demand, and by subtracting annual surface-water diversions the annual groundwater demand was derived.

The slope of the water consumption versus energy generation plot (Figure B-11) is 2.088 acre-ft/GWh, equivalent to 18.4 ± 1.9 acre-ft/MW, roughly 50% higher than assumed by SNWA. Instead of relying on generating capacity or energy deliveries, MAI has utilized measured groundwater consumption for Unit 1 as reported by Maxey and others (1966) (Figure B-12), and interpolated groundwater demand for the 1968-76 interval when Units 1-2 were operating (Figure B-13) using measurements of combined Units 1-3 demand from 1989-94 (Figure B-14); Unit 4 diversions from the headwaters area have been measured since diversions there began in 1988.

With Reid Gardner Unit 1 demand (1965-1968) estimated from Maxey's data, combined Units 1+2+3 demand (1976-present) from the 1989-1994 measurement record, and combined Units 1+2 demand (1968-1976) derived by interpolation, a lag estimate for the industrial phase of the Lewis Well Field can be derived. Figure B-15 represents Water Years 1978 through 1985, when daily measurements of power diversions from the Muddy River were made by the USGS. When the Muddy River hydrograph is reconstituted to account for all known diversions through 1985 and compared with EMD-derived daily pumping rates from the Lewis Well Field, an average lag time of 58 days between maximum pumping and minimum River discharge is obtained (Figure B-15). Applying this lag to the Lewis diversion record and adding the lagged diversion rates day-by-day to the River hydrograph produces the reconstituted hydrograph of Figure B-16, minimizing residual seasonality during the evaluation interval.

The question arises as to where surface water from the Muddy River was diverted between 1968 and 1976, when Reid Gardner Unit 2 imposed water demands that could not be met by the Lewis Well Field (Figure B-13). To test the hypothesis that surface water was diverted below the Moapa Gage, we examine a reconstituted hydrograph that does not account for the portion of winter demand met by River diversions (Figure B-17). The prominent winter deficits beginning in the winter of 1969-1970 suggest that winter diversions above the Moapa Gage occurred from that time to the present. With this information, the reconstitution of Figure B-18 incorporates all major diversions and their associated lags through 1987, except for testing activities at MX-5 that occurred in 1981.

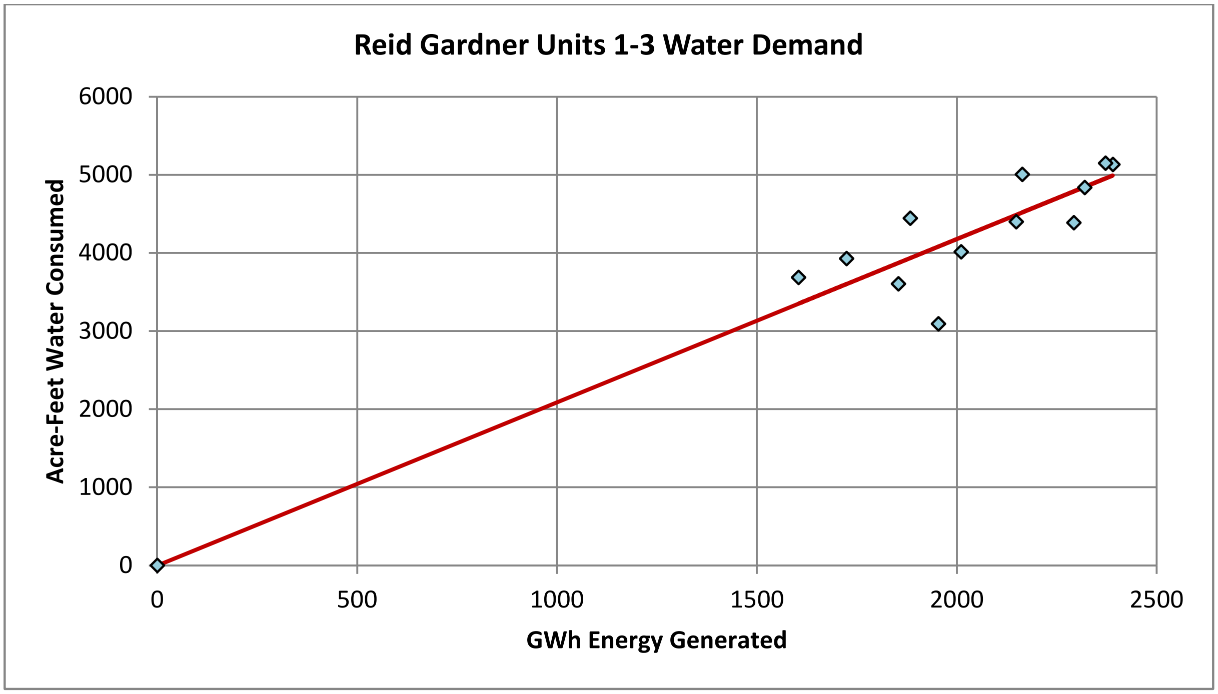


Figure B-11. Relationship of water demand to energy deliveries from Reid Gardner Units 1-3 [file NPCgeneration2.xlsx, sheet 'WaterDemand']

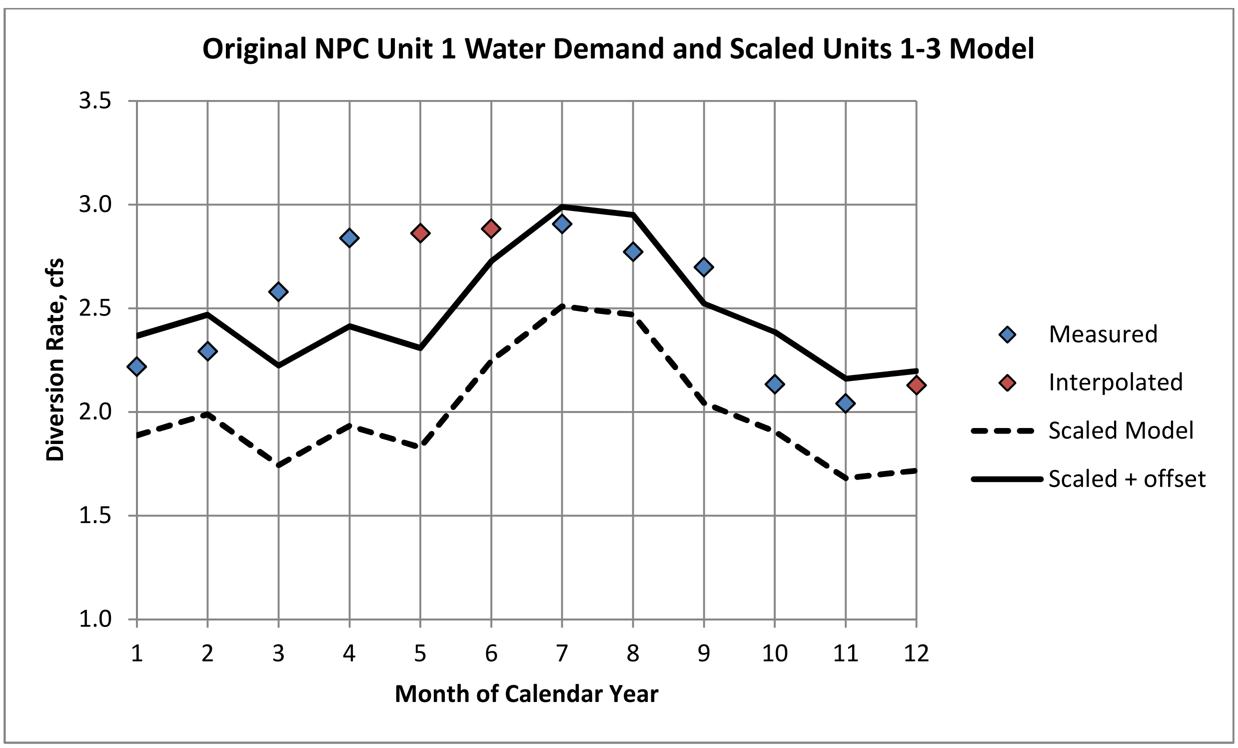


Figure B-12. Reid Gardner power diversions 1965-68, based on measurements by Maxey and others (1966) for the first year of operation. "Scaled Model" represents 1/3 of combined Units 1+2+3 total demand; offset fits Maxey's data. [file Maxey1965-66Qv3.xlsx, sheet '1964-66']

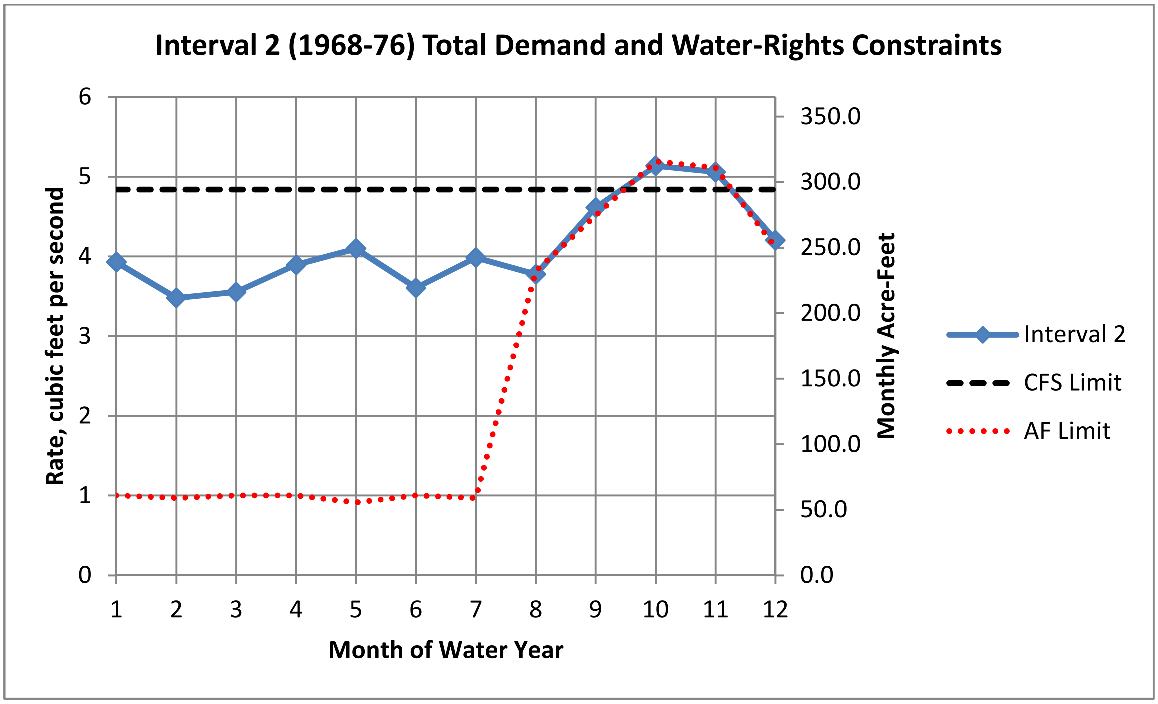


Figure B-13. Reid Gardner total water demand 1968-76 for combined Units 1-2. Summer demand was met by the Lewis well field; the acre-ft limit (deficit) imposed by Ruling 957 was met by a lease of winter Muddy River water of up to 7 cfs and total duty of 2,000 acre-ft. May-September demand is assumed to have been met by the Lewis Well Field; total duty constrains Lewis production during winter (October-April) to about 1 cfs. [file Maxey1965-66Qv4.xlsx, sheet '1964-66']

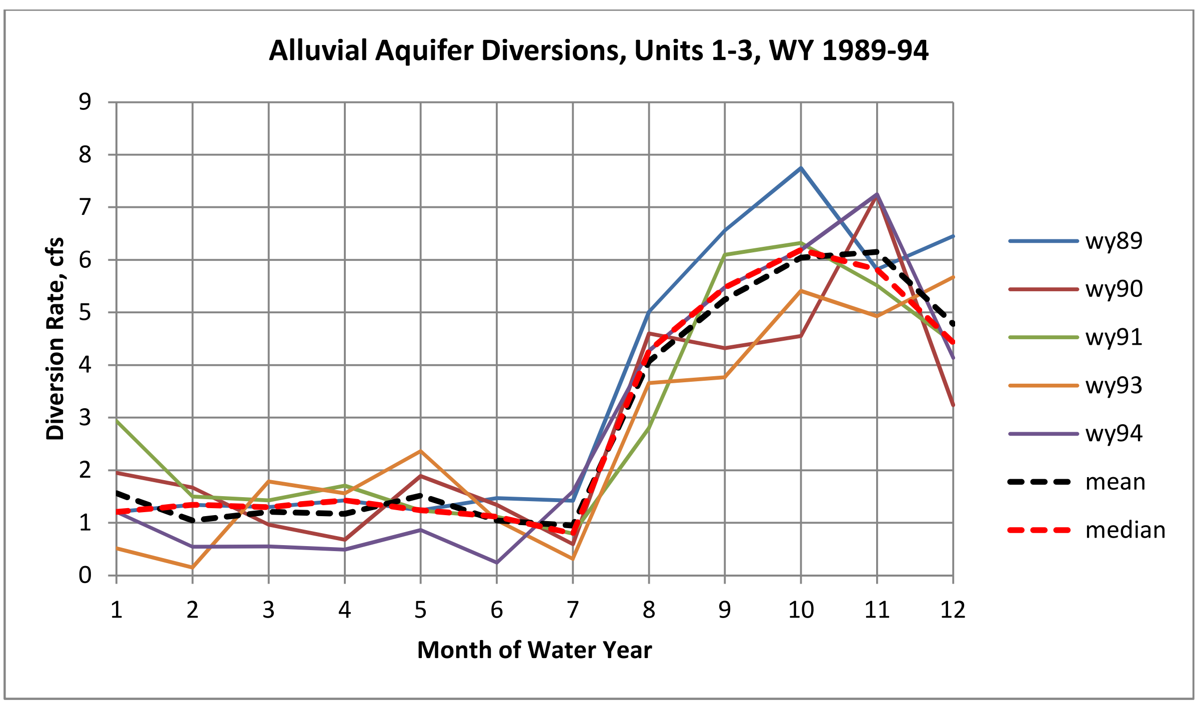


Figure B-14. Reid Gardner alluvial aquifer diversions used as basis for estimating groundwater demand of combined Units 1-2 (1968-76), interpolating between Unit 1 (1965-68) demand shown in Figure B-5 and those of Units 1-3 (1989-94) shown here. [file Units123demand88-11.xlsx, sheet 'MonthlyData']

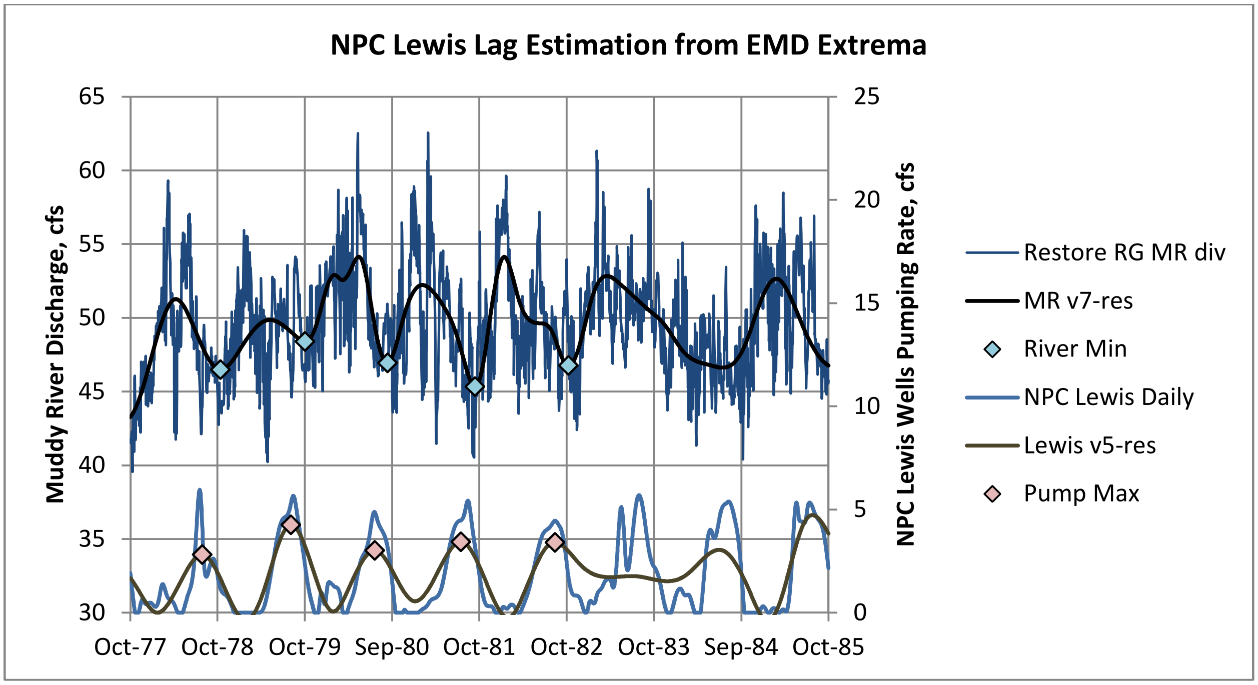


Figure B-15. When the Muddy River hydrograph is reconstituted to account for all known diversions *except* those from the Lewis Well Field and compared with the EMD approximation of daily Lewis Well Field pumping rates, an average lag of 58 days between maximum pumping rate and minimum River discharge is derived. [file IllustrateEMD.xlsx, sheet 'TrialNPCLewis']

