DOCUMENTATION OF THE ADMINISTRATIVE GROUNDWATER MODEL FOR THE MIDDLE RIO GRANDE BASIN

GREAT SEAL OF THE STATE OF NEW MEXICO
1912

BY

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Table of Contents

Introduction and Background

The Middle Rio Grande Basin (MRGB) is a located in central New Mexico and includes the area between Cochiti Dam and San Acacia (Figure 1). Groundwater in this region is obtained from a basin-fill alluvial aquifer, which is in hydrologic connection with the Rio Grande and other related surface water features. The degree of hydrologic connection is of vital interest to the state, as this connection controls the amount of stream depletion induced by wells. The Office of the State Engineer (OSE) has calculated these depletions using the analytical Glover-Balmer method. Drawdowns caused by groundwater pumping have been typically calculated using the Theis equation. This report documents a new model which is recommended to replace these procedures.

In recent years, the City of Albuquerque, and State of New Mexico and Federal agencies have pursued extensive hydrologic and hydrogeologic studies of the MRGB (also referred to as the Albuquerque Basin). Data from these studies has allowed hydrologists to produce a detailed model that can simulate groundwater and the interaction of groundwater and surface water in the MRGB. The Hydrology Bureau of the OSE has been working with the USGS for several years on MRGB research projects. Our goal is the development of a groundwater model suitable for administrative use to estimate drawdowns and stream depletions.

In the early 1990's, the Water Resource Division of the USGS developed a MODFLOW groundwater model of the Albuquerque Basin (Kernodle et. al. 1995). This modeling work was funded by the City of Albuquerque (COA), and while the entire basin was included, modeling efforts were most concentrated on the greater Albuquerque area. The OSE considered using this model (the original Kernodle model) for basin administration, but decided that the model was not yet suitable for our purposes. The most important reasons for this decision were as follows:

1. The model was computationally huge, and was deemed to be too cumbersome;

2. The model had been insufficiently tested and validated (in part because of its computational size); and

3. Additional observational data were needed (groundwater and surface water) to support the model.

Kernodle and his colleagues continued working on this model, correcting some errors in model structure and published a revised report in 1998 (Kernodle, 1998). The revised Kernodle model is still computationally huge, and does not resolve some of the OSE's technical concerns, so the OSE has not chosen to use this version administratively.

USGS modeling work has continued. The original and revised Kernodle models were the subject of additional work and revision by Claire Tiedeman, a USGS research hydrologist in

Menlo Park, assisted by USGS personnel Mike Kernodle and Doug McAda in Albuquerque. The revised Kernodle model was rediscretized in order to reduce computation time, and then inverse parameter estimation techniques were applied to the system. These techniques allow the modeling program to select hydrologic parameters (such as hydraulic conductivity, storage and natural recharge) that will best simulate the observational water level and groundwater discharge data. The purpose of this work was to determine if parameter estimation techniques could be applied on a regional scale (it was determined that they could), and to test them on the Albuquerque Basin model. Parameterization was tested on six different conceptual models, or subsurface configurations (as will be described more fully in the next section). The results of this study, summarizing six model versions, were published in Tiedeman et al. 1998.

The Tiedeman study appeared to address most of the OSE's major concerns with the Kernodle model. Tiedeman's models are much smaller computationally, and therefore less cumbersome to test and use. Tiedeman's work involved numerous model test runs, with extensive sensitivity analysis. Some of the recently obtained geologic data, groundwater level data and surface water data were included in this study. Of especial interest was the inclusion of observed baseflow gain/loss data for the Rio Grande surface water system; such data had not been included in earlier modeling efforts.

Because the OSE's concerns have now largely been addressed, the Hydrology Bureau recommends that the OSE use a model based upon Tiedeman's work to administer water rights in the Albuquerque basin on an interim basis. The latest hydrogeologic data, presently being compiled, will be incorporated into a 'final' groundwater model, as described in the next section. The Hydrology Bureau is now convinced that the Albuquerque Groundwater model described in this report is appropriate for administration of the MRGB, and will provide more accurate and more realistic results than the analytical techniques we have previously used. We note that some problems in the MRGB will still require analytical methods, such as calculating hydrologic effects at small distances for pumping wells, calculating the effects of very small stresses, or calculating the effects of pumping outside of the useful boundaries of the model.

Testing of Tiedeman's models has uncovered some technical concerns, but these have been resolved by a few model modifications. A description of these modifications, and an explanation of the reasons behind them is the purpose of this report. The modified version of the model that is recommended for administrative use is named the OSEMRG model.

Planned Future Work

Since the release of the original Kernodle model, there has been continued research into the basin structure and hydrology by the USGS, OSE, the City of Albuquerque (COA) and other State, Federal, and private agencies. Some of this new data was incorporated into the Tiedeman model as it became available. As research continues, the USGS and OSE plan to incorporate these results into a new model version.

