ground water

The AEM and Regional Carbonate Aquifer Modeling

by Cady Johnson[1] and Martin Mifflin[2]

Abstract

The analytic element method (AEM) has been applied to a 15,000-km^2 area of the Paleozoic carbonate rock terrain of Nevada. The focus is the Muddy River springs area, which receives 1.44 m^3/s (51 ft^3/s) of regionally derived ground water, and forms the Muddy River. The study was undertaken early in 2000 to support the development of a cooling water supply for a gas-fired generation facility 20 km south of the Muddy River springs. The primary objectives of the AEM modeling were to establish a better understanding of regional fluxes and boundary conditions and to provide a framework for examination of more local transient effects using MODFLOW. Geochemical evidence available in 2000 suggested two separate flow fields, one in the north discharging at the springs, and a southern area of small hydraulic gradients. To be conservative, however, hydraulic continuity between the two areas was maintained in the 2000 AEM model. Using new monitoring well data collected in the south, and analyses confirming that seasonal pumping effects in the north are not propagated to the south, a later AEM model that included a barrier calibrated with relative ease. The analytic element model was well suited for simulating an area larger than the immediate area of interest, was easy to modify as more information became available, and facilitated the stepwise development of multiple conceptual models of the site.

Introduction

In 1989, Las Vegas Valley Water District (LVVWD) filed landmark applications for all unappropriated water, ~2.7 × 10^6 m^3/d (800,000 acre-ft/year) in 26 hydrographic basins of eastern Nevada, later reduced to a maximum of 6.1 × 10^5 m^3/d (180,800 acre-ft/year) in 17 basins. Alarmed by the potential impacts on springs and associated habitats, the National Park Service (NPS), U.S. Fish and Wildlife Service, Bureau of Land Management, and Bureau of Indian Affairs requested that the USGS quantitatively evaluate the effects of this pumping on regional flow and spring discharge. A highly generalized finite-difference model of the Carbonate Rock Province of the Great Basin was developed, consisting of two layers of 3660 cells, each 8.05 km (5 miles) wide by 12.1 km (7.5 miles) long (Schaefer and Harrill 1995). A flow reduction on the order of 11% was predicted at the Muddy River springs after 100 years of pumping. Conceptually, these results were not unanticipated but offer no guidance as to where the ground water resources might be developed to minimize or prevent impacts.

Beginning in 2000, the analytic element method (AEM) was adopted as a primary modeling strategy in evaluating flow patterns and boundary conditions in a large (15,000 km^2) area of carbonate rock terrain in southeastern Nevada, characterized by interbasin ground water flow and overlapping an area targeted for development by LVVWD. This application of the AEM, using GFLOW 2000 from Haitjema Software, was a departure from traditional methods in the region; previous modeling efforts generally relied on flux estimates based on hydrographic basin water budgets. In the AEM method, fluxes are determined from Darcian and mass conservation principles using aquifer characteristics and water-level data, with measured discharge of the Muddy River springs as a calibration target. The operational challenge of fitting model components to the geologic framework was aided by generally good regional exposures and was anchored by information from four local areas where characteristics of the carbonate aquifer were known from multiwell pumping experiments.

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The primary objective of the study was to forecast impacts of a 25- to 45-year, 8.6×10^6 m^3/year (7000 acre-ft/year) pumping stress. Calpine Corporation would use the water for power generation at the proposed 750-MW Moapa Paiute Energy Center (MPEC). The MPEC wellfield targeted Paleozoic carbonate rocks that underlie much of the western portion of the Reservation. The first test well, ECP-1, yielded ~6.3×10^{-2} m^3/s (1000 US gallons/min) for a 7-d constant-discharge test. The fundamental question for the Calpine project was the relationship of the carbonate aquifer of the site area to the Muddy River springs, the flows of which support the endemic Moapa dace, an endangered fish that inhabits the spring areas, and to senior water rights on the Muddy River, which originates at the springs and is fully appropriated under Nevada water law. Potential long-term impacts on another major spring complex, Rogers and Blue Point Springs, located ~40 km southeast of the MPEC in the Lake Mead National Recreation Area, were a concern of the NPS.

The area extending some 15 km northwest from the Muddy River springs is a zone of extremely high transmissivities, with small hydraulic gradients indicating flow toward the Muddy River springs (Ertec Western Inc. 1981). In contrast, hydraulic gradients between 2 and 30 km south of the springs were not known at the beginning of this study, nor were the properties of the aquifer, so fluxes within the carbonate rock terrain of the Reservation could not be estimated (Mifflin 1992; Dettinger 1989). Ground water flux in the project area is of great practical interest from the standpoint of tribal water rights as the magnitude and pattern may ultimately determine the allowable level of development based on Nevada water law.

The objective of this paper is to describe the application of the AEM to a poorly understood subregional area with hydrogeology dominated by highly transmissive carbonate rock terrain, and supporting analyses that allowed for refinement of subregional boundary conditions. The paper's scope includes monitoring well databases through the end of the year 2002 and brief observations on data acquired since 2002.

Hydrogeology

In the broadest terms, the hydrogeologic setting of the study area is one of ground water discharge from large springs at the southeastern margin of the Carbonate Rock Province of the eastern Great Basin (Figure 1 inset). Thinning and major facies changes in the carbonate rock section occur as a northeast-trending "hinge line" passing through the study area (Tschanz and Pampeyan 1970, 5); the hinge line represents the approximate boundary between the continental shelf and "miogeosyncline" for much of Paleozoic time. Also, overthrusts of the Sevier orogenic belt (Armstrong 1968) are exposed in a corresponding zone that extends from the Spring Mountains to the southwest to east of upper Moapa Valley (Figure 2). Regional-scale thrust faults, dismembered by Tertiary extension (Axen et al. 1990), ramp to the surface and place carbonate rocks above much less permeable Mesozoic red beds along a northeast trend. The combined effects of stratigraphic thinning and structurally induced damming by Mesozoic and Cenozoic lithologies are thought to induce regional ground water discharge in the study area.