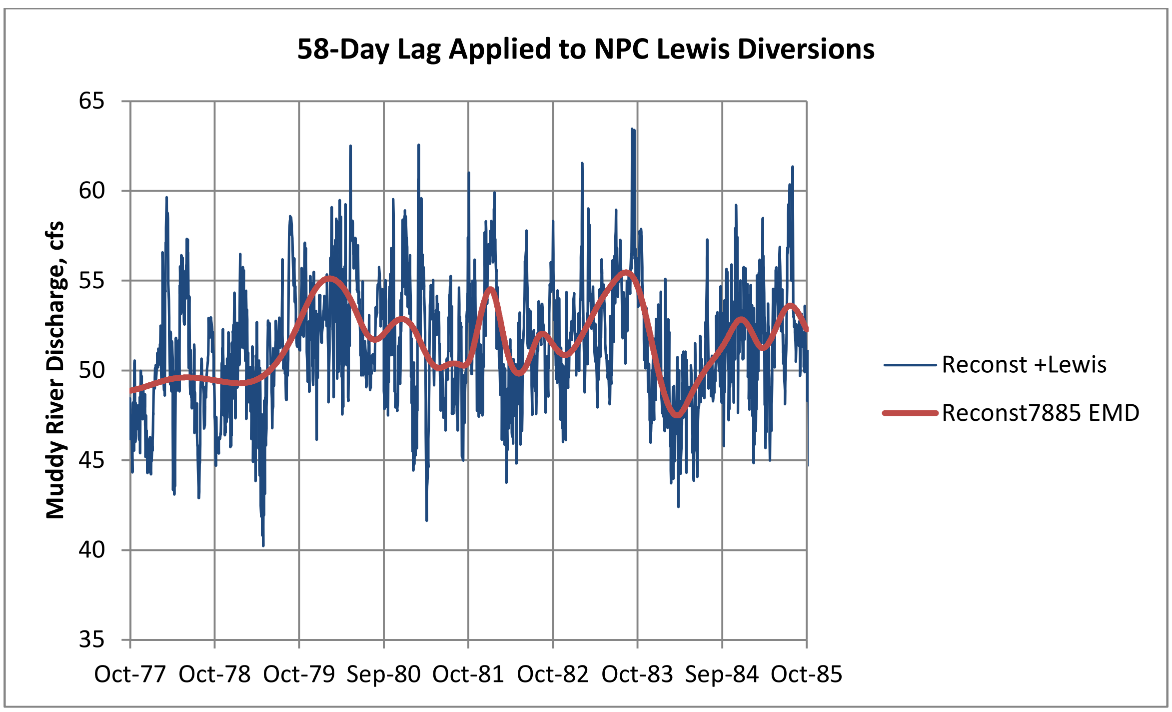


Figure B-16. Reconstituted base flows for Water Years 1978-1985 based on a 58-day lag associated with Lewis Well Field pumping and groundwater export by NPC [file ReconstSimple4.xlsx, sheet 'RG123']

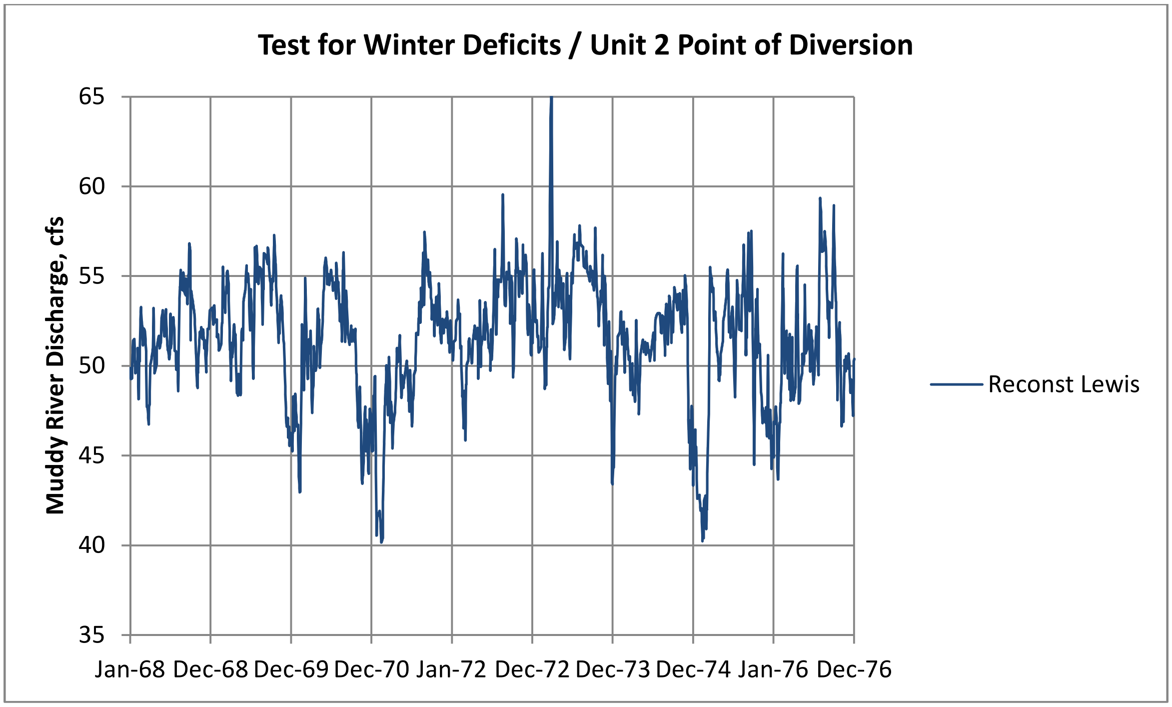


Figure B-17. Prominent winter deficits occur if surface-water diversions above the Moapa Gage are not included in the reconstitution from the winter of 1969-1970 onward [file ReconstSimple4.xlsx, sheet 'RG123']

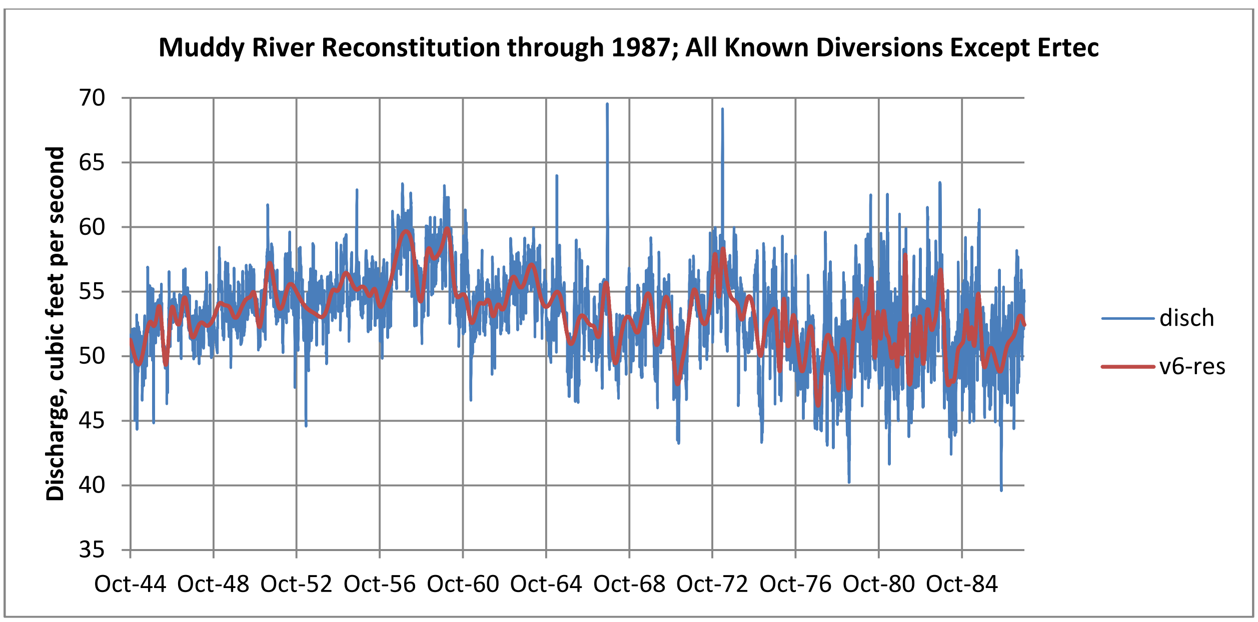


Figure B-18. Reconstituted base flow of the Muddy River through 1987, accounting for all major diversions except Ertec's MX-5 aquifer test in 1981. Sustained pumping in Coyote Spring Valley did not begin until late 2005; diversions associated with the Ertec test are incorporated with the final reconstitution step. [file ReconstSimple4.xlsx, sheet 'ReconstMR4487EMD']

Reid Gardner Unit 4 entered service in 1983, but all water demand was met by the Meadow Valley Wash well field until mid-1988. Deteriorating water quality from that source caused deterioration of concrete in the cooling towers, and forced NPC to acquire additional water rights in the headwaters area. The Taylor E well was rehabilitated to become LDS E, the LDS C well was drilled, and separate pumps for Unit 4 were installed above the Moapa Gage. The LDS E and C wells are adjacent to Big Muddy Spring and the Muddy River, so we assume there is no significant lag between pumping at these wells and reduction of River flow. LDS E entered service in June of 1988, and LDS C in July of the same year. River diversions for Unit 4 began the following winter, and monthly diversion records from all 3 sources are available from January of 1988 to the present. Reconstitution to account for Unit 4 demand is therefore straightforward, and results in the base-flow hydrograph of Figure B-19, which does not yet include the effects of Arrow Canyon Well (ACW) and Coyote Spring Valley (CSV) pumping.

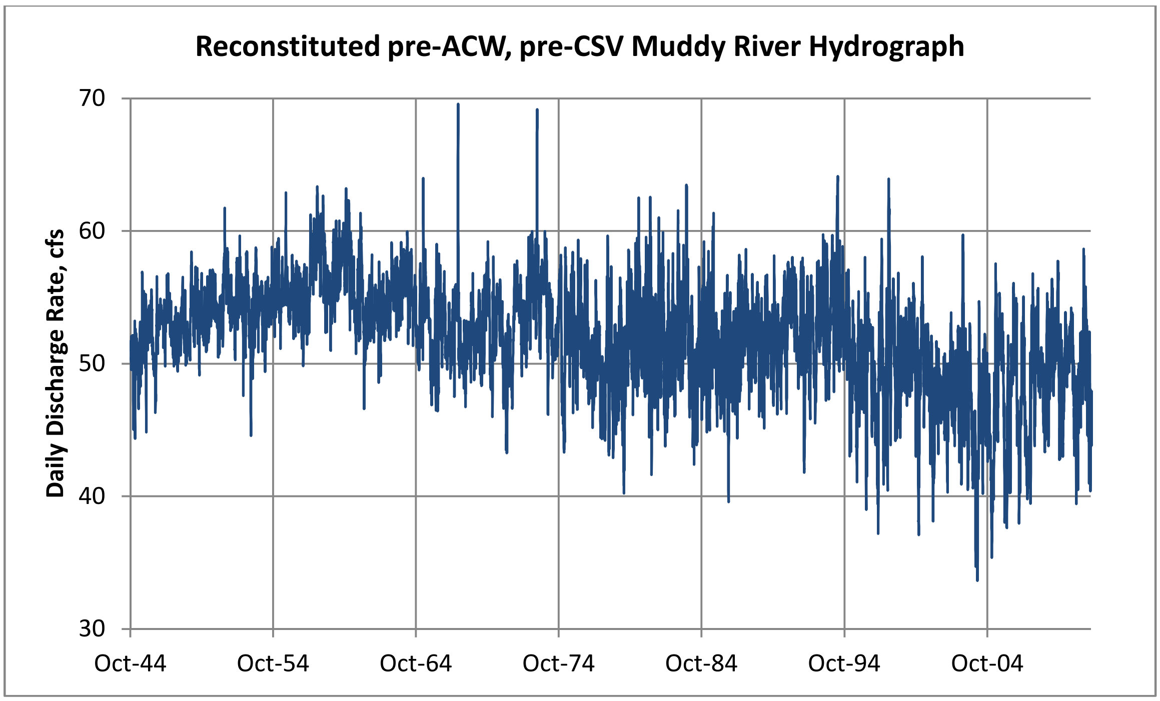


Figure B-19. Reconstituted Muddy River hydrograph, incorporating all major diversions except those from the Arrow Canyon Well(s) and Coyote Spring Valley [file ReconstSimple4.xlsx, sheet 'RG4']

The Arrow Canyon #1 well went online in June of 1992, operating at 900 gpm. A 31-day constant-discharge test at 606-793 gpm was conducted in April-May 1993, and step-drawdown and 72-hour constant-discharge tests were conducted in October of 1993. A 121-day constant-discharge test at 2,900 gpm was conducted between December of 1993 and April of 1994. Minima in the reconstituted hydrograph of Figure B-19 best align with pumping maxima when the pumping is lagged 156 days (Figure B-20).

The final step in the reconstitution is to include pumping in Coyote Spring Valley, which is represented as a backward-looking 3-year average pumping rate for all active wells (CSI-1, CSI-2, CSI-3, CSI-4, and MX-5), consistent with the derivation of Bredehoeft (2011). The reconstituted natural-flux hydrograph of Figure B-21 remains within the historic range for 2011-2012, the Order 1169 testing interval.

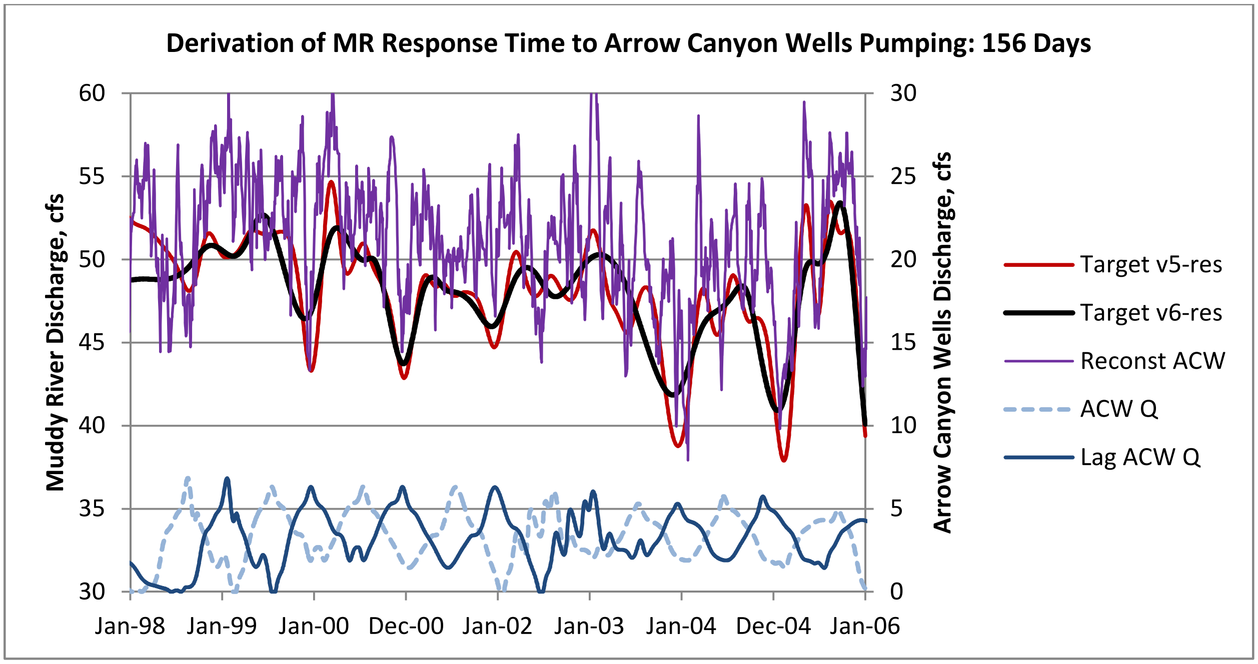


Figure B-20. Alignment of pumping maxima with target minima occurs with a 156-day lag, and produces a reconstituted hydrograph with minimum seasonality. There is no evidence the Arrow Canyon Wells are not equally responsible (in proportion to diversion rates) for seepage reductions, since they intercept deeply-circulated groundwater that would otherwise transit the Lewis Well Field to discharge in the headwaters area. [file ReconstSimple4.xlsx, sheet 'ACW']