Over the next year, Doug McAda of the USGS and myself are scheduled to work together to incorporate all of the most recent hydrogeologic data into the groundwater model. Of especial interest are:

1. The most recent water level data from the newly installed piezometers,

2. The findings of the USGS Geologic Division's intensive study of the geology and hydrogeologic structure of the northern part of the Basin,

3. New surface-groundwater interaction data, and

4. The results of more localized groundwater flow models.

It is hoped that the inclusion of this data will lead to a better calibrated and better supported groundwater model for the basin. We anticipate that this work will be finalized in the year 2000.

Summary of Tiedeman's Results

The Tiedeman groundwater model of the Albuquerque Basin is a MODFLOW numerical computer model. The grid of the Tiedeman groundwater model is shown in Figure 2. Hydraulic conductivity (K) is zoned following the distribution of hydrogeologic units (as originally defined in Hawley and Haase, 1992; Hawley et al. 1995). The zonation varies somewhat from layer to layer, representing change in geologic structure with depth. (More detail can be found in Tiedeman et al. 1998. Discretization and model coordinates is described more fully at the end of this report.) The Rio Grande and its associated irrigation canals and drains are simulated as head-dependent flux (RIV package) boundaries. Tributary and mountain-front recharge (Figure 3), as well as irrigation and septic return flows are simulated as specified fluxes using the RCH package. Evaporation of phreatophytes is simulated using the EVT package. Groundwater pumping and interbasin underflow is simulated using the WEL package. The model's calibration period is 1901 through 1995, and calibration targets are water levels from both predevelopment and recent times (Figure 4), including one value of discharge between the Rio Grande and the aquifer based upon measurements in the Albuquerque reach of the river.

Tiedeman used MODFLOWP (Hill, 1992), a version of MODFLOW which estimates which values of hydraulic conductivity (and/or other parameters selected by the modeler) will produce the best fit to the observational head and flow data. The parameters Tiedeman estimated using MODFLOWP are the hydraulic conductivity (K) of several hydrogeologic units, some components of natural recharge, and the aquifer vertical anisotropy (Kh/Kv).

Tiedeman's report presents six different subsurface configurations, and the best fit parameters (K, recharge etc.) for each. The different configurations were tests of how well different conceptual models of the system could be calibrated. The six configurations are summarized below in Table 1.

Table 1. Summary of Tiedeman Subsurface Configurations

Subsurface Configuration Number (SC#)	Description	Layers/Approximate Total Model Saturated Thickness
SC1	Base Model	6 layers/ 1600 ft
SC2	Deeper version of Base Model	9 layers/ 5000 ft
SC3	High K zone associated with west Albuquerque groundwater trough	6 layers/ 1600 ft
SC4	Deeper version of SC3	9 layers/ 5000 ft
SC5	Low K fault west of west Albuquerque groundwater trough	6 layers/ 1600 ft
SC6	Deeper version of SC5	9 layers/ 5000 ft

SC1 and SC2 are basically variations of Kernodle's rediscretized model, that have gone through the parameter estimation process. It was found that neither of these configurations could simulate the large groundwater "trough," an area of anomalously low and flat water levels, west of Albuquerque (Figure 4). In order to simulate this feature, it was necessary to make significant modifications to the model. SC3 and SC4 introduced a large, thick, high K zone in order to drain water from the trough area towards the alluvium associated with the Rio Grande. SC5 and SC6 introduced a low-K fault zone along the western boundary of the trough to reduce inflow into the trough area and thus reduce heads. These four configurations were more successful at simulating water levels west of Albuquerque, and it was found that the K parameters estimated by these configurations were less unrealistic than the K's from SC1 and SC2. However, it is not known whether the hydrogeologic features these models introduce are actually present. The available hydrogeologic data does not support a large, thick zone of high K west of Albuquerque (as in SC3 and SC4). Geologic mapping does support the existence of lengthy north-south striking faults in this part of the basin, some of which are known to impede groundwater flow. This makes the extremely low K fault west of the trough (in SC5 and SC6) plausible, but the actual extent and permeability of such a feature is somewhat speculative.

The purpose of the additional layers in SC2, SC4 and SC6 was to test whether a thicker model would be substantially different or better than the original version. The parameters estimated for the thicker model configurations were somewhat different, and in some cases more realistic than those in their shallower counterparts, but there was no significant improvement in the calibration or calibratability of the deeper models.

Tiedeman concluded that none of the subsurface configurations was "completely satisfactory", but SC4 and SC6 were preferred because they provided the best calibration with the most reasonable parameter values, and include more of the total basin thickness. Heads and historical drawdowns in the central part of the Basin, in and near Albuquerque, are reasonably well simulated by these configurations (Figure 5, and Appendix A). Heads in the northern part of the basin are not very well simulated by the six proposed subsurface configurations (Figure 5).