The oasis at the headwaters of the Muddy River, which supplies the entire base flow of this perennial stream, is referred to herein as the Muddy River springs area. The temperature, chemical characteristics, and temporal stability of discharge from these springs clearly indicate the "regional" character of the aquifer system that sustains their flow (Mifflin 1968). Flow in the Muddy River at Warm Springs Road has been monitored intermittently since 1913 by the USGS (site ID 09416000, "Muddy River near Moapa, Nevada") and reported as average daily flow. From the inception of monitoring until the early 1960s, base flow averaged ~1.3 m^3/s (47 ft^3/s).

Figures 1 (inset) and 2 (solid yellow lines) illustrate a series of hydrographic basins in the Carbonate Rock Province (Mifflin 1968, 1988; Dettinger et al. 1995) that were delineated by Eakin (1966) as the combined catchment for the White River flow system (WRFS), with a terminal discharge area at the Muddy River springs (H1 in Figure 1) in upper Moapa Valley (Figures 2 and 3). In Figure 2, Pahranagat Valley (PV) is the location of three large springs classified as "regional" in the Mifflin (1968) study along with the Muddy River springs. The two northernmost basins of the Eakin (1966) WRFS in Figure 2, Long Valley and Jakes Valley, were subsequently noted by Mifflin and Wheat (1979) to display pluvial-climatic-state hydrologic evidence of leaking to the west into Newark Valley (to balance basin surface water catchment areas with pluvial lake areas in these basins). If these two northernmost basins' contributions are removed from Eakin's (1966) classical water balance that was derived for discharge measured at Muddy River springs, a balance is achieved at Pahranagat Valley. Eakin's balance requires the majority of discharge for the Muddy River springs to be derived from flow that passes from Pahranagat Valley south through Coyote Spring Valley and then southeastward to the springs (F3 to K2 to K3 to H1 in Figure 1). Water discharging in Pahranagat Valley is, however, almost devoid of fluoride and isotopically much lighter than Muddy River springs. Muddy River springs' fluoride and stable isotope compositions are more akin to water in upper (northern) Meadow Valley Wash (Figure 2) than to those in Pahranagat Valley (Thomas et al. 1996).

The Muddy River spring area hydrology is locally complex, with an alluvial aquifer comprising coarse gravel lenses inset into the fine-grained Muddy Creek Formation (Schmidt et al. 1996). Between 1987 (Mifflin & Associates Inc. 1987) and 1996 (Mifflin and Adenle 1996), the status of known wells and springs in the upper Moapa Valley was documented on a quarterly basis. The alluvial aquifer is supplied by subsurface inflow from the northwest of roughly 8.3×10^4 m^3/d (34 ft^3/s) from the carbonate rock flow system. An additional 4.1×10^4 m^3/d (17 ft^3/s), or one third of the total ground water discharge (Figure 4), issues from large springs via carbonate-cemented conduits through the alluvial gravels. Roughly 0.1 m^3/s (4 ft^3/s) is lost to evapotranspiration on an annualized basis. A well-developed seasonal cone of depression forms around