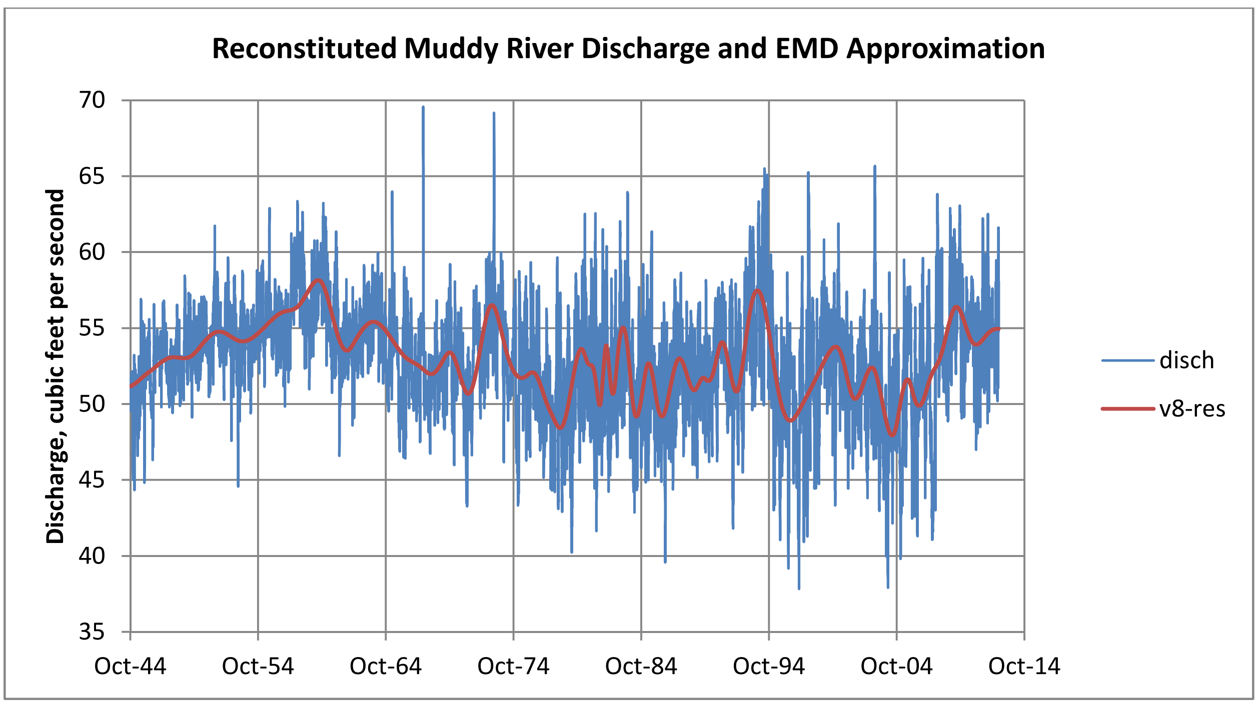


Figure B-21. Fully reconstituted Muddy River hydrograph expressed as natural groundwater flux to the headwaters area, based on backward-looking 3-year average for Carbonate-Rock Aquifer production [file ReconstSimple4.xlsx, sheet 'ReconstMR4412EMD']

Appendix C. Climate Index

Estimates of infiltration losses in Meadow Valley Wash and surge flows recorded at the Glendale gage extend the 60-year record of precipitation at Adaven that was used by Eakin (1964, 1966), providing a composite indication of moisture availability in the region (Figure C-1). Using the logarithms of infiltration losses and surge flows, and the month-by-month departures from the cumulative average precipitation at Adaven for a given month, a composite moisture-availability index was prepared by scaling and averaging the three parameters (Figure C-2). Comparing the lagged climate signal to reconstituted base flow in the Muddy River reveals that the River responds to climate on decadal time scales, as postulated by Maxey and others (1966) and Eakin (1966); the signals align best with a lag of 248 months (Figures C-3, C-4).

The lag of over two decades between climate extremes and River responses allows the future discharge trends of the Muddy River to be forecast with a 20-year event horizon, as indicated in Figure 5 of the main body of this report.

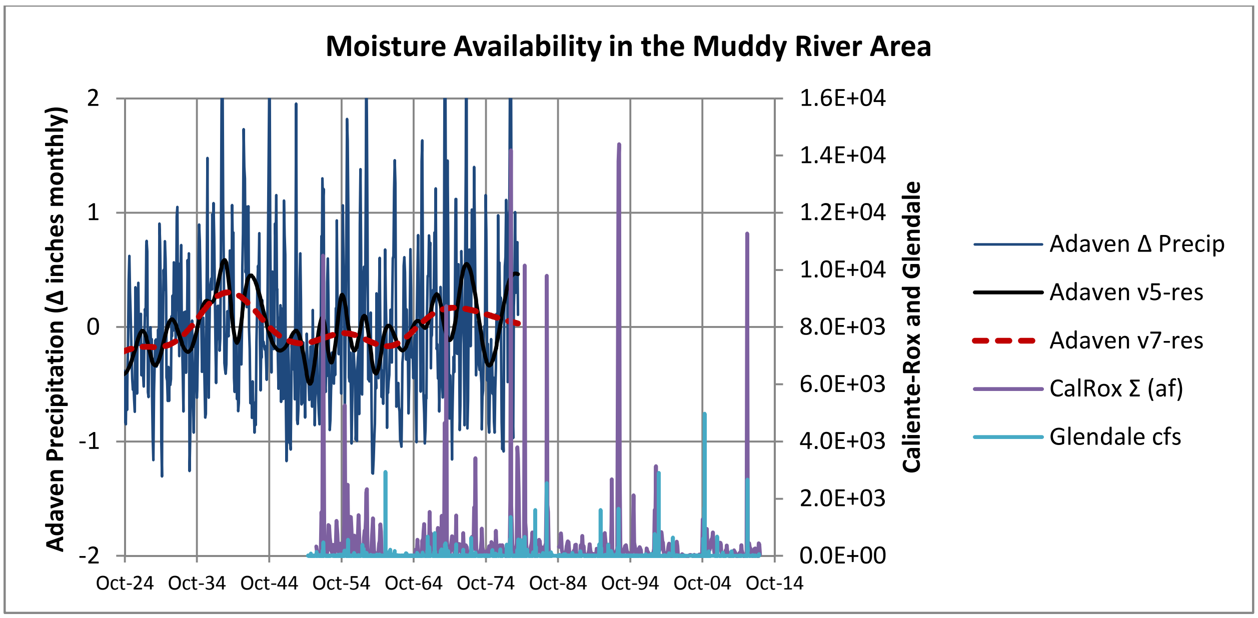


Figure C-1. Components of the composite climate index: Adaven precipitation departure from monthly average, shown with EMD-derived intrinsic modes; infiltration losses between the Caliente and Rox gages; and storm runoff at the Glendale gage derived by base flow separation [file 3climateIndicesV4.xlsx, sheet ‘MonthlyDaily’]

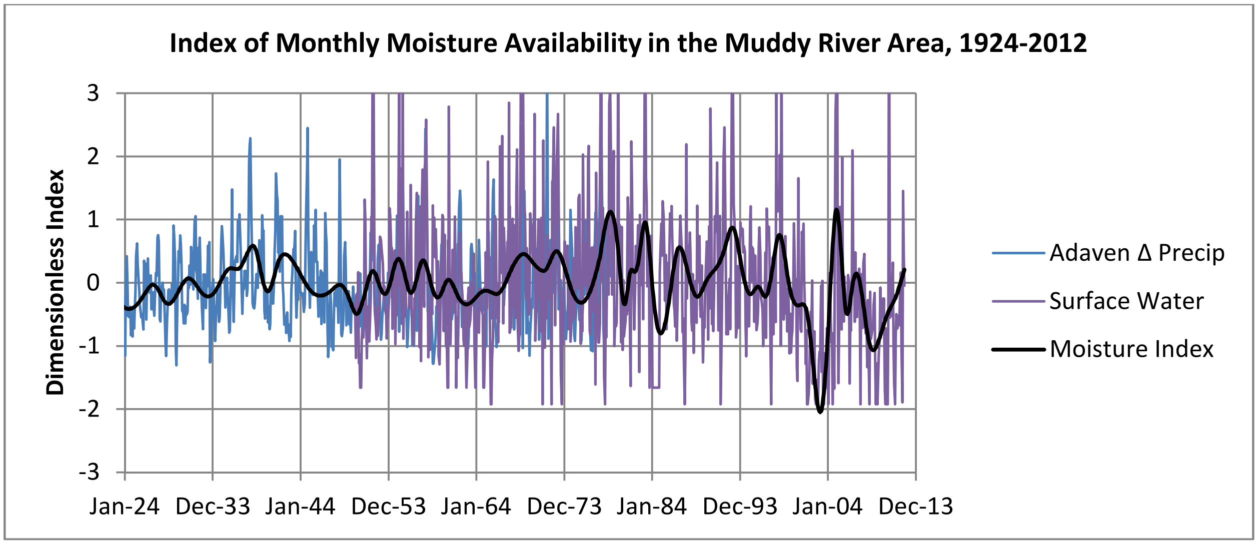


Figure C-2. Surface-water components of the climate index scaled and offset to combine with the Adaven precipitation record, with the composite moisture index derived by empirical mode decomposition [file 3climateIndicesV4.xlsx, sheet 'PlotData']

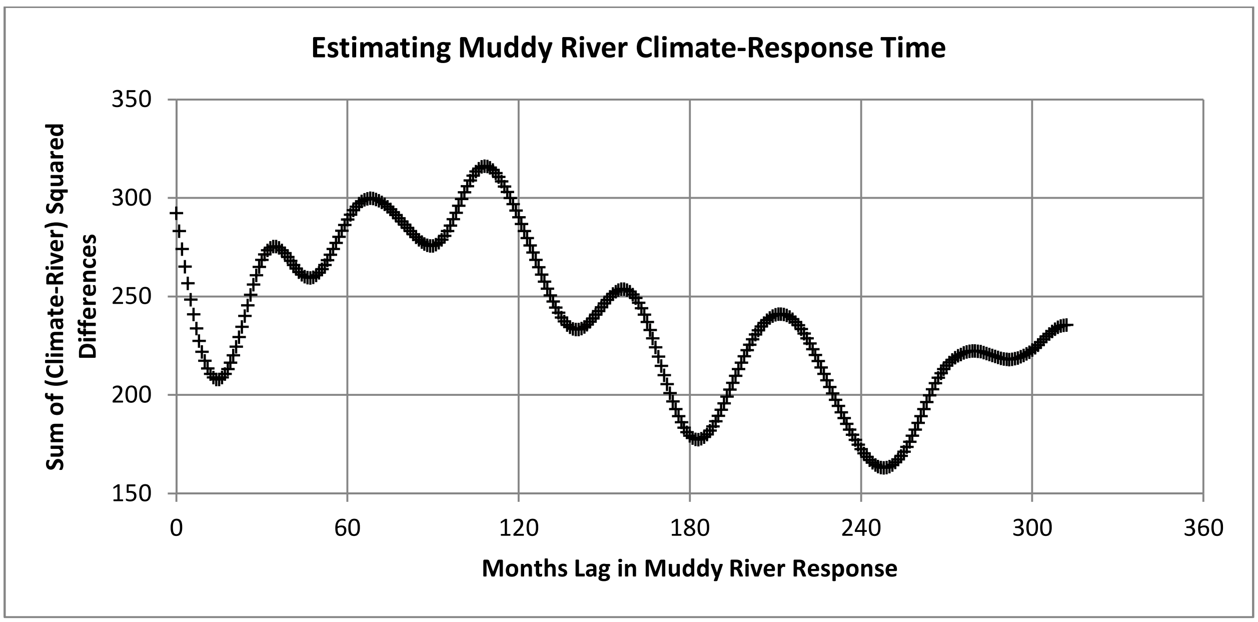


Figure C-3. Derivation of climate-response time by minimizing the sum of squared differences between the climate index and the reconstituted Muddy River hydrograph for Water Years 1945-2005 [file 3climateIndicesV5.xlsx, sheet 'LagHydrograph']

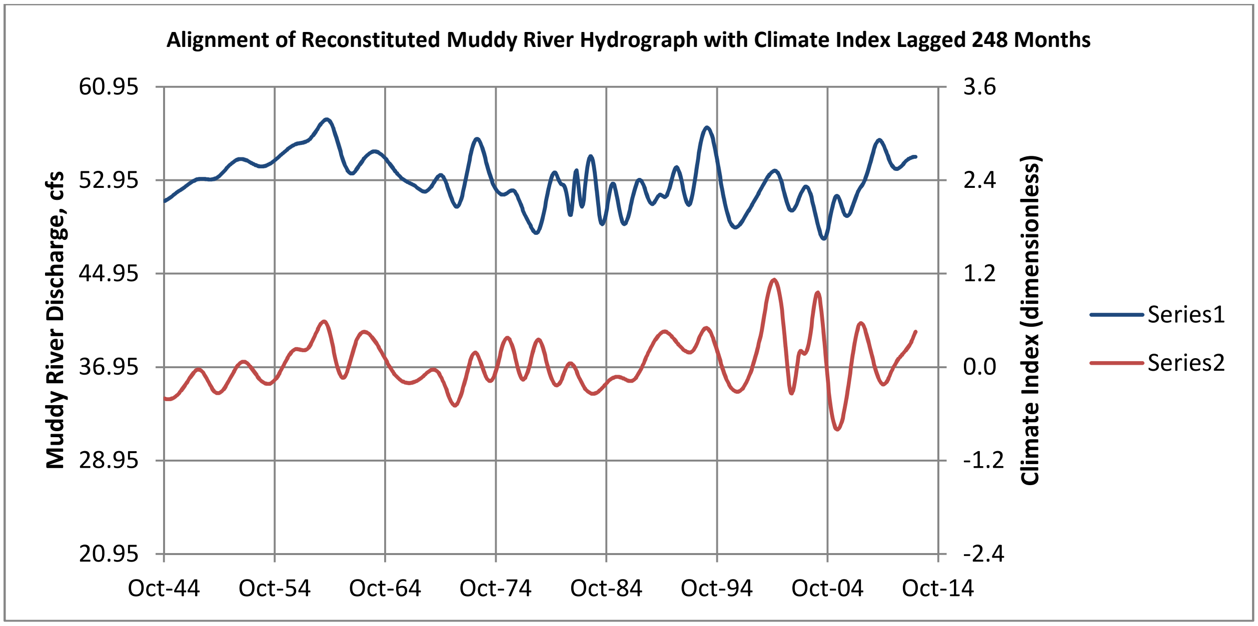


Figure C-4. Best match of reconstituted Muddy River hydrograph to climate index occurs when River discharge lags climate by 248 months. [file 3climateIndicesV4.xlsx, sheet 'LagHydrograph']

Appendix D. Selected Temperature Records

Mean annual water temperatures of the Muddy River at the Moapa Gage exceed mean annual air temperatures recorded at Nellis Air Force Base in Las Vegas Valley (Figure D-1). Temperatures at RW-2 in Coyote Spring Valley are of the order of 35°C (Figures D-2 and D-3), decreasing along groundwater flow paths to the order of 30°C at EH-5b (Figure D-4) and the Lewis Well Field (Figures D-6 and D-7) in upper Moapa Valley. At EH-4, shallow groundwater is much cooler, of the order of 25°C (Figure D-5), reflecting the effects of continued cooling along flow paths, hydraulic isolation from the proximal Pederson and Plummer Spring areas, and infiltration of relatively cool waters along Battleship Wash. Still, groundwater at EH-4 is 5°C warmer than the mean annual air temperature, reflecting its origins in a deeply-circulating flow system.

Continuous spring and stream temperatures in the headwaters area are available from March of 2008 until April of 2013, with an important data gap from July of 2010 until March of 2012. Temperatures of the Refuge and Apcar Streams (Figures T1 and T2) indicate a warming trend over the 5-year period of record, consistent with the recent interval of relatively high natural groundwater flux to the headwaters area derived by reconstitution and illustrated by the top curve in Figure 4. Annual variability of the Apcar Stream is greater than the Refuge Stream, but diurnal variations appear to be similar. The “ecohydraulic” model reported by Hatten and others (2013) appears to represent a snapshot in time with respect to stream temperature, for their Figure 3B shows a range of less than 1°C from a (presumably daytime) survey in the spring of 2009. Their finding that water temperature was less associated with dace locations than water depth, substrate, Froude number, or velocity is therefore questionable.

Figures D-8 and D-9 indicate an overall warming trend from 2008-2013, but the data gap prevents confirmation that the trend persisted during the majority of the Order 1169 test. There may be a recent trend reversal, however, based on the 2012-2013 data. Peak annual temperatures occur during the summer, but winter temperatures at some downstream stations over the period of record are less than the maxima by 9° C, and in Apcar Stream for many successive days have been less than the 26°C environmental threshold for Moapa dace cited by Hatten and others (2013). A temperature trend reversal could be very significant to the dace population.