Tiedeman's work builds upon the Kernodle models, and has produced models more suited for administrative use. Tiedeman's models are better calibrated than the Kernodle models, less cumbersome, and include recent hydrologic data, including flow data.

Concerns with Tiedeman's Models

After the publication of the Tiedeman et al. (1998) report, the consultant for the City of Albuquerque (COA) made a number of test runs of the Tiedeman model. They made historical runs in order to estimate the stream depletions caused by the COA's pumpage. It was found that the stream depletions estimated by the Tiedeman model (SC4 and SC6) were quite high, closer to those calculated by the Glover-Balmer analytical method than those calculated using the original Kernodle model or revised Kernodle model. Some of these results are summarized in Table 2.

Table 2.
Calculated Surface Water Depletion caused by COA diversions as Tabulated by McAda, 1999

Model or Method	River Depletion in 1993 (AF/yr)
Glover-Balmer (COA calculations)	79,000
Kernodle et al. 1995 (Kusf1 = 15 ft/day)	53,000
Kernodle 1998 (Kusf1 = 15 ft/day)	57,000
Tiedeman SC4 (Kusf1 = 40 ft/day)	71,000
Tiedeman SC6 (Kusf1 = 39 ft/day)	70,000

Further testing and consideration revealed that the stream depletions caused by COA pumping are very sensitive to the hydraulic conductivity of the Upper Santa Fe #1 unit (Kusf1). Tiedeman's preferred models (SC4 and SC6) have Kusf1 values of about 40 ft/day (and even higher values for some of the other subsurface configurations). Aquifer tests within that unit, however, provided a much lower value: typically between 5 and 15 ft/day. At a meeting in December 1998, the COA argued that the parameter estimation technique had probably artificially elevated the value of this parameter. Elevation of this parameter may have compensated for model error associated with the simulation of the groundwater trough or some other part of the model. OSE staff agreed that this issue needed further investigation, as will be described in the following section.

In addition, the COA argued that the Tiedeman model poorly simulated the observed baseflow gain/loss data from the Rio Grande, and that this data was not given sufficient weight in the parameter estimation process. OSE staff agree that this data should be given more weight, but note that there is a large degree of uncertainty in this data. Data of this type were not considered at all by previous groundwater models of the basin because of the difficulty in accurately measuring this quantity.

Mike Kernodle indicated that he thought SC3 and SC4 were unrealistic, because the extensive west-mesa high-conductivity zone included in these models is speculative, and cuts across units of different ages. He stated his opinion that such an age-transgressive feature is not possible. I would not agree that such a feature is impossible: high K zones are often related to post-depositional processes, and therefore can appear to be time-transgressive. However OSE staff agree with Kernodle there is not enough hydrogeologic evidence to support such an extensive high K zone in the west mesa area.

Kusf1

In an attempt to resolve the issue of Kusf1, OSE Hydrology Bureau staff reviewed the aquifer test data relating to the hydraulic conductivity of unit USF1. Doug McAda of the USGS provided a preliminary list of 16 hydraulic conductivity results from wells and tests within the USF1 zone, and the values range from 5.9 to 27.7 ft/day (this highest value is suspect), averaging 12.9 ft/day. McAda later reported an average of 12 ft/day based upon 27 unlisted values (McAda, 1998).

In order to provide our own check on the hydraulic conductivity data, OSE staff compiled aquifer test data for the USF1 zone, from original sources. One set was from Bjorklund and Maxwell, which consists of 5 tests performed in the 1950's ranging in length from 5 to 20 hours; the maximum K value in this set is 19.3 ft/day, the average is 13.7 ft/day. Another set consists of 27 COA well tests performed in the mid 1980's, lasting 200 minutes (original data from COA, also listed in Thorn et al., 1993). The maximum K value in the later test set is 25.0 ft/day, the average K is 10.83 ft/day. The data from the earlier test set has the advantage of longer test length, and is less likely to be impacted by aging well problems. Preliminary results from the long term Griegos aquifer test also support a Kusf1 value between 10 and 15 ft/day (McAda, personal communication, 1998).

In addition, it was found that the highest K value for this unit cited by McAda: 27.7 ft/day from Atrisco II 5, is probably in error. We believe that this K was calculated from T using an incorrect screen length: use of the correct screen length produces a K estimate of 6.33 ft/day.

Hydraulic conductivity values obtained from short aquifer tests can be systematically lower than those from long tests or from calibrated regional models. This discrepancy may be a result of scale-dependence in hydraulic conductivity, or well inefficiency effects. We do not expect this to be a strong factor for the present case.

We therefore conclude that it is likely that a hydraulic conductivity value of 40 ft/day is not representative of the USF1 zone. The K value for this zone of the model should more closely approximate aquifer test data.