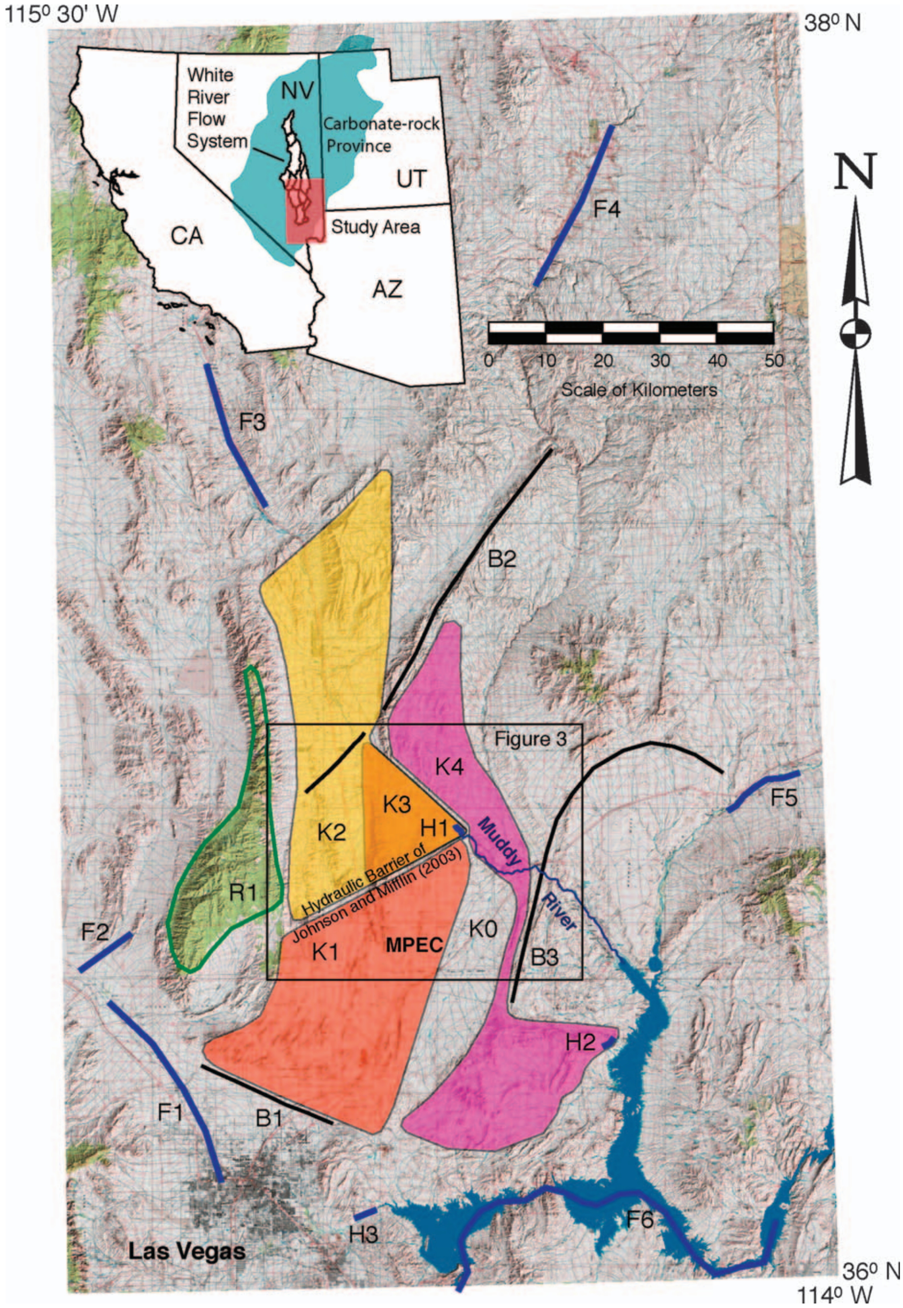

Figure 1. Analytic element representation of the study area, showing hydraulic conductivity domains (K), no-flow barriers (B), far-field features (F), near-field discharge (H), and recharge (R); see reference Table 1 for details.

Nevada Power Company's production wells in the alluvial aquifer and migrates down-valley toward the Muddy River springs during the summer pumping season; there was recovery each winter until 1997. Flow reductions are attributed to effects of the pumping cone on seepage flux from the unconfined alluvial aquifer into the headwaters channels of the Muddy River.

Upstream of the spring area near the Nevada Power Company (NPC) Lewis Well Field (Figure 5), there is local hydraulic continuity between the carbonate aquifer, source for the Arrow Canyon well, and the alluvial aquifer, local source for the Lewis wells. Between this important zone of inflow to the alluvial aquifer and Big Muddy Spring, the alluvial aquifer remains unconfined, but evidence for hydraulic connection with the carbonate aquifer is absent. Near Big Muddy Spring, the alluvial aquifer discharges via seepage into headwaters channels of the Muddy River, and spring outflow channels combine flows to establish the total discharge represented by the Muddy River gauge (Figure 5). Spring conduits (active and relic) are encased by highly cemented zones and, for the most part, hydraulically isolated from the alluvial aquifer. Two wells (LDS East and Central), finished in conduit-cemented gravels (relic conduits), respond instantaneously to pumping stress changes, suggesting a high degree of hydraulic continuity with the carbonate aquifer based on the response characteristics and elevated temperatures. Downstream of the spring area, the alluvial aquifer becomes confined and hydraulically separated from the river channel and remains so southeastward to where monitoring