One of the important yet unresolved questions is that of recruitment-habitat temperature requirements. During the earliest studies when dace populations were much larger and more widely distributed, the impression developed that outflow-channel reaches (“springbrooks”) close to the spring-orifice areas were the probable recruitment habitats. As flows have been reduced in some of the habitat reaches, it is possible that the temperature variability might have been less than the present 9° C in Apcar Stream and 4° C in Refuge Stream. If flows continue to decrease, flow velocities will decrease correspondingly, and winter water temperatures will reach new lows as more heat loss to the atmosphere is favored. We think USFWS needs to prioritize temperature monitoring and rectify known problems their subcontractors have experienced maintaining continuous, reliable temperature records and effectively integrating those records with dace-population studies.

The temperature-monitoring network should be restored to its full pre-2010 configuration to include North Fork, South Fork, Cardy Lamb, and mainstem Muddy River locations that were decommissioned in 2010. USFWS and its subcontractors should elevate the priority of stream-temperature monitoring if possible, and attempt to recover disorganized and error-prone data.

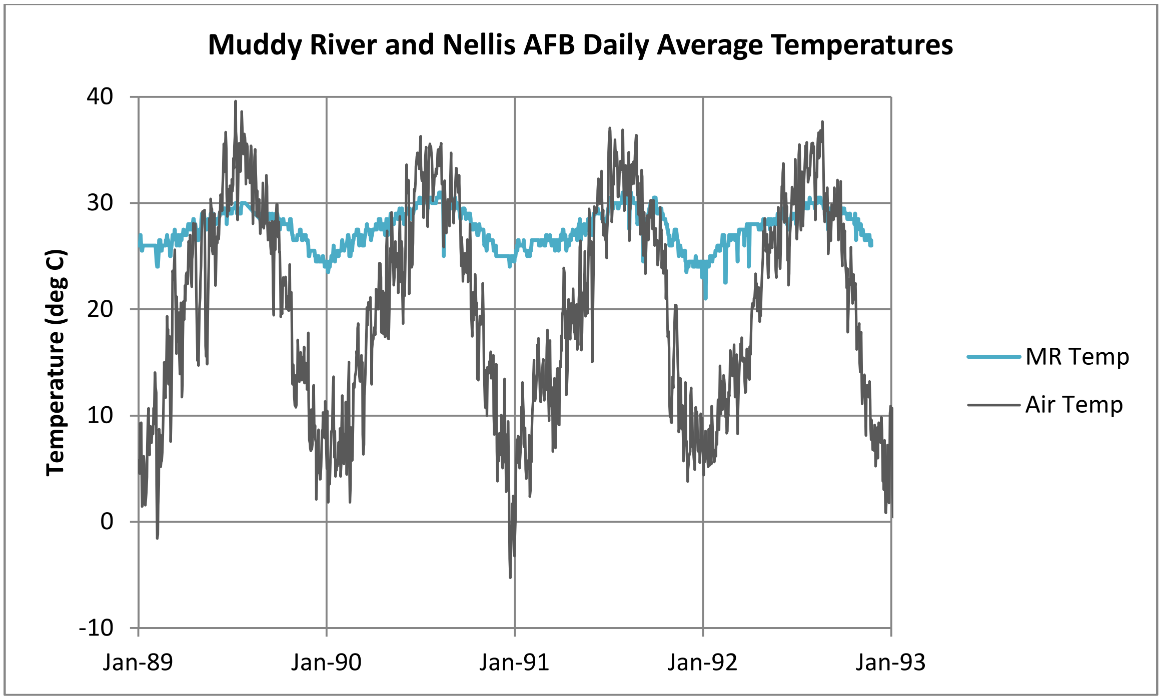


Figure D-1. Average daily water temperatures of the Muddy River and air temperatures at Nellis Air Force Base. The mean annual temperature of the Muddy River is 27.5°C, 7.5°C greater than the mean annual air temperature at Nellis. In the spring and fall, when the air and water temperatures correspond, open-channel heat exchange between the water and air is at a minimum, and the water temperature at those times is representative of a mixture of source waters. [file MRdailyTempEC.xlsx, sheet 'NellisAirT']

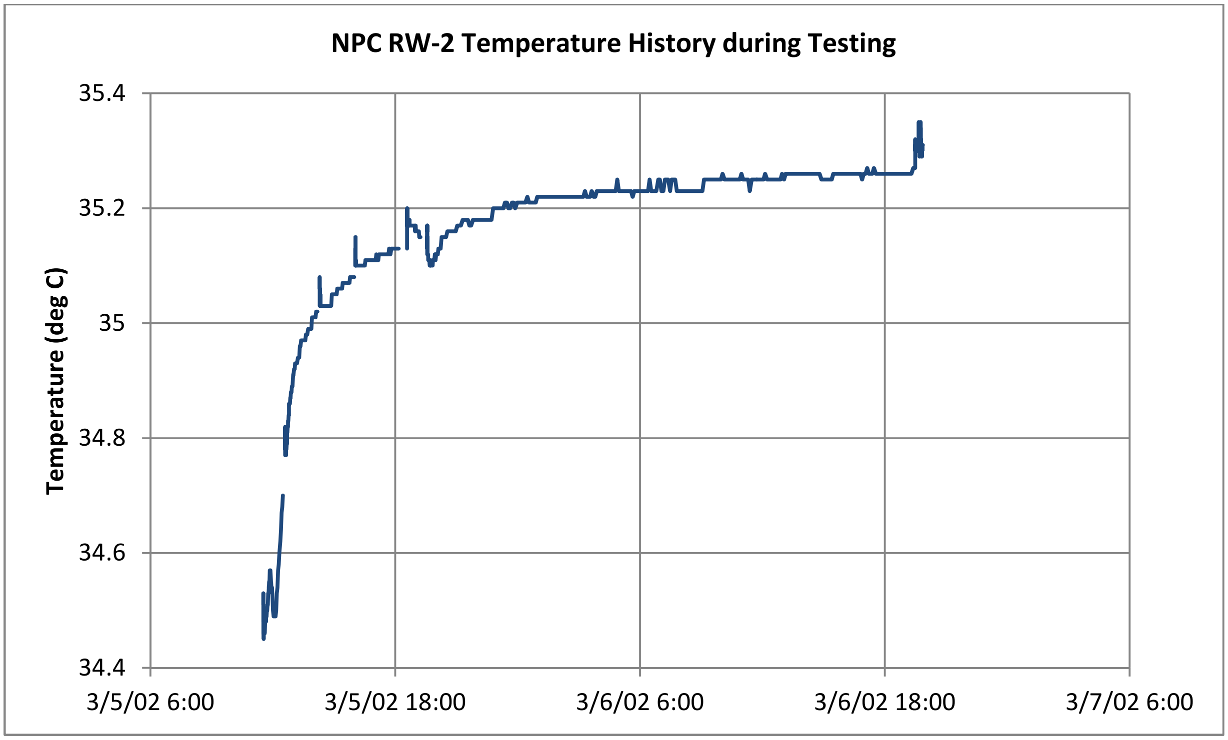


Figure D-2. RW-2 temperature data provided by Converse Consultants [file RW2allDataCJ.xlsx]

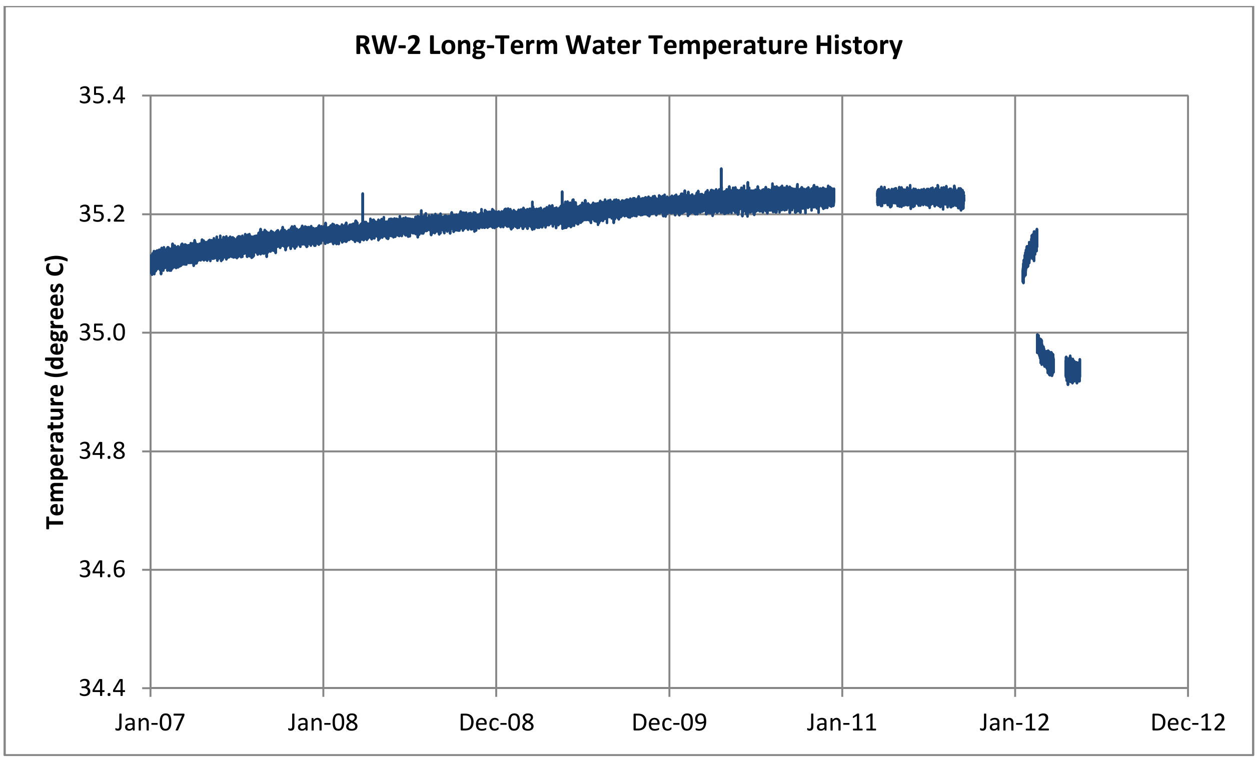


Figure D-3. RW-2 temperature data provided by Converse Consultants [file RW-1, RW-2, Eh-4, Eh-5b Houly 2003-2012V2.xlsx, sheet 'RW-2']

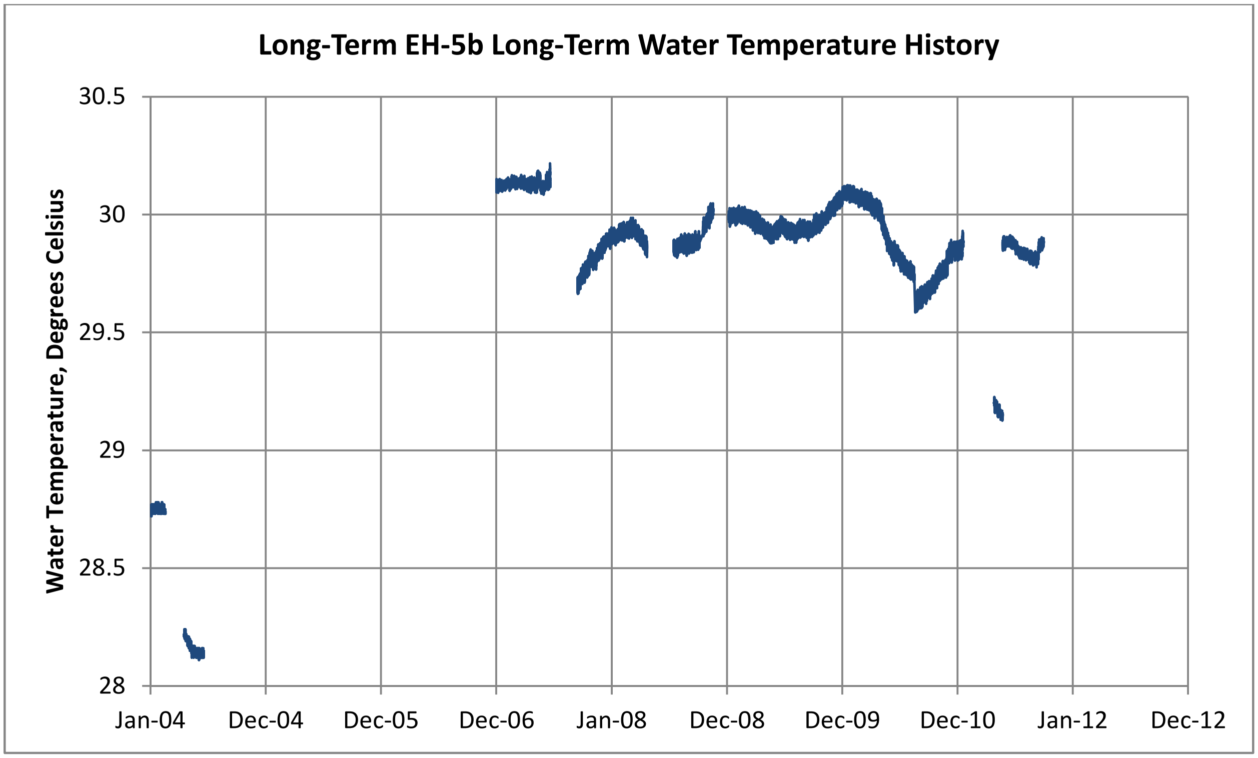


Figure D-4. EH-5b temperature data provided by Converse Consultants [file RW-1, RW-2, Eh-4, Eh-5b Houly 2003-2012V2.xlsx, sheet 'Eh-5b']

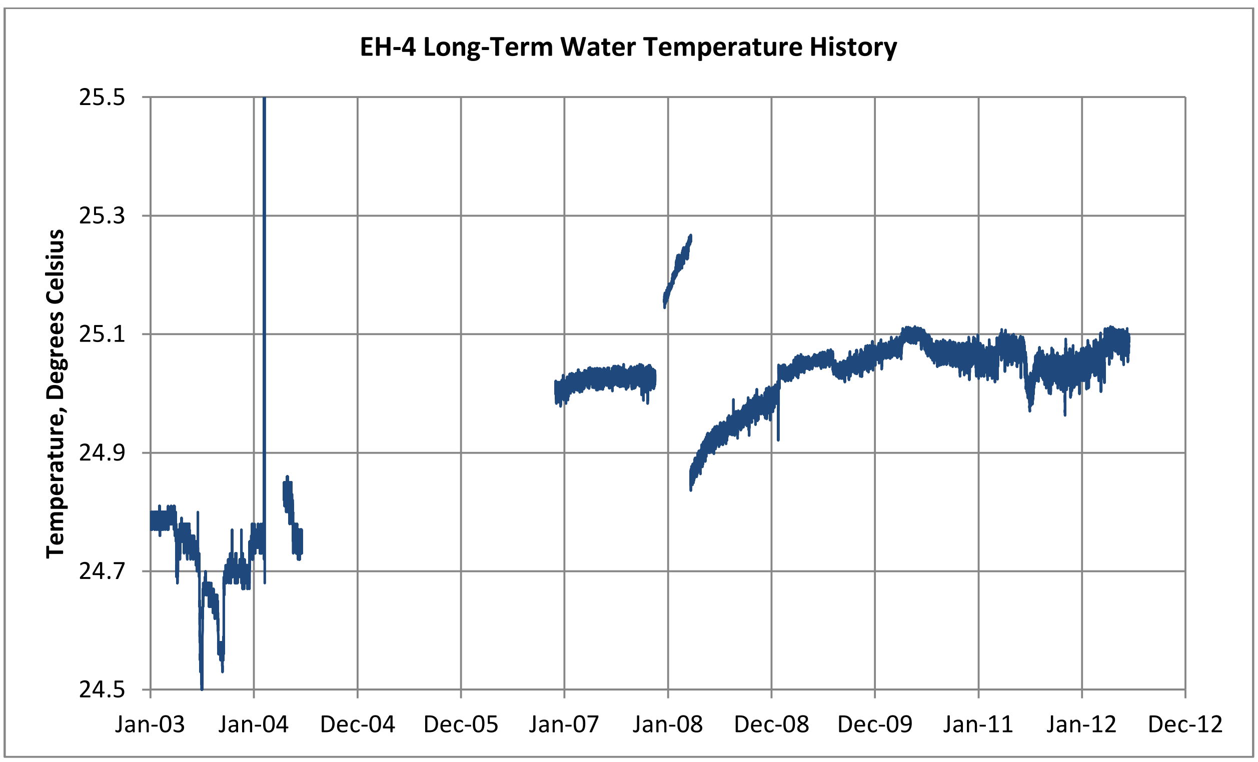
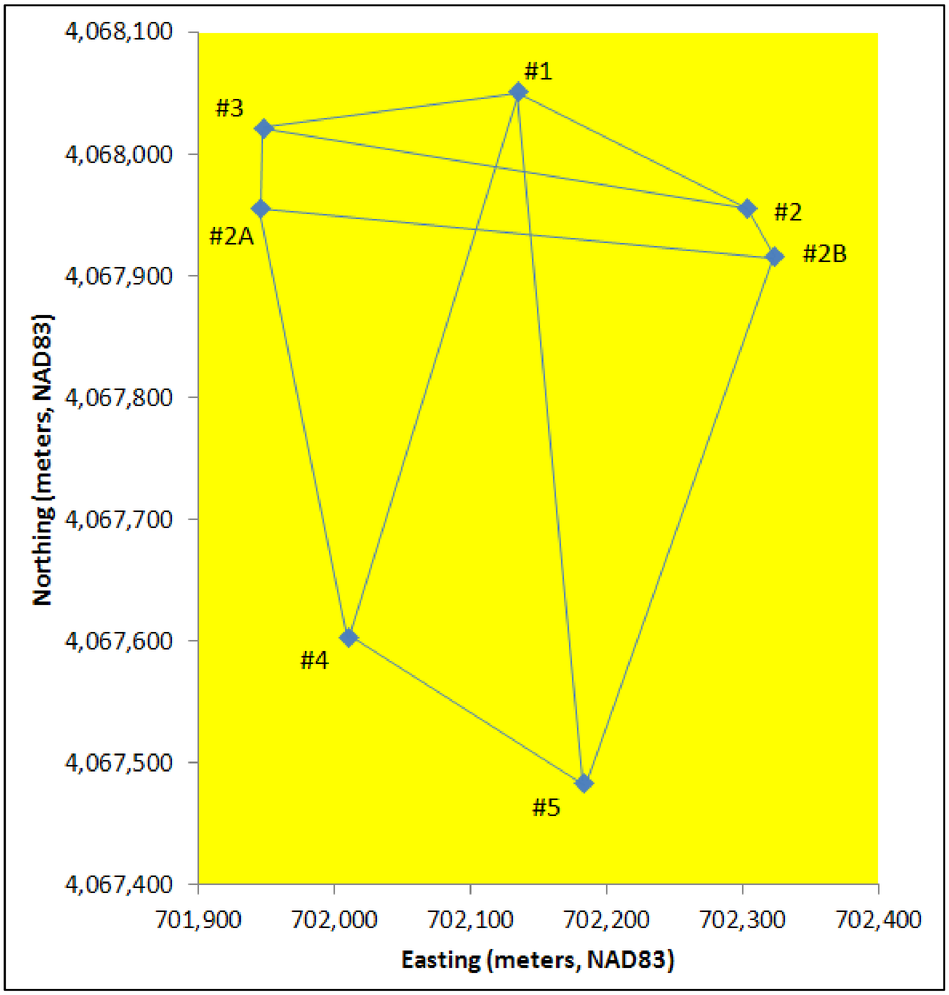