Preferred Model Configuration

The model configurations preferred by Tiedeman are SC4 and SC6. These configurations were preferred largely because the parameters estimated by MODFLOWP for SC4 and SC6 more closely fit the predetermined reasonable ranges. Neither SC4 nor SC6 is calibrated significantly better than the other, nor is either clearly preferable because of its parameter values. After much discussion, OSE staff decided to work with SC6. Our reasoning is as follows: the extremely large high K zone in SC4 is not supported by hydrogeologic data, while, on the other hand, the principle that faulting can produce linear low K zones (as used in SC6) is already accepted and had already been incorporated in some form into other areas of the model. The linear low-K feature incorporated into SC6 corresponds reasonably well with known, mapped faults, including the West Atrisco fault.

OSE Model Revision: OSEMRG

Having concluded that the Kusf1 parameter is probably excessively high, the OSE decided to review the other model parameters, and test model calibration with a variety of other parameter values. The parameters chosen for variation were Kusf1, Storage: unconfined specific yield (Sy) and confined specific storage (Ss), ANIV: horizontal/vertical anisotropy in hydraulic conductivity, the hydraulic conductivity of the Middle Santa Fe group (Kmsf) and the thickness of the model. These parameters were chosen in part because of apparent model sensitivity, and also because the values of these parameters in the Tiedeman model differed from those in the Kernodle model or those observed by other methods.

Kusf1: This parameter has been discussed at length above. It was decided to change this parameter to a value within the observed range, between 3 - 25 ft/day. The value 15 ft/day was eventually chosen as being close to the average, but near the high end of the largest cluster of observed values.

Sy (unconfined specific yield) was set at 0.20 in Tiedeman's models. MODFLOWP failed to estimate this parameter satisfactorily and so 0.20 was chosen by Tiedeman as a reasonable value. Kernodle chose 0.15 for his models. **Ss** (confined specific storage) was set at 2x10E-06 per foot in the Kernodle and Tiedeman models, based upon site specific work using extensometers. A rule-of-thumb value from Todd (1980) is 1x10E-06 per foot, and this value was used in an earlier basin model.

OSE staff were concerned that since both Sy and Ss in the Tiedeman model are on the high end of the range of values from previous models, that perhaps the net storage of the system (i.e. the composite of both confined and unconfined storage) is being overestimated. Model testing showed that reduction in Sy and reduction in Ss had similar effects on model performance. Both improved model performance somewhat, but when Sy was set to 0.15 a number of the observation well cells went dry, making model comparisons difficult. It was decided to leave Sy at 0.20, and reduce Ss to 1x10E-06 per foot to account for a possible overestimation in net system storage.

ANIV (the ratio of horizonal to vertical hydraulic conductivity) was estimated by MODFLOWP in Tiedeman's work, and a large range of values resulted. Tiedeman's preferred subsurface configurations had ANIV values of 330 (SC4) and 1,200 (SC6). Kernodle used a value of 200. The models are highly sensitive to this parameter, since a high anisotropy will result in low vertical hydraulic conductivities, which will act to reduce the impact of deep pumping on shallow aquifers and surface water bodies. Model testing revealed that ANIV could not be reduced very much without significant model degradation, but that more modest decreases in ANIV actually improved model performance. A value of 750 was selected for the OSE modified version of SC6.

Kmsf (hydraulic conductivity of the Middle Santa Fe Group (MSF)) was estimated by MODFLOWP at 8.4 ft/day in SC6. The MSF zone in the model is very large and extends from the surface in some areas, to great depth. The hydraulic conductivity of 8.4 ft/day is higher than the range of values from available aquifer tests, and OSE staff suggests a value closer to 5 ft/day would be more appropriate for the shallower MSF unit. There is no aquifer test data for deeper MSF deposits; the hydraulic conductivity of the deeper part of the unit are likely to be even lower due to compaction. Model drawdown predictions are very sensitive to this parameter. Tests made with Kmsf set to 5.0 ft/day resulted in a significant degradation in model performance. In the end it was decided to reduce the net model thickness instead (as described below), which effectively reduced the transmissibility of the deeper half of the model while retaining the parameters of the upper half.

Model Thickness: Three of Tiedeman's subsurface configurations had a net model thickness of about 1600 feet, which is close to the net thickness of the Kernodle models, while the other three subsurface configurations had three additional layers at depth making the model about 5000 feet thick. The structure of the additional layers was extrapolated from the structure in the upper layers, and from other hydrogeologic data. Hydrologic properties of each unit/zone in the deeper layers is assumed to be the same as in the upper layers. Since there is very little quantitative hydrologic data from such depths, the hydrologic properties of the deeper layers are poorly constrained. The model assumption that the hydraulic conductivities in the MSF and Lower Santa Fe group do not vary with depth is highly uncertain.

Testing by OSE staff indicated