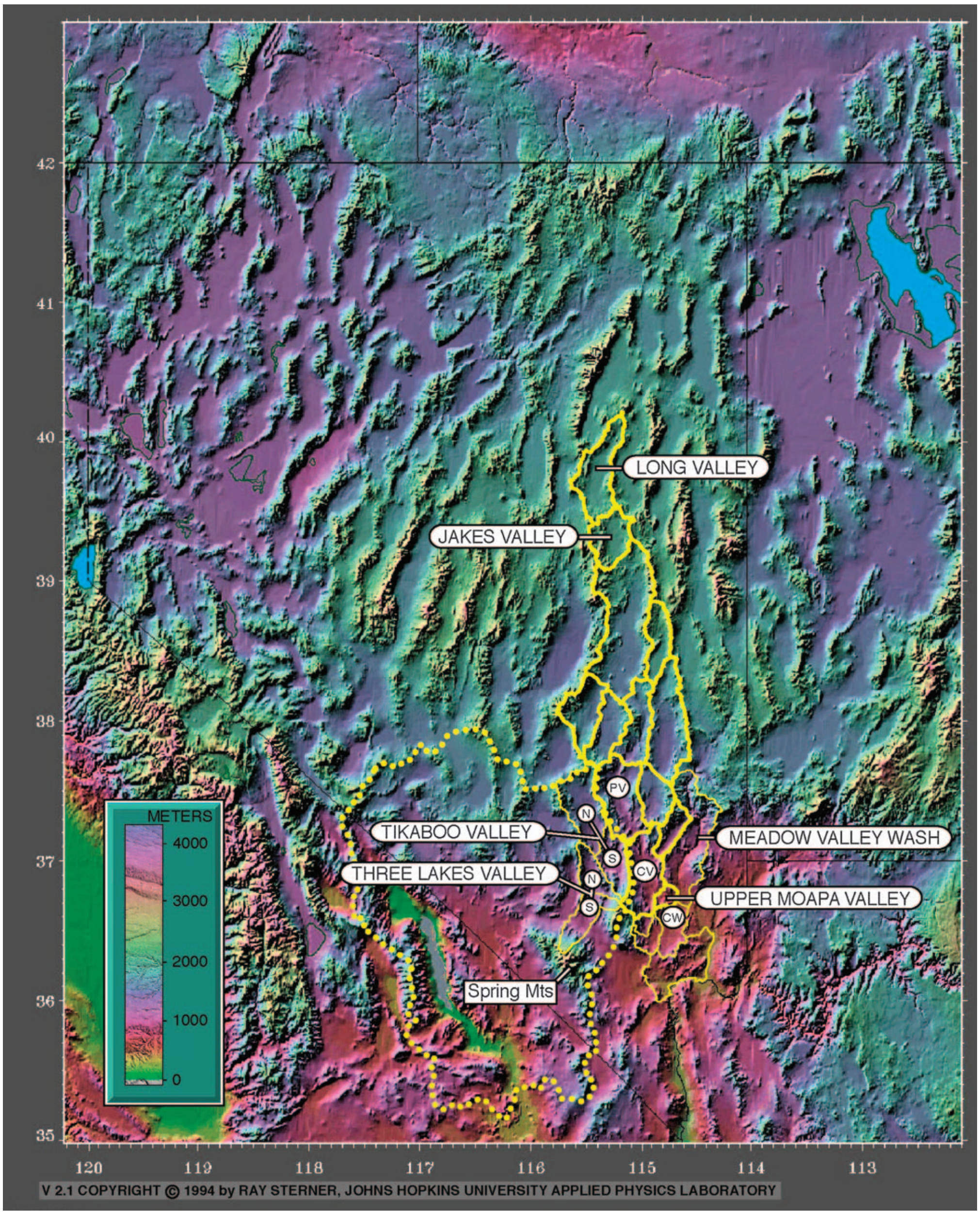

Figure 2. Regional topography showing Eakin's (1966) WRFS delineation (bold outline); flanking southern basins (narrow outline); Death Valley Regional Flow System (dotted) (U.S. Department of Energy 2002); and north (N) and south (S) subdivisions of Tikaboo and Three Lakes Valleys (Southern Nevada Water Authority 2003). PV = Pahranagat Valley; CV = Coyote Spring Valley; CW = California Wash. Base map mosaic copyright 1994 to 2002 by Andrew D. Birrell, used with permission.

well control ends. The Warm Springs Road Muddy River gauging station is located on the reach where there is no hydraulic continuity between the alluvial aquifer and river channel.

In 1985, NPC expanded its monitoring activities to include carbonate aquifer water levels in addition to monthly production totals from each of its wells in the Muddy River springs area. Monitoring records from carbonate rock aquifers became available in 1986, when NPC wells EH-4 and EH-5b were fitted with chart recorders and the USGS began taking monthly water-level measurements in MX-4. Seasonal fluctuations and long-term decline followed by recovery after the drought years of 1987 to 1992 are evident in all the three records. In the California Wash hydrographic basin (Figure 2), a water resources appraisal was conducted for LVVWD in 1990 (Wildermuth et al. 1990), but no potentiometric data were available from carbonate rock aquifers within 18 km of the proposed MPEC facility until 1998 (Terracon; unpublished data). Systematic monitoring in this southern area began late in 2000, and the first full year of record was 2001 (Figure 6).

Basin Water Budgets, Interbasin Flow, and Subregional Fluxes

Hydrographic basin water budgets are the fundamental accounting system used by the Nevada Division of Water Resources to administer the State's limited but uncertain ground water resource. Using the Maxey-Eakin

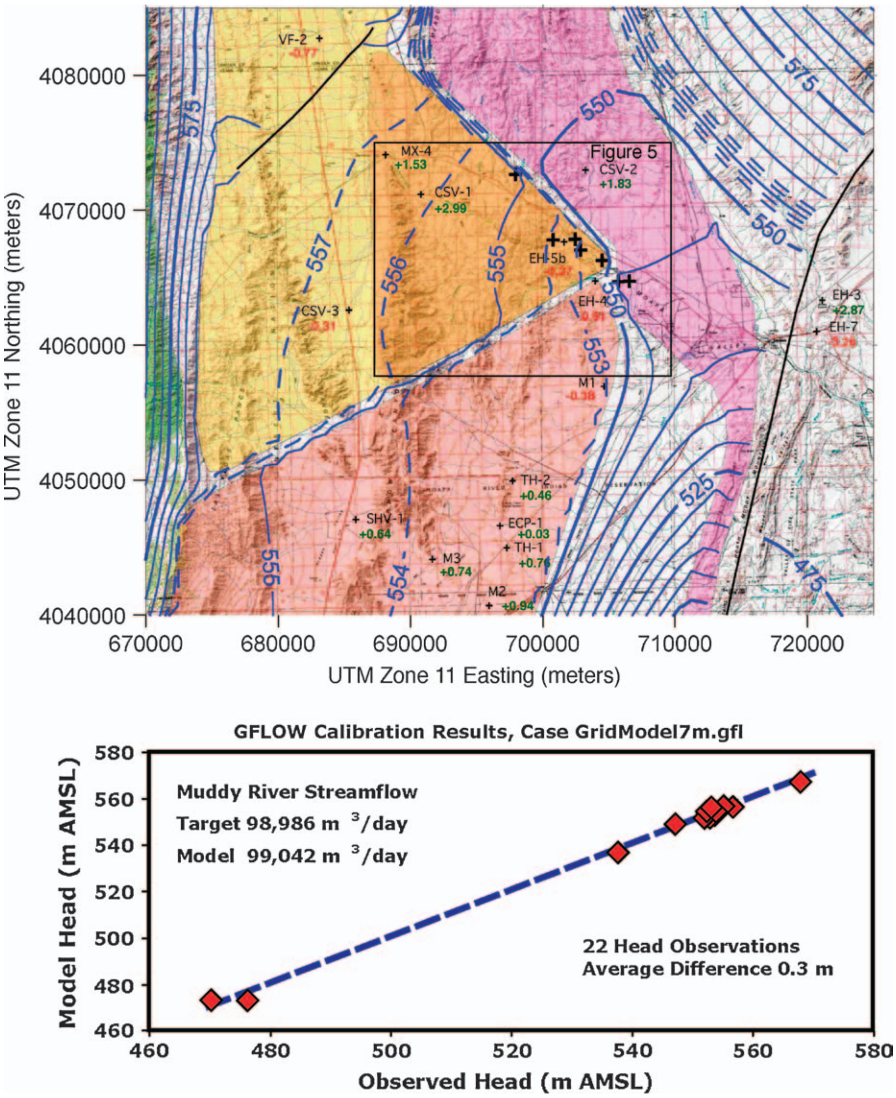

Figure 3. AEM model results for year 2001 conditions with calibration summary, showing head contours (meters above mean sea level) and residuals (meters + or −) at monitoring well locations. Contour interval is 1 m where dashed, 5 m elsewhere. "+" indicates model locations of ground water extraction by Nevada Power Company and Moapa Valley Water District.