Figure D-5. EH-4 temperature data provided by Converse Consultants [file RW-1, RW-2, Eh-4, Eh-5b Houly 2003-2012V2.xlsx, sheet 'Eh-4']

Figures D-6 and D-7 (following 2 pages). Fence diagrams represent contrasting 3-dimensional temperature distribution in the Lewis Well Field. Temperature profiles were measured in the 7 Lewis wells between 1987 and 1995; the wells and fence locations are identified as follows:



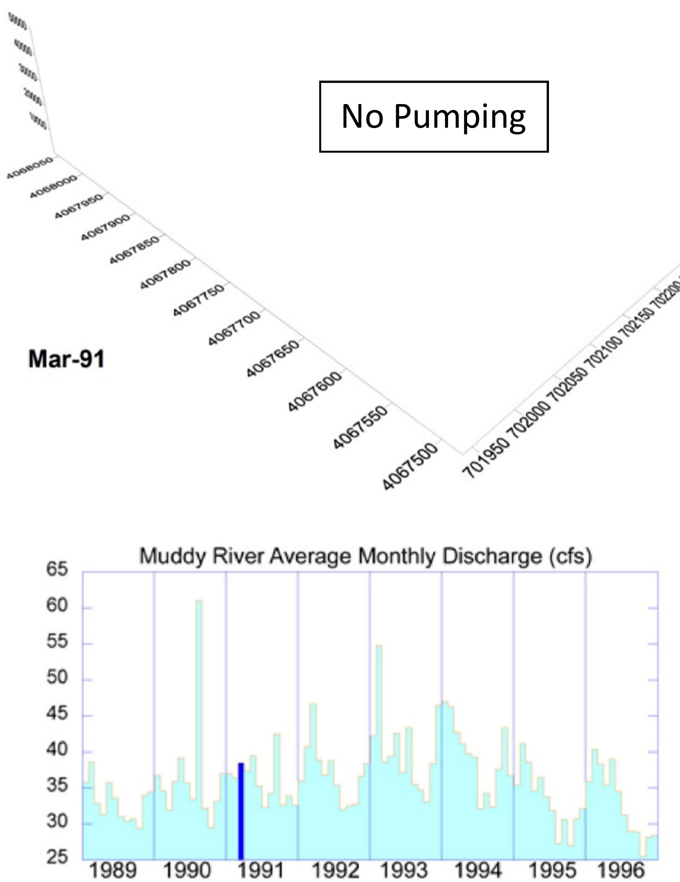
The distribution of pumping in the Lewis Well Field is represented qualitatively as a bi-quadratic trend surface in the upper left of each figure for months when pumping occurred, and the average monthly discharge rate of the Muddy River is shown as a bar chart in the lower left.

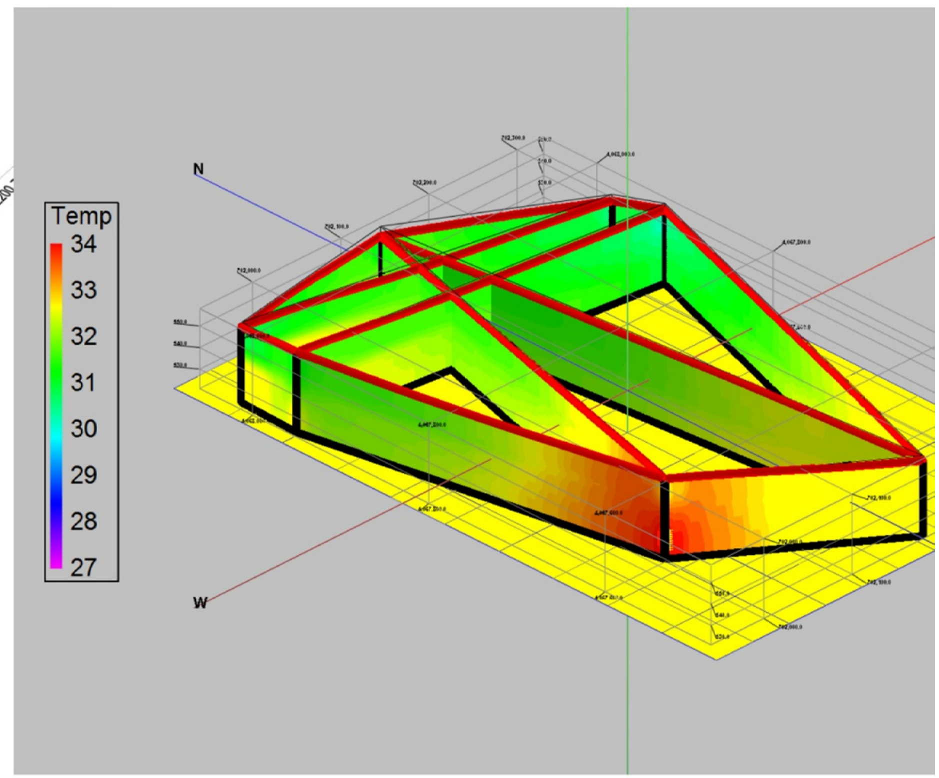
With no Lewis production after a dry winter and reaming of the Arrow Canyon #1 well in late 1990, temperatures in NPC #4 are elevated (Figure D-6); after an unusually wet 1992-93 winter and minimal Lewis production temperatures in NPC #1 are depressed (Figure D-7) [files Mar91LewisTempFence2.jpg and Mar93LewisTempFence2.jpg , modified after file LewisTvsProduction89-96.pptx]

Lewis Well Field

Production Effects on Groundwater Temperatures

- Measured Temperatures

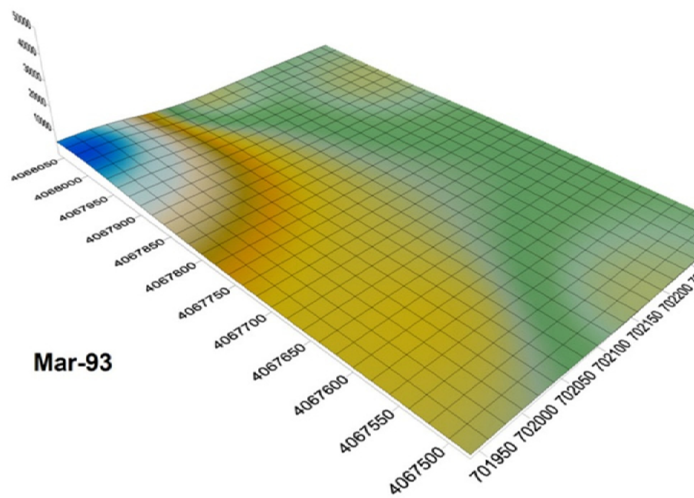


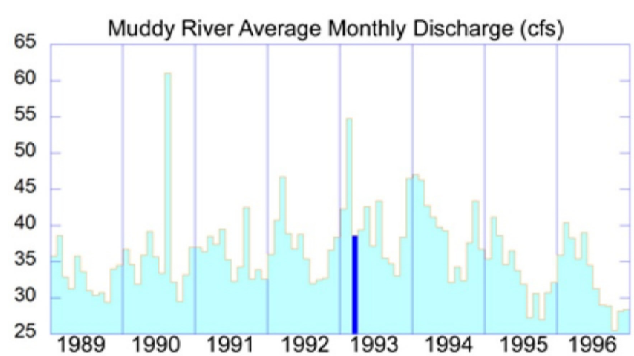


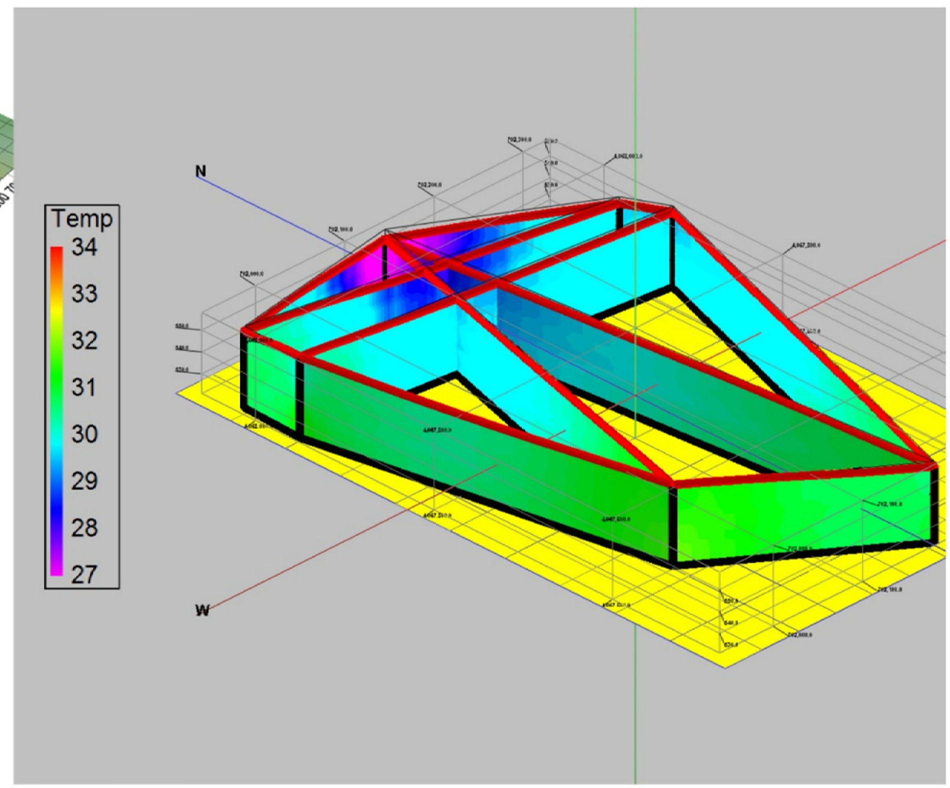
Lewis Well Field

Production Effects on Groundwater Temperatures

- Measured Temperatures







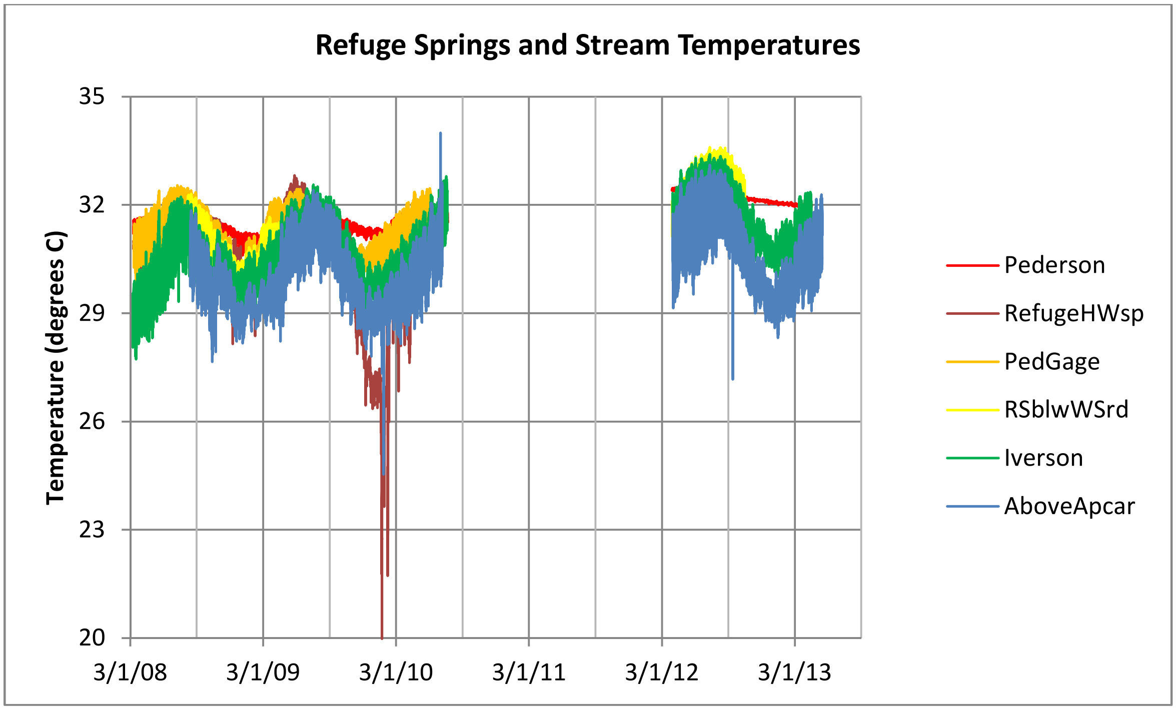


Figure D-8. Temperature record from the Refuge Stream and tributary springs: Pederson Spring (N56178), "Headwaters Spring Refuge Tributary" (N56179?), Pederson Gage (N56170), Below Warm Springs Road (N56185), Iverson Flume (N56168), and Above Apcar Confluence (N56182) [RefugeStreamComparison.xlsx]

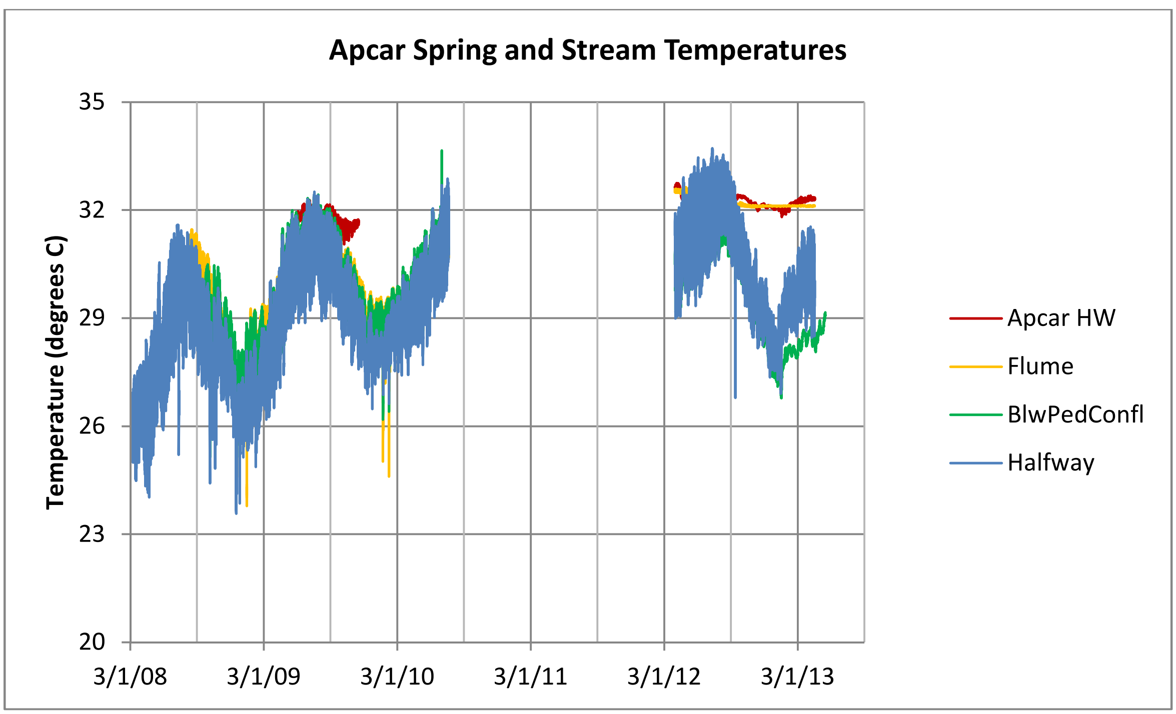


Figure D-9. Temperature record from Apcar Headwater Spring (N56186?), NDWR Flume (N56177), below the "new" (October 2008) Pederson confluence (N56172), and "halfway up Apcar at culvert" (N56181) [ApcarComparison.xlsx]

Appendix E. Mixing and Mass-Balance Observations and Calculations

In the Eakin (1964) dataset, EC at three field-measurement sites was determined in the USGS laboratory (sites 1, 10, and 11 from the 1963 synoptic survey as shown in Figure 2 of this report).