method for estimating recharge (Maxey and Eakin 1949), percentages of precipitation falling within elevation zones were designated as recharge, with higher recharge efficiencies associated with the higher elevation (precipitation) zones. The contributions of each elevation zone to recharge were adjusted iteratively so that their sum would balance with discharge estimates in several control basins. Recharge estimates, established in this way as empirical percentages of precipitation assigned to elevation zones in the control basins, were then extrapolated to hydrographic basins throughout the Great Basin. The Maxey-Eakin method relies on two basic assumptions that appear to hold in the control areas:

- The hydrographic basin is also a hydrologically closed basin.
- The efficiency of recharge is uniform regardless of terrain lithology.

However, neither of the above assumptions is necessarily met in the more general case of the Carbonate Rock Province. The carbonate lithologies are likely more efficient in capturing greater percentages of incident precipitation, and hydrologic closure for many hydrographic basins remains uncertain.

The Eakin (1966) water budget approach is based on a "series" configuration of interbasin flow; water is transferred through a series of discrete compartments (basins) down a regional gradient. The method as generally applied does not accommodate "parallel" configurations, proposed by Tóth (1962, 1963) and explored through modeling analyses by Freeze and Witherspoon (1966, 1967, 1968). In suitable hydrogeologic environments, regional interbasin flow may bypass more localized ground water flow systems. The observed geographic distributions of the "regional"-class springs of Mifflin (1968) suggest that the parallel configuration of interbasin flow may be common and frequently unidentified by the basin water budget analytical procedure.

The efficiency of recharge for a given precipitation zone could be significantly greater in carbonate terrain than assigned in the Maxey-Eakin method, but there has been little comprehensive study to determine how much more efficient. The AEM-derived fluxes are independent

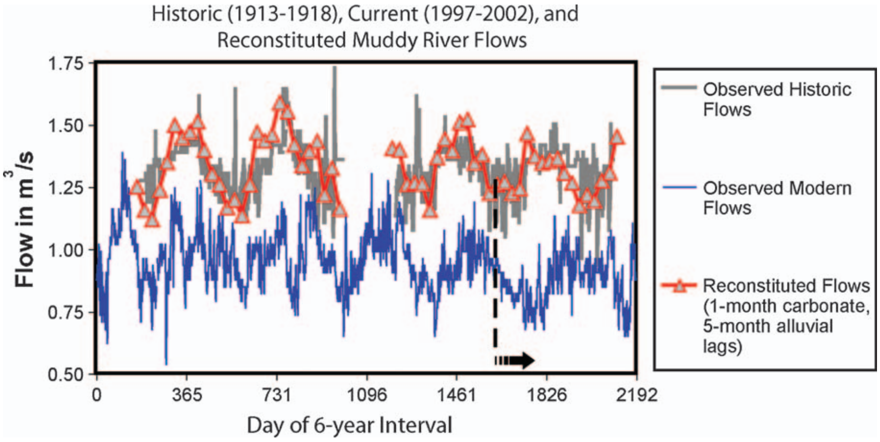

Figure 4. Flow reductions due in part to ground water pumping, accompanied by time lag in occurrence of seasonal discharge pattern of the Muddy River. The Muddy River responds to surface diversions immediately, to pumpage from the carbonate aquifer the following month and does not sense extractions from the alluvial aquifer until 5 months after they occur. Lag relations are attributable to depletion of storage in the alluvial aquifer, observed in monitoring records.

of hydrographic basin water budgets, thereby providing an alternative to Maxey-Eakin–derived flux estimates and their implicitly assumed configurations of interbasin flow. With evidence accumulating that the Muddy River springs are not the terminus of the WRFS (two independent lines of evidence suggest it terminates at Pahranagat Valley and excludes Jakes Valley and Long Valley), the AEM is elevated in importance for evaluating subregional fluxes related to interbasin flows.

The AEM Model and Supporting Analyses

Table 1 summarizes the features and properties of the AEM model as constituted in Figure 1. The AEM was selected to support a fast-track, year-2000 effort to locate a wellfield site, conduct aquifer characterization, establish a monitoring network, and provide an impact assessment for the proposed ground water extraction that would supply MPEC (Johnson et al. 2001). In the subregion of the study area, only four widely spaced areas with aquifer testing in carbonate aquifers were available to suggest material properties for the model (Ertec Western Inc. 1981; Mifflin & Associates Inc. unpublished Bonneville Pacific/Nevada Cogeneration Associates data; Buqo 1994; Johnson et al. 2001). Even less aquifer test data were available from Muddy River alluvium (Mifflin & Associates Inc. 1987) and the Muddy Creek Formation (Johnson et al. 1986). Regional relationships of hydrochemistry and water temperature (Thomas et al. 1996), a few key continuous monitoring well records (USGS, Nevada Power Company, and Mifflin & Associates Inc. unpublished), and distribution of pumping stress (unpublished data in files of Nevada State Engineer) were also available. Major structural features and the resulting distribution of lithologies are complex, but the carefully documented flux of the Muddy River spring area, pumping records, and Muddy River flow records tightly constrain the magnitude of ground water discharge.

In the early efforts toward constructing an AEM representation of the area, reviews of the regionally estimated fluxes, mixing models based on basin water budgets, and isotopic mass balance (Kirk and Campana 1990; Thomas et al. 1996, 2001) were considered in efforts to constrain the more troublesome uncertainties, such as recharge fluxes in adjacent mountainous terrain. The result of these efforts, facilitated by stepwise AEM modeling, was a set of revised conceptual models that addressed uncertainties and inconsistencies in prior analyses, some of which (notably Eakin 1966) have stood unquestioned for decades.

The model has been based on an infinite aquifer, 1524 m (5000 feet) in thickness throughout its stages of development. Two primary observations governed the thickness estimate: measured thicknesses of carbonate rock in the stratigraphic section (Longwell et al. 1965) and ground water temperatures in the 29°C to 35°C range (9°C to 15°C above the mean annual temperature) from Coyote Spring Valley to the Muddy River springs area and south beyond the MPEC site (Johnson et al. 2001). Although this is a remarkable thickness for widespread vertical hydraulic continuity, available evidence supports this order of magnitude thickness of transmissive rock and active ground water circulation in the subregion. The fundamental assumption in application of the AEM is that Dupuit-Forchheimer approximation of the flow field (Freeze and Cherry 1979; Haitjema 1995) is appropriate. In considerations of regional flow, where vertical variations in fluid potential are much less than those that occur over the lateral extent of the model domain, calculations based on Dupuit-Forchheimer flow should compare favorably with more rigorous methods (Haitjema 1995).

Monitoring records were instrumental in driving the evolution of the conceptual model of the area and its AEM representation (Figure 3). In 2000, no monitoring records suggestive of the hydraulic barrier between K1 and K3 existed. A feature limiting or blocking southward ground water flow from the Muddy River springs (H1) area was suspected based on incompatible water chemistries between the spring area discharge water and the southern flow field (K1). Available water-level data suggested that any lateral flow from the K3/H1 spring area southward should result in compatible hydrochemical

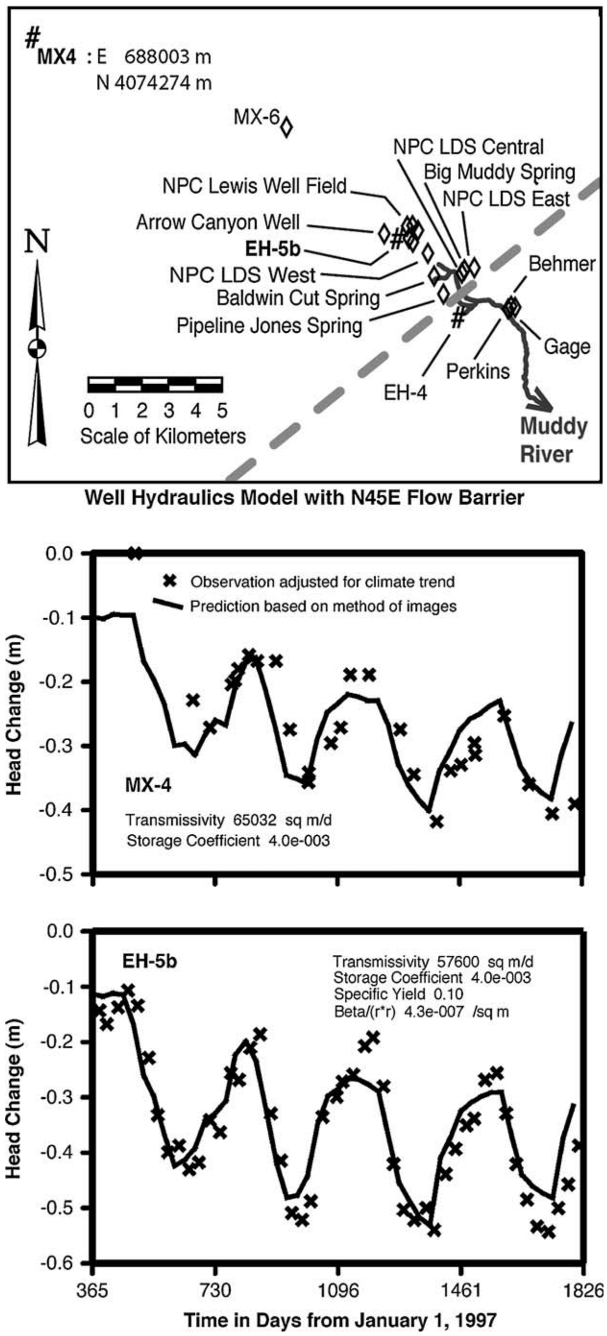

Figure 5. Parameter estimation for Zone K3, based on monthly stress periods, 1997 to 2001, and fitting 1998 to 2001 water levels. Image-well boundary trending N45E through EH-4 location (dashed line) was assumed. Raw measurements by USGS (at MX-4) and NPC (at EH-5b) were detrended to remove -8.32×10^{-2} m/year climate effect, based on southern flow field records (Figure 6).