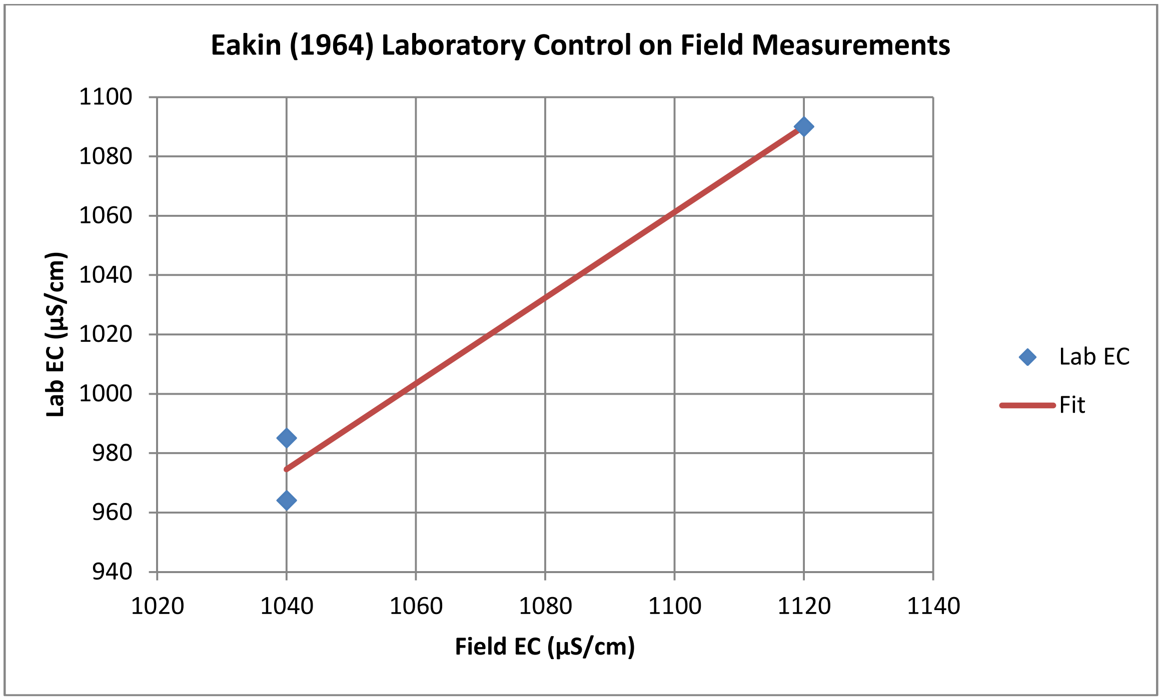


Figure E-1. Laboratory and field EC measurements reported by Eakin (1964, Figure 3 and Table 6) from the Muddy River, "Warm Spring" (Big Muddy) and Iverson Spring (Plummer); $EC_{LAB} = 1.444*EC_{FIELD}-527$ µS/cm. Note that Eakin's laboratory measurements do *not* correspond in time with his field measurements; the mean daily EC of the Muddy River from automated monitoring by the USGS between 1988 and 1993 was 1,013 µS/cm, with a standard deviation of 42 µS/cm (Figure E-2). This standard deviation gives an indication of the representativeness of a River sample taken at the Moapa Gage, and therefore the uncertainty in the upper-right data point here. [file EakinLabFieldEC.xlsx]

During the synoptic survey of February 2001, Beck and others (2006) made field measurements of discharge, EC, and temperature on South Fork and below the North and South Fork confluence (Figure 2). At the Baldwin Springs flume (partial-record station 7 on Figure 2), the USGS measured 4.10 cfs; below the confluence (upstream of continuous-record station 2 on Figure 2) they measured an average of 15.55 cfs, a gain of 11.45 cfs along about 0.3 miles of stream. Temperature and EC were not measured in the field at the flume, but EC measurements from samples taken to the USGS laboratory in Las Vegas were 977 µS/cm at the flume and 989 µS/cm below the confluence. Temperature below the confluence was 28.2°C on February 6, 2001. The 11.45 cfs of seepage can be characterized using Equation 2, where X = 4.10/15.55 = .264, as C2 = (989-0.264*977)/(1-0.264) = 993 µS/cm.

Earlier observations help us constrain the amount and quality of seepage inflow to the uppermost reach of South Fork. ERTEC (1981) monitored Baldwin Spring (Figure 2) during early aquifer tests at MX-5; discharge, temperature, and EC at Baldwin Spring and closely-adjacent Baldwin Cut were monitored from June 28 to September 30, 1981. The combined discharge of Baldwin Spring and

Baldwin Cut averaged 0.99 cfs during the ERTEC study. Note that ERTEC monitored Baldwin Spring itself, not the “Baldwin Spring” flume on South Fork (Beck and others, 2006, Tables B-40 and B-42), from which the Nevada Division of Water Resources (NDWR) recorded daily discharge (but not temperature or EC) for the same time interval. Flow at the flume, shown as site 7 on Figure 2, averaged 1.72 cfs during the ERTEC test, close to the historic minimum. The only known close-in-time measurements of temperature and EC at Baldwin Spring and the Baldwin Spring flume were made by MAI on April 8 of 1987; temperatures were 31.9 and 30.3 degrees Celsius and field ECs were 966 and 1021 µS/cm from the Spring and flume, respectively, indicating cooling and quality degradation associated with influx of seepage along about 0.2 miles at the headwaters of the South Fork tributary.

Laboratory EC measurements on samples collected from the Baldwin Springs pump house by MVWD indicate 941 µS/cm on December 9, 1997 and 944 µS/cm on January 5, 1999 (Beck and others, 2006, Table B-43). Virtually identical values of 948 and 947 µS/cm were obtained from Apcar (Pipeline Jones) Spring on the same days (Beck and others, 2006, Table B-39). ERTEC’s laboratory measurements on Baldwin Springs samples were 870 µS/cm on June 5, 1981 and 930 µS/cm on September 30, 1981. At the closely-associated Baldwin Cut, ERTEC (1981) reports laboratory values of 837 µS/cm and 950 µS/cm on the same dates. Beginning in mid-April 2009 Apcar water was transferred to a sump at Baldwin Spring before being treated and distributed or bypassed to the Baldwin Springs flume; pumping at Apcar Spring ceased in late 2010 (Joseph Davis, MVWD General Manager, personal communication, 2013).

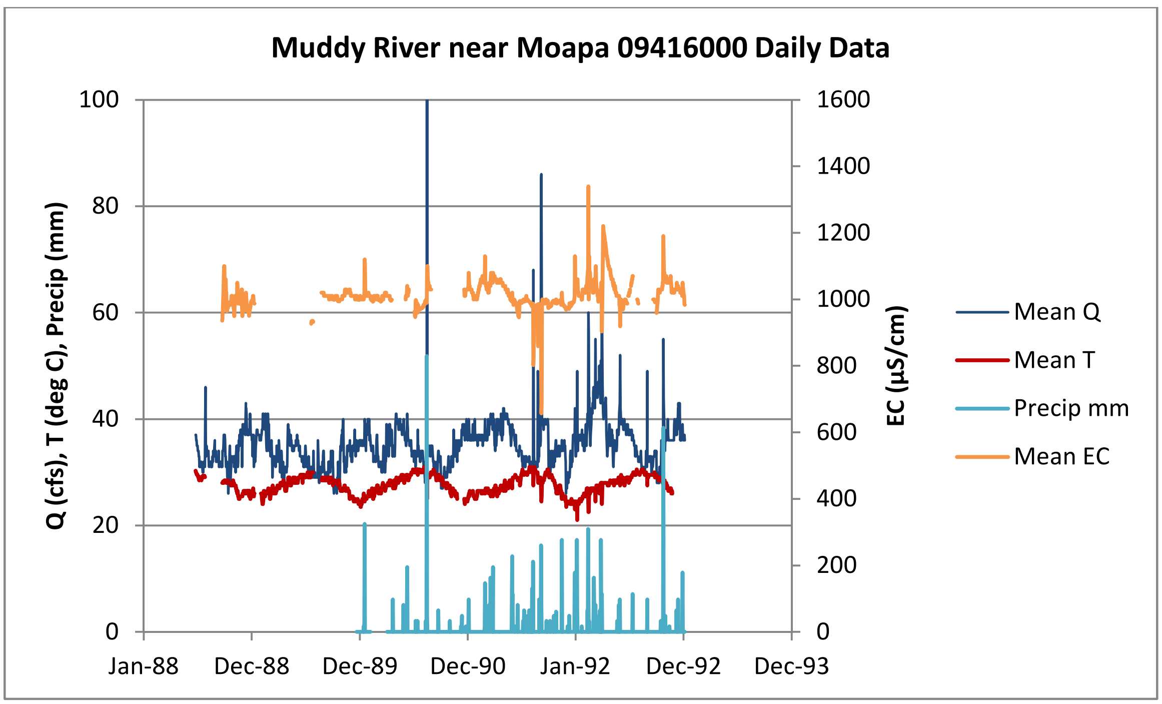


Figure E-2. Average daily discharge, temperature, electrical conductivity, and precipitation at the Moapa gage from USGS records [file MRdailyTempEC.xlsx, sheet ‘MRtempEC’]

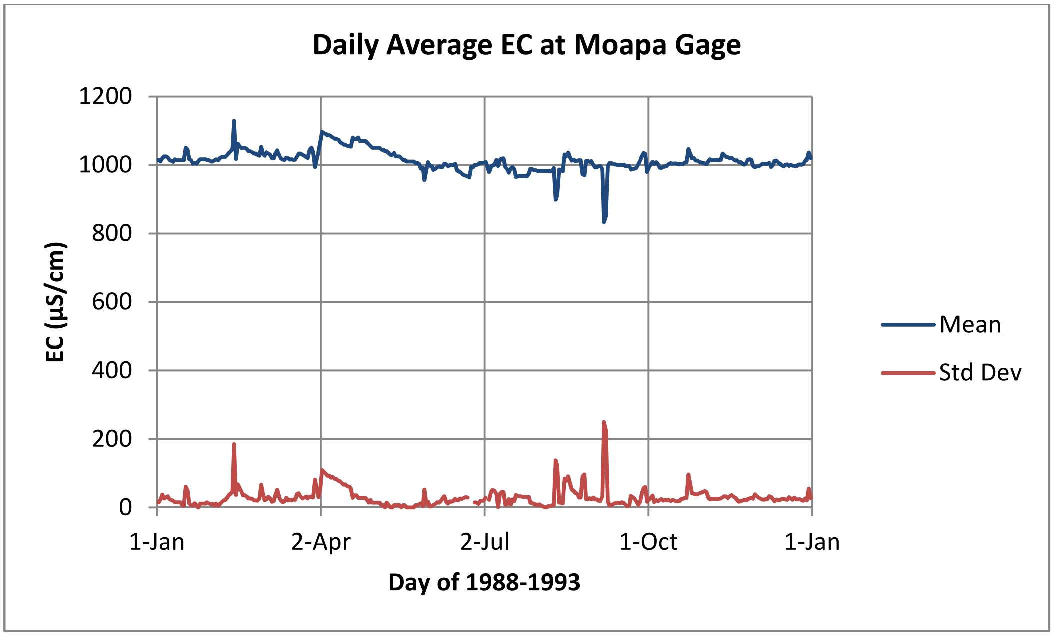


Figure E-3. Average electrical conductivity of the Muddy River at the Moapa gage for individual days during the period when temperature and EC data were collected by the USGS [file MRdailyTempEC.xlsx, sheet 'MRtempEC']

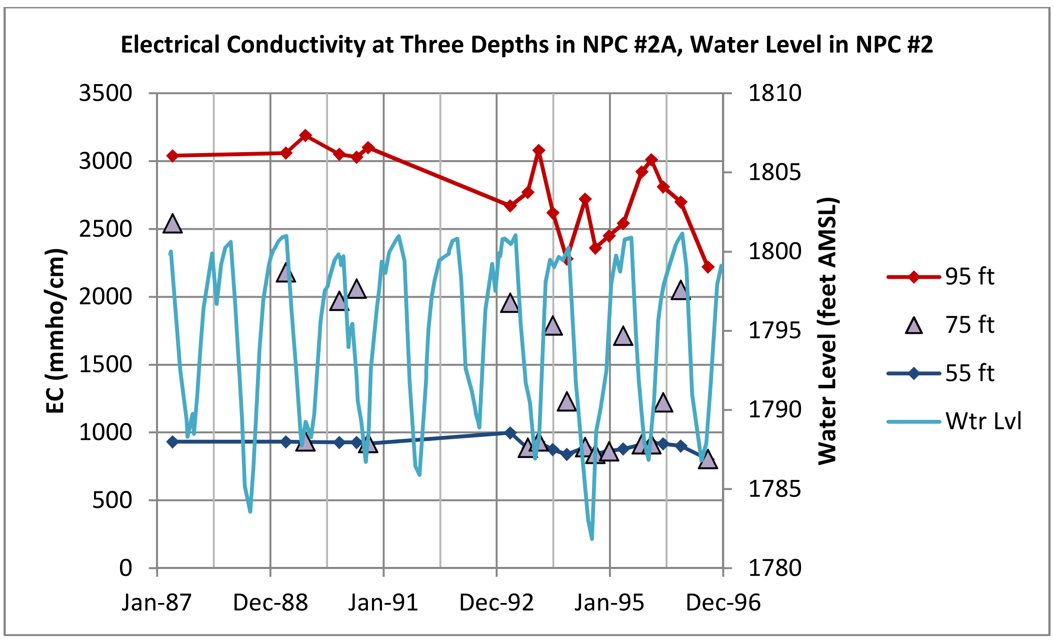


Figure E-4. With the single exception of July 1990, recovery from summer pumping in the Lewis well field is associated with incursion of poor-quality water into the lower portion of monitoring well NPC #2A. This counter-intuitive relationship may be due to the lag associated with delayed yield (leakage) from the Muddy Creek Formation. Note also the trend toward improvement in overall water quality over the 10 years of record, suggesting that pumping stress is inducing inflow of low-TDS water from the Carbonate-rock Aquifer and slowly flushing pathways through the Muddy Creek Formation of stagnant waters. The interface between brackish and fresh waters fluctuates about the 75-foot depth level (1750 feet AMSL), rising and falling in synchronicity with pumping as the water table does, without evidence of upconing that is typical of these situations in, for example, coastal areas.

Using the 4.23 cfs at 1,330 µS/cm for North Fork and 9.22 cfs at 1,170 µS/cm for South Fork that Eakin (1964) reports (points 32 and 33, respectively, on Figure 2), the EC of the calculated 13.45 cfs of combined flow immediately below the confluence is obtained by the mass-balance relation

$$C_{MIX} = XC_1 + (1\text{-}X)C_2 \quad (1)$$

where C_1 and C_2 are concentrations of the constituent of interest (EC in this case) in the mixing end-members, C_{MIX} is concentration in the mixture, and X is the mixing fraction of constituent C_1 in the mixture. Taking C1 to represent the EC of North Fork water so X = 4.23/13.45 = 0.314 (the mixing fraction of North Fork water), C_{MIX} = 0.314*1330+(1-0.314)*1170 = 1,220 µS/cm for the mixture.