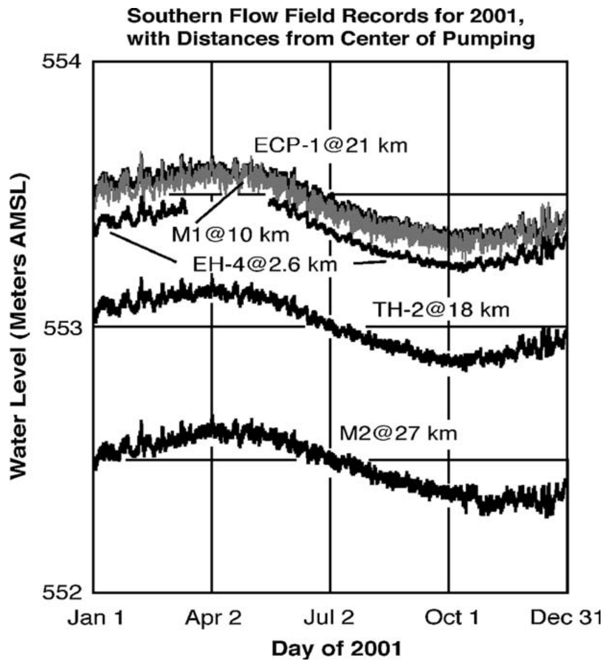

Figure 6. Evidence for hydraulic barrier between southern (Zone K1) and northern flow fields (Zones K2 and K3). Signals are essentially identical from 2.6 to 27 km south of the weighted center of pumping, indicating no distance-drawdown relationship and therefore no pumping effects.

evolution. A decision was made to adopt a conservative modeling approach by allowing hydraulic continuity to carry through from the northern domain to the southern domain in accord with the apparent continuity of carbonate rock (Schmidt et al. 1996), which, in retrospect, made the early AEM calibration difficult. In this manner, conservative analyses of impacts on spring flows were obtained, and the available evidence suggesting a barrier was discussed but not embedded in the AEM or derivative MODFLOW modeling analyses of the transient pumping impacts (Johnson et al. 2001).

As the Reservation area (northern K1) monitoring records accumulated during 2001, the first physical (as contrasted to hydrochemical) evidence for a barrier between the areas was developing. The characteristic pumping-induced asymmetry of the EH-5b and MX-4 monitoring well hydrographs is not present in those from K1; instead, a uniform annual water-level fluctuation cycle and long-term decline are characteristic of the southern records. Two of these wells (EH-4 and M1) are closer to the pumping area than MX-4, and one (TH-2) is about the same distance; yet, no clearly defined asymmetry of the seasonal pulse is evident in the 2001 data. These observations encouraged further analyses in an attempt to better understand the periodicities and regional multiyear water-level declines. It should be noted that the 2002 to 2004 monitoring records indicate the same downward trend and congruent hydrographs in the K1 domain.

Figure 3, a realization from the second-generation AEM model, incorporates a low-permeability "hydraulic barrier" of K0 material between the K1 and K3 domains in Figure 1. In the model, the barrier terminates at its northeast end against the K4 domain, which supplies the flow to Rogers and Blue Point Springs, H2. The area where the barrier approaches K4 presents the greatest uncertainty in the model, which is quite sensitive to the poorly constrained conditions there. Structural elements responsible for the barrier may in fact continue far to the northeast, the area where the Weiser Syncline (B3) terminates in a large drag fold against the Mormon Mountains (Axen et al. 1990), but no monitoring well records are available to support this idea. The southwestern extent of the barrier is suggested by an abrupt transition between upright and overturned beds in the Arrow Canyon Range, and the northern termination of the Dry Lake Thrust Fault (Page 1992).

The Figure 3 AEM realization, with a "soft" or "leaky" version of the barrier of Johnson and Mifflin (2003), calibrates well with water-level data and observed spring flow. A hydraulic barrier between K1 and K3 was established as a fundamental model component on the basis of (1) the Figure 4 analyses of sources of ground water pumped in the Muddy River springs area (K3); (2) the Figure 5 parameter estimation based on EH-5b and MX-4 monitoring well hydrographs in K3; and (3) the Figure 6 Reservation area (K1) monitoring well records that became available in 2001. These analyses and monitoring well records, when combined with the geochemical differences between the water of the K1 and K3 domains (Johnson et al. 2001), support the inclusion of the low-permeability zone between these areas depicted in Figures 1 and 3. The northeast-southwest trend passing just north of monitoring well EH-4 is constrained to that location and orientation by the affinity of the EH-4

Table 1
Features and Properties of the MPEC Analytic Element Model (from Figure 1)

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/d, obtained by calibration
K1	Southern flow field	$K = 6.1$ m/d from 7-d 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 subregional hydraulic barrier described by Johnson and Mifflin (2003 and this study), 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/d, 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/d from analysis of seasonal pumping response, 1997 to 2001 (Johnson and Mifflin 2003 and this study). Bounded on west by normal fault on west side of Arrow Canyon Range
K4	Glendale cell	$K = 5.5$ m/d, 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 d
H2	Rogers/Blue Point Springs	Specified heads 488 to 463 m, hydraulic resistance 2.7 d
H3	Southern receptor zone	Specified heads 450 to 396 m at south end along Las Vegas Wash, hydraulic resistance 2 d
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 ground water (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/year in forested highlands, by calibration. Recharge area encompasses 420 km^2, total 2.94×10^6 m^3/year (2380 acre-ft/year). Previous estimates include 2000 acre-ft/year (Eakin 1966), 5000 to 6000 acre-ft/year (Kirk and Campana 1990) and 14,000 acre-ft/year (Thomas et al. 1996)

hydrograph with several others to the south (Figure 6), which as a group are distinct from those northwest of the barrier (Figure 5), and by the need for a no-flow boundary in close proximity to the center of pumping for the image-well analysis of Figure 5.

Figure 4 reconstitutes Muddy River flows for the period 1997 to 2002 by adding monthly surface water diversions and ground water pumpage to base flows, with carbonate aquifer pumpage delayed 1 month and alluvial aquifer pumpage delayed 5 months. The exercise is simple addition by spreadsheet, with the lags obtained by trial-and-error comparison of trial results with the 1913 to 1918 record. These lag estimates are compatible with a cone of depression that develops each summer in the alluvial aquifer, migrating down-valley over the pumping season until it intersects the headwaters channels of the Muddy River, then recovering completely by the next pumping season (Mifflin and Adenle 1996). The reconstituted record compares remarkably well with the 1913 to 1918 Muddy River record in both timing and magnitude of seasonal flows. Three key relationships are recognized:

- The flux reaching the spring area has remained constant for almost a century.
- The seasonal variability of flows in the 1913 to 1918 record is likely due to evapotranspiration in the heavily vegetated headwaters area of the Muddy River based on the close correlation of flow differences to seasonal temperatures.
- All ground water diversions of the 1997 to 2002 record are manifested by 1:1 decreases in Muddy River discharge.

The latter point, all water is accounted for in the Muddy River springs system, has bearing on the multiyear downward trend observed in all the monitoring wells in K1, K2, K3, and K4 during the 1997 to 2004 drought. When the analysis of Figure 5 was performed, the data in K3 were detrended according to the rate that is characteristic throughout the K1 domain, where the long-term decline is attributed entirely to drought. The analysis, performed with Aquifer^{win32} from Environmental Simulations Inc. (Reinholds, PA) attempted to replicate the pumping-induced hydrographs of monitoring wells EH-5b and MX-4 of the K3 domain. The forcing function for the well hydraulics analysis was based on monthly production totals from 10 wells that produced at a combined average rate of 2.14×10^4 m^3/d (8.74 ft^3/s) in 2001, a typical year (Table 2) with pumping heavily weighted toward the summer months. To match the hydrographs, a no-flow boundary condition was necessary (from image-well analysis), consistent with the "hydraulic barrier" proposed by Johnson and Mifflin (2003). The derived parameter estimates also proved consistent with the AEM calibration of K3 with Muddy River spring discharge, adding additional confidence in the interpretation of the "barrier" as well as the interpretation of the asymmetrical hydrographs as representing a pumping signal.

Figure 6, the synchronous, but geographically widely distributed 2001 hydrographs of the new monitoring wells in the Reservation area of K1, and EH-4 near the Muddy River spring area, are suggestive of a barrier and encouraged the above analyses. The synchronicity, identical amplitudes both near and far from the pumping center, and absence of a hint of the asymmetry seen in the EH-5b and MX-4 signals (Figure 5) suggest that the periodicity in these wells cannot be a porous-media response to seasonal pumping in K3 to the north. On the other hand, a loading or tidal mechanism for this magnitude of annual aquifer response does not seem reasonable. It is conceivable that a seasonal pumping signal could be propagated southward, with little attenuation along fractures of the Hogan Spring Fault Zone (Schmidt et al. 1996), thus supplying a similar response to the larger K1 area. A 7-d aquifer test (Johnson et al. 2001), however, produced a porous-medium response with no evidence of direct fracture connections between ECP-1, TH-1, and TH-2 (Figure 3). Though the periodicity observed in the K1 domain remains enigmatic, the weight of the evidence indicates that the annual periodicity in the southern flow field is not directly related to seasonal pumping in upper Moapa Valley.

Table 2
Ground Water Diversions, 2001

Well ID	Annualized Q (m^3/d)
Arrow Canyon	8224
MX-6	1046
Lewis 1	369
Lewis 2	64
Lewis 3	1462
Lewis 4	1243
Lewis 5	1351
LDS West	2365
LDS Central	3215
LDS East	2046
Behmer	2761
Perkins	1654

Note: Behmer and Perkins data were used in the regional AEM model but not in the well hydraulics model since they are located southeast of the image-well boundary.

Benefits of the AEM Approach

AEM modeling facilitated a realistic, simple beginning of hydrogeologic assessment but also allowed the easy incorporation of complexity as additional data became available. The ability to simulate a large domain was important for maintaining flexibility in the site area while minimizing boundary artifacts and was easily accommodated by the AEM assumption of an infinite aquifer. A strength of the method lies in the mechanics of its implementation, a logical progression from embedding what is known and easily seen at the land surface to exploring the effects of changes to the underlying conceptual models. The ease of adding and deleting analytic elements helps to determine if a conceptual model with added complexity makes sense or should be discarded. In practice, the AEM approach allows many more realizations within a given time frame (project duration) than alternative methods.

Testing multiple conceptual models is critically important for understanding the effects of adding features that may not exist, or omitting key features that do. The more sparse the constraining databases, the more important this insight—as demonstrated by our initial failure to embed the hydraulic barrier between the northern (K3) and southern (K1) flow fields. Hydrochemical evidence alone, however compelling in terms of indicating a non-Muddy River springs–type water source for southern water, was insufficient to negate the possibility of hydraulic continuity between the northern and southern areas. Moreover, assuming a hydraulic barrier on the basis of hydrochemical evidence alone would likely have been challenged due to its importance for estimating impacts of pumping on the regional spring flows. The quantitative framework provided by the AEM model, and the field data collected after the initial modeling, provided a more encompassing and defensible conceptual model for the site area. While the modeling was a critical part of the investigation, the value and information content of the continuous water-level monitoring cannot be overstated.

Conclusion

The AEM proved to be a powerful approach for conceptualizing ground water flow in a large subregion with poorly understood regional flow in carbonate rock aquifers. During the work, two aspects stood out: (1) its suitability for developing regionally appropriate models while removing the potential for boundary condition artifacts on the local scale of interest, and (2) the ease in which minor or major changes are accommodated and conceptual model hypotheses are "tested." Elements of an existing AEM model were easily modified, removed, or supplemented without starting over. Finally, we believe that the AEM fosters development of a conceptual model that is compact yet complete—a characteristic that is well suited for evaluations of competing models that are often the de facto decision framework for ground water resource management.

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