Downstream roughly 0.3 mile from the confluence of North and South Forks, before inflow from the Muddy Springs Tributary occurs, Eakin (1964) reports a flow rate of 19.5 cfs and EC of 1,290 µS/cm (point 27 on Figure 2). The gain is 6.05 cfs, and the calculated EC of the water entering the Muddy River between the North Fork / South Fork confluence and Eakin's Point 27 is

$$C_2 = (C_{MIX}\text{-}XC_1)/(1\text{-}X) \quad (2)$$

where C_1 is the previously computed EC of water entering the reach and X is its fraction of the 19.5 cfs, 13.45/19.5 = 0.690, so C2 = (1290-0.690*1220)/(1-0.690) = 1,447 µS/cm. Between the Lewis Well Field and Big Muddy Spring, prior to 1990, the degradation in quality of seepage entering the Muddy River along the trend of North Fork is evident. Underflow associated with North Fork represents the poorest-quality water entering the Muddy River as seepage. This relationship allows a test of the hypothesis that this poor-quality underflow has been diminished by export of groundwater from the headwaters area, and therefore water quality in the Muddy River should have improved as flows have decreased.

Considering 1963 and 2001 measurements on the Muddy River near the LDS Farm (points 27 and 09415885 on Figure 2), measured flow was 3.55 cfs less in 2001, unadjusted for ET, which would increase the difference by perhaps 1-2 cfs by normalizing September (1963) and February (2001) measurements for seasonal ET. Based on the limited control provided by Eakin's 3 laboratory EC measurements (Appendix E), Eakin's field EC of 1290 µS/cm at his point 27 is equivalent to a laboratory EC of 1335 µS/cm. In 2001, at the same location, a field EC of 942 µS/cm and laboratory EC of 988 µS/cm were obtained (Beck and others, 2006, Table E3). This significant freshening and discharge decrease is consistent with elimination of relatively poor-quality seepage into the Muddy River. Using the laboratory-equivalent EC of seepage obtained above with Equation (2), 1,562 µS/cm, the seepage flux reduction required to cause the improvement can be calculated independently by:

$$X = (C_{MIX}\text{-}C_2)/(C_1\text{-}C_2) \quad (3)$$

where X is the fraction of C_1=1,563 µS/cm seepage that previously mixed with C_2=988 µS/cm River water to produce the C_{MIX}=1,335 µS/cm of Eakin (1964) at point 27. The result, 0.605, implies a loss of seepage flux since 1963 double that obtained by available discharge measurements. This loss is consistent with **hydraulic continuity between the alluvial aquifer in the Lewis Well Field area and the headwaters of the Muddy River, and diminished seepage to the River is a consequence of diminished throughput of groundwater in the Lewis Well Field gravels.**

Appendix F. Parameter Estimation for Order 1169

A common mistake nearly all have made in past efforts to determine how water-level changes are related to pumping stresses in the Carbonate-Rock Aquifer of the Arrow Canyon Range Cell (ACRC) of Mifflin (1992) is the assumption that the most dominant features of well hydrographs throughout the ACRC, multiyear water-level trends and superposed annual water-level cycles, are pumping signals. These large fluctuations “look” like pumping-induced responses because pumping is also seasonal, but they are not. The widespread, synchronous nature of water-level fluctuations leads to interpretations that pumping is the causative factor, but no significant lag or attenuation of the superposed pumping responses with distance from any of the three candidate pumping centers (upper Moapa Valley, southeastern Coyote Spring Valley, or the Apex area) has been detected. Instead, northwestward propagation of the water-level signal between monitoring wells in both California Wash (Figure 17) and Coyote Spring Valley (Figure 20) is evident, suggesting that crustal loading rather than pumping is forcing the annual fluctuations. Climate is the most probable cause of multi-year trends.

Hydrogeologic assessment of water-level monitoring records should begin with the development of aquifer-parameter estimates from the well hydraulics of pumped wells (Kruseman and de Ridder, 1994) and by tidal methods that rely on lag and attenuation of a water-level signal where the signal is found to propagate from a system boundary (Smith, 1999). The well-hydraulics and supporting modeling analyses summarized below have provided aquifer-parameter estimates and evidence of boundary conditions that constrain the possible configurations of pumping-related cones of depression that can be demonstrably attributed to pumping stress. These cones are much shallower and more localized than one would infer by mistakenly equating regional water-level changes with drawdown.

Johnson and Mifflin (2012b) derived transmissivity and storage coefficient estimates for the unconfined Carbonate-Rock Aquifer in southeastern Coyote Spring Valley from drawdowns resulting from pump starts at production wells MX-5 and RW-2. Barometric efficiency, tidal effects, and antecedent trends were accounted for as detailed in the referenced HRT report. Relatively impermeable boundaries cause drawdown rates to increase in that area after just a few hours of pumping, requiring parameter estimates to be based only on the earliest phase of drawdown history. Optimized matches of early pumping-response data to a theoretical type curve are given in Figures F1 through F5, and a good match to late data was achieved using a finite-difference model of a bounded domain (Table F1 and Figure F6).

Mifflin and Johnson (2005) conducted and analyzed a 7-day aquifer test in the Southern Flow Field at ECP-1, where transmissivities an order of magnitude lower than those characteristic of southeastern Coyote Spring Valley and a recharge (upwelling) boundary to the unconfined Carbonate-Rock Aquifer were identified (Figure F7). A sub-regional analytic element model (Johnson and Mifflin, 2006) incorporating parameters derived from this test and consistent with the later Coyote Spring Valley results described above, satisfies water-level and boundary constraints in the model domain (Figure F8, Table F2).

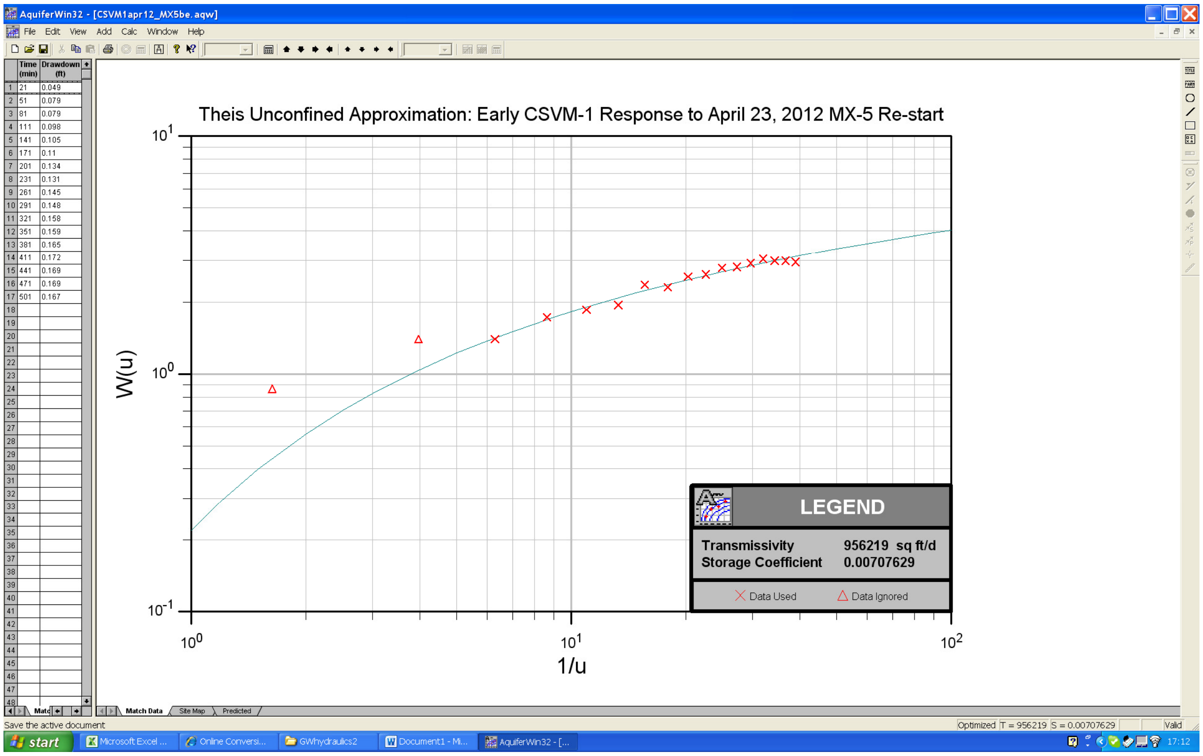


Figure F1. Optimized match to early-time drawdown data, MX-5 pumping rate 3,551 gpm [File CSVM120120423be.tif, screenshot from file CSVM1apr12_MX5be.aqw]

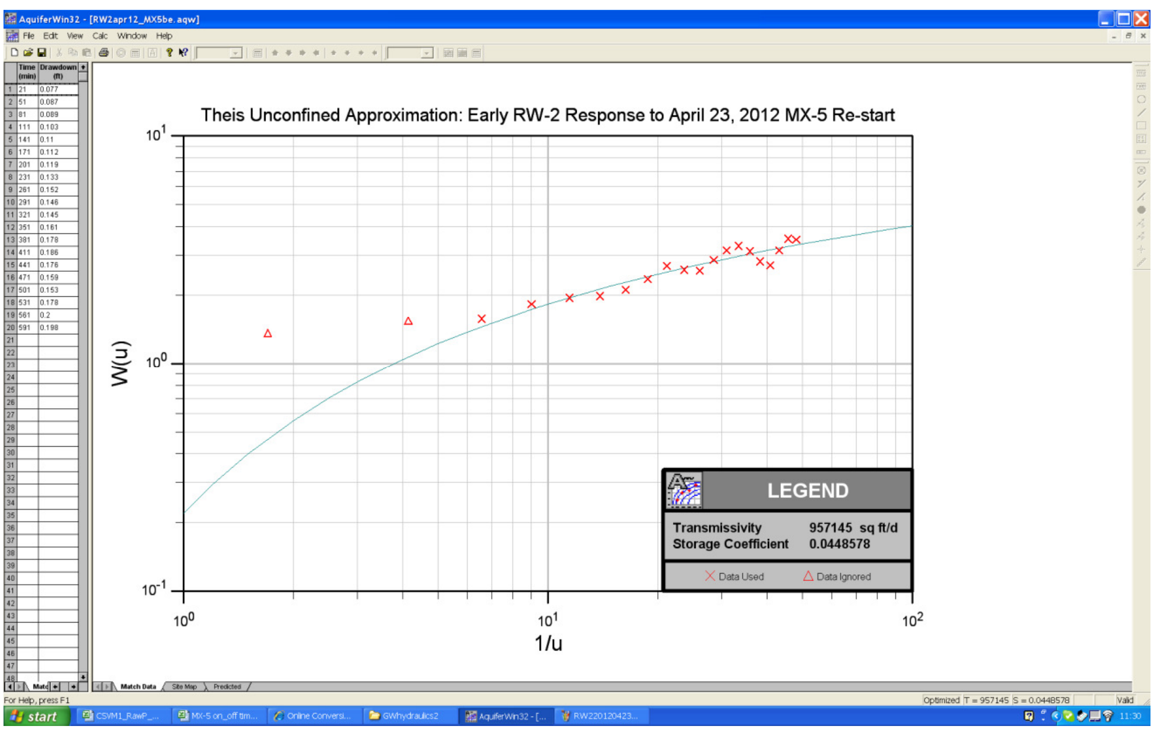


Figure F2. Optimized match to early-time drawdown data, MX-5 pumping rate 3,551 gpm [File RW2120120423be.tif, screenshot from file RW2apr12_MX5be.aqw]

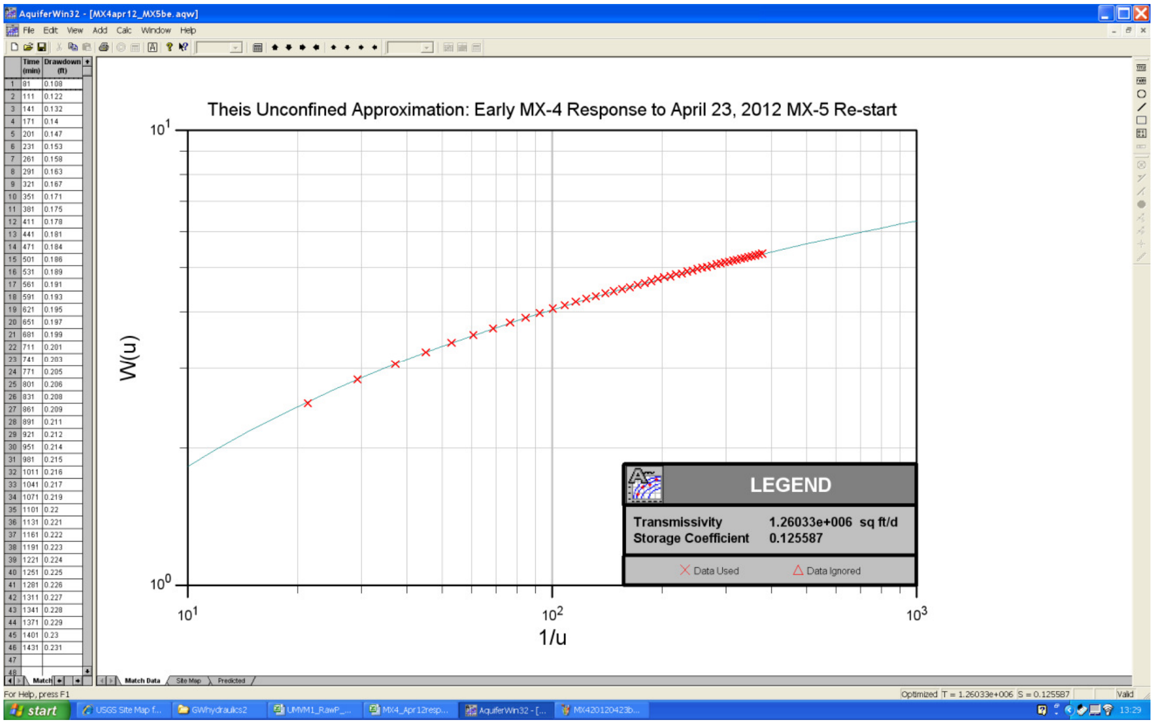


Figure F3. Optimized match to early-time drawdown data, MX-5 pumping rate 3,551 gpm [File MX4120120423be.tif, screenshot from file MX4apr12_MX5be.aqw]

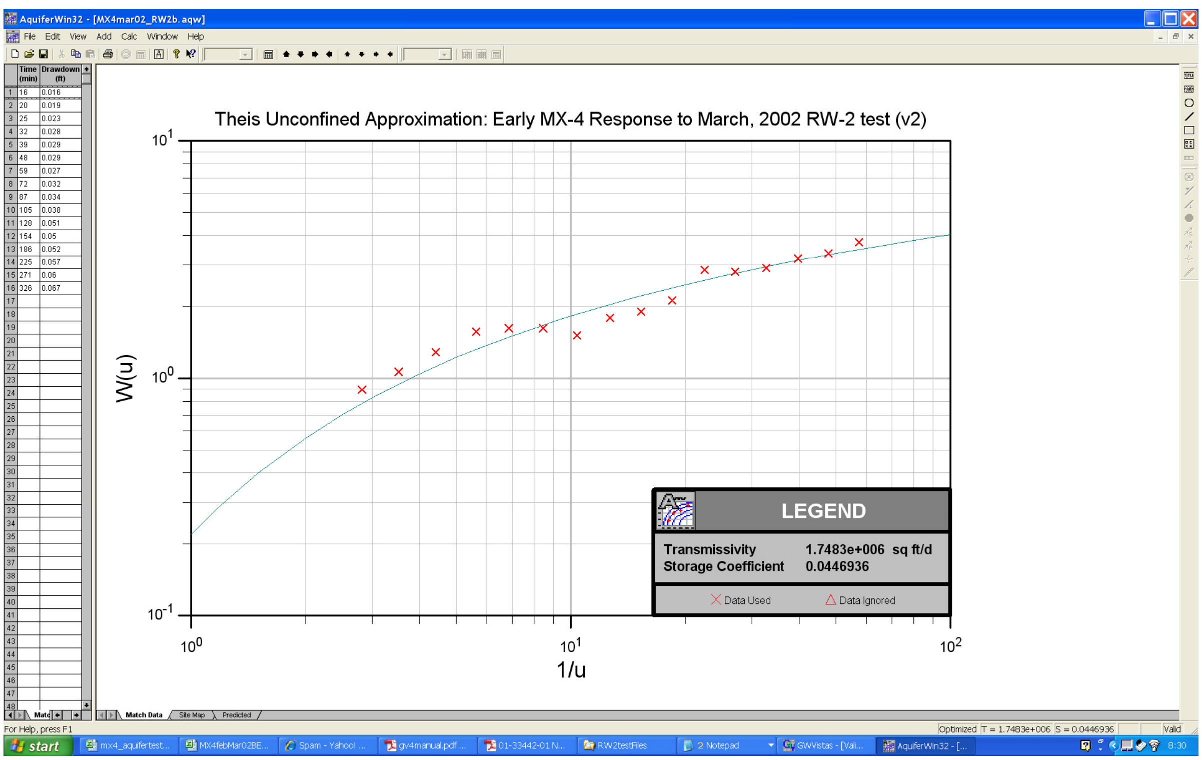


Figure F4. Parameter estimates from early MX-4 response to RW-2 constant-rate test, March 5-6, 2002 [File MX42002RW2v2.tif, screenshot from file MX4mar02_RW2b.aqw]

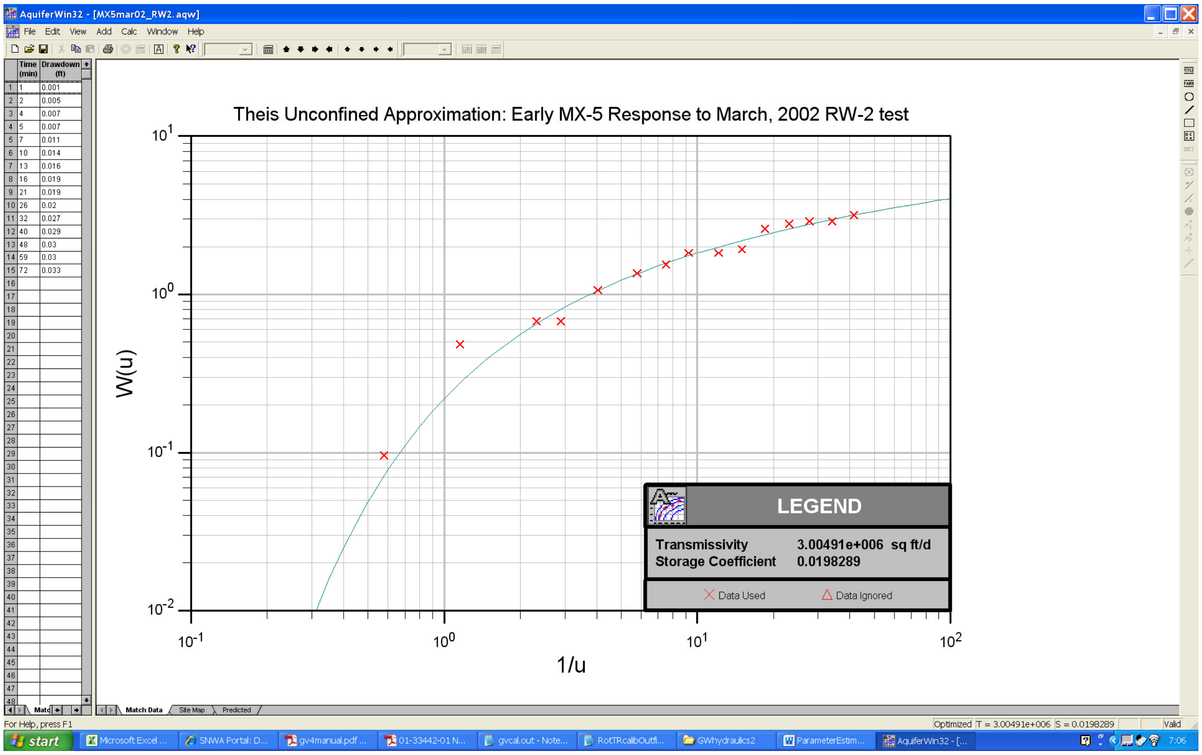


Figure F5. Parameter estimates from early MX-5 response to RW-2 constant-rate test, March 5-6, 2002 [File MX52002RW2.tif, screenshot from MX5mar02_RW2.aqw]

Table F1. Single-Layer Finite-Difference Model Configuration

Domain Extent:	20 miles NW-SE, 10 miles SW-NE, 4000 feet thick		
Grid Origin Location:	E 673742 m, N 4073832 m, UTM Zone 11,NAD83		
Rotation about Origin:	35.62° clockwise		
Number of Cells:	5000		
Cell Dimensions:	x	1056 ft	
	y	1056 ft	
	z	4000 ft	
Parameters:	K_X	329 ft/day	
	K_Y	274 ft/day	
	S_Y	0.003	
Boundary Conditions:	Inflow	4,320,000 ft^3/day	50 cfs specified steady-state flux
	Outflow	1846 ft	specified total head (includes barometric pressure)
	MX-5	-683615 ft^3/day	(3551 gpm)
MX-5 Stress Periods:	1	730 days	70 time steps, 1.2 time step multiplier

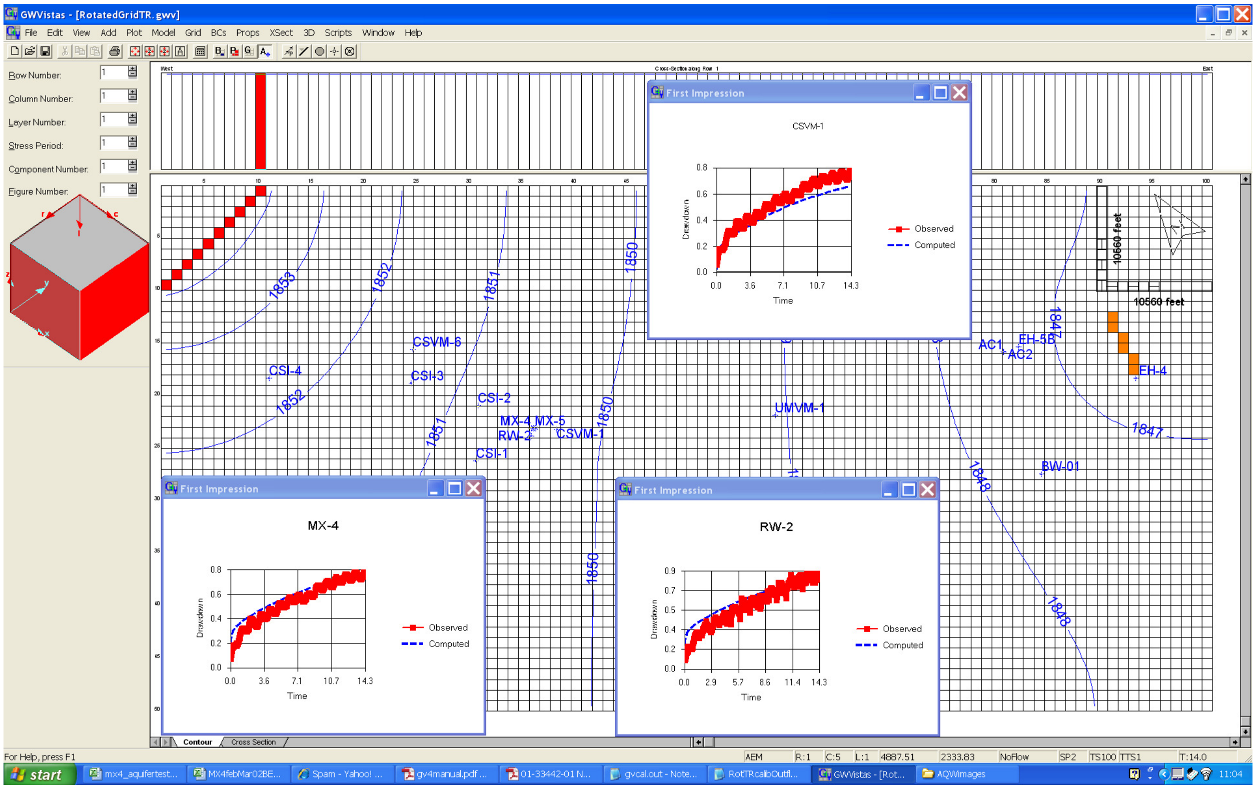


Figure F6. Simulated responses to April 23, 2012 re-start of MX-5 in anisotropic, bounded domain with properties given in Table 1. [File MX42012GWV.tif, screenshot from file RotatedGridTR.gwv]

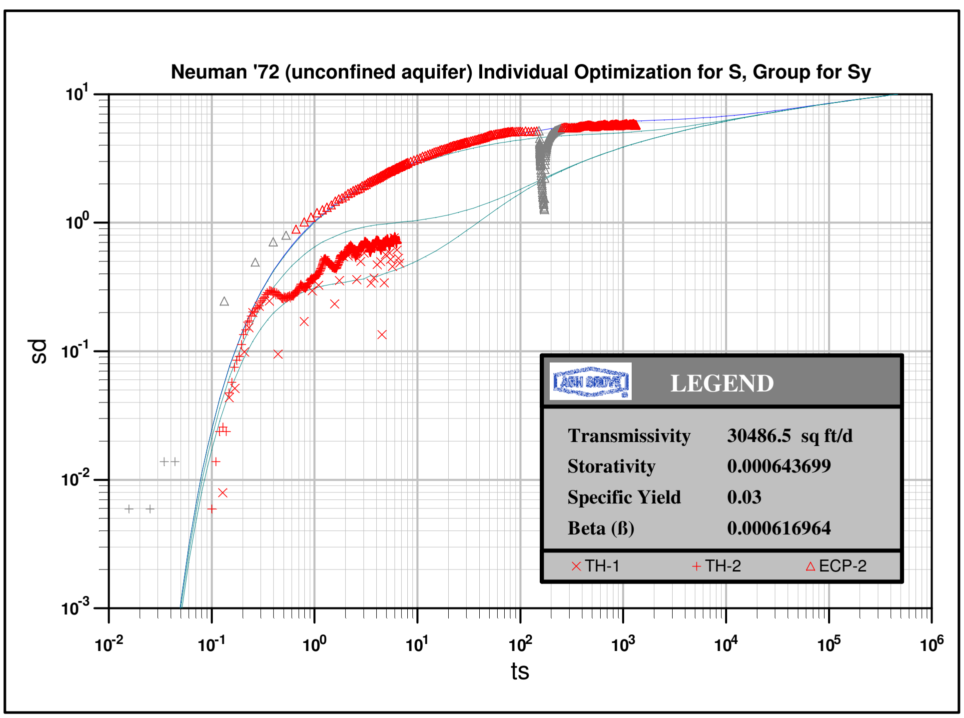


Figure F7. Parameter estimation based on the model of Neuman (1972), from 7-day test in July of 2000 in which ECP-1 was pumped at 1005 gpm. [Mifflin and Johnson, 2005]

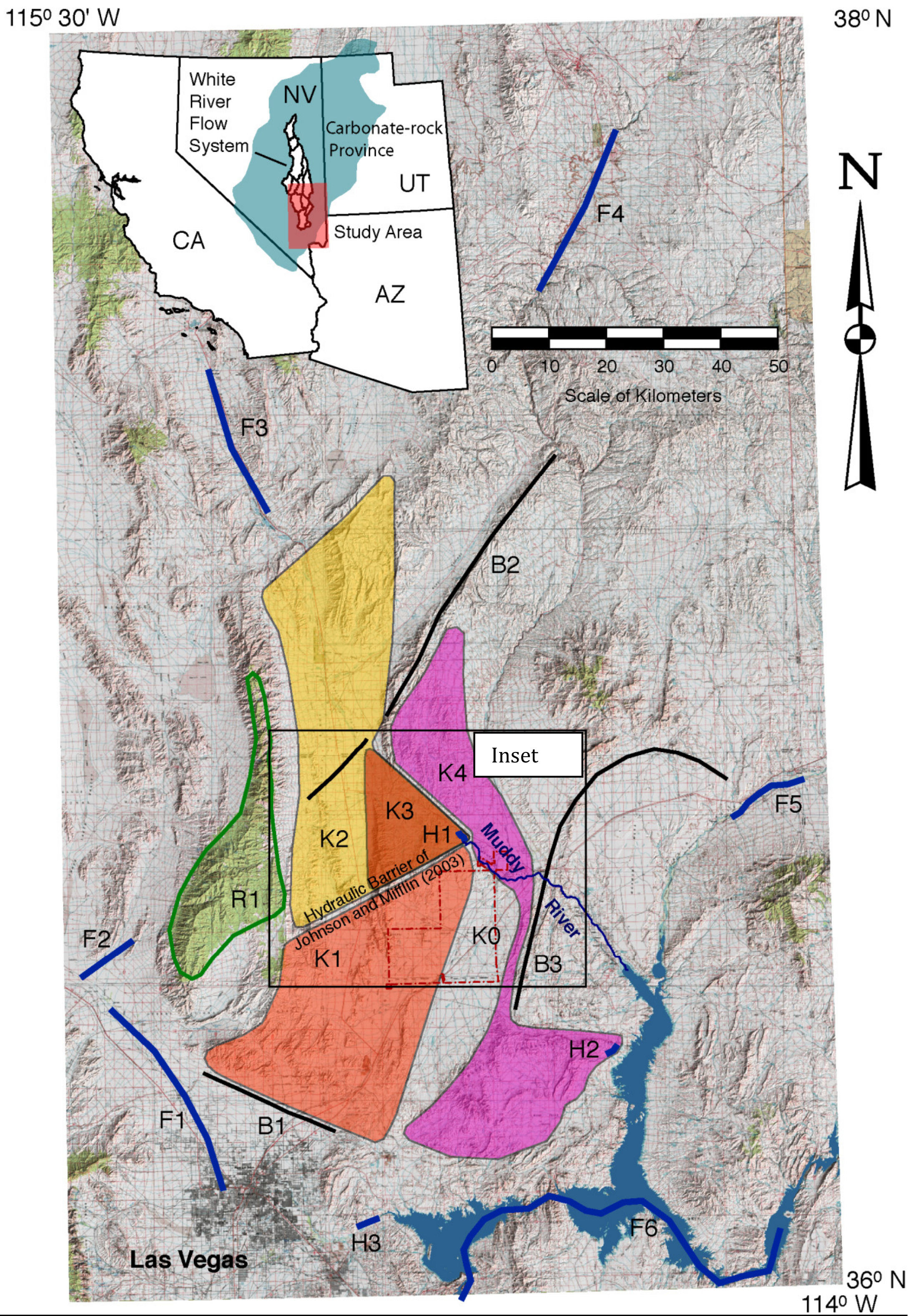


Figure F8. Analytic element representation of the study area, showing hydraulic-conductivity domains (K), no-flow barriers (B), far-field features (F), near-field discharge (H), and recharge (R); reference Table F2 for details [file AshGroveFig2.tif; Johnson and Mifflin (2006)]

Table F2. Features and properties of the analytic element model (from Figure F8)

Far-field controls		
F1	Corn Creek to Las Vegas	Specified heads 892 to 652 m
F2	Divide Well to Cow Camp	Specified heads 895 to 867 m
F3	Pahranagat Valley	Specified heads 1100 to 900 m
F4	Upper Meadow Valley Wash	Specified heads 1500 to 1300 m
F5	Virgin River	Specified heads 500 to 450 m
F6	Colorado River	Specified heads 250 to 200 m
Inhomogeneities		
K0	Far-field zone	K=0.064 m/day, obtained by calibration
K1	Southern flow field	K=6.1 m/day from 7-day aquifer test reported by Johnson et al. (2001). Bounded on south and west by Las Vegas Shear Zone and Gass Peak Thrust, respectively (Longwell et al., 1965); on north by sub-regional hydraulic barrier described by Johnson and Mifflin (2003 and this report), and on east by down-faulted Tertiary (K0) sediments of California Wash (Johnson et al., 1986; Langenheim et al., 2001,2002)
K2	Northern flow field	K=12.2 m/day, obtained by calibration. Bounded on west by Gass Peak Thrust, on north by Menard Lake Fault, and on east by Delamar Mountains Thrust and fold belt (Tschanz and Pampeyan, 1970).
K3	Arrow Canyon zone	K=36.6 m/day from analysis of seasonal pumping response, 1997-2001 (Johnson and Mifflin, 2003 and this report). Bounded on west by normal fault on west side of Arrow Canyon Range.
K4	Glendale cell	K=5.5 m/day, obtained by calibration. Isotopic data reviewed by Pohlmann et al. (1998).
Near-Field Discharge		
H1	Muddy River springs	Specified heads 536 to 530 m, hydraulic resistance 1.35 days
H2	Rogers / Blue Point Springs	Specified heads 488 to 463 m, hydraulic resistance 2.7 days
H3	Southern receptor zone	Specified heads 450 to 396 m at south end along Las Vegas Wash, hydraulic resistance 2 days
No-flow barriers		
B1	Las Vegas Shear Zone	Accounts for large hydraulic gradient between Southern flow field (K1) and Las Vegas Valley, and absence of candidate outflow component in Las Vegas Valley groundwater (Johnson et al., 2001)
B2	Kane Springs Wash Fault	Diverts flow from north around area of exposed basement rock in Mormon Mountains (Tschanz and Pampeyan, 1970); southwestward extension in Coyote Spring Valley required to fit VF-2 and CSV-3 water levels (Figure 3).
B3	Weiser Syncline	Continuous feature per Axen et al. (1990), bent and rotated clockwise at northern end by Moapa Peak Shear Zone; required to match EH-3 and EH-7 water levels (Figure 3)
Recharge		
R1	Sheep Range	0.7 cm/yr in forested highlands, by calibration. Recharge area encompasses 420 km^2, total 2.94 x 10^6 m^3/yr (2380 acre-ft/yr). Previous estimates include 2,000 acre-ft/yr (Eakin, 1966), 5,000 to 6,000 acre-ft/yr (Kirk and Campana, 1990) and 14,000 acre-ft/yr (Thomas et al., 1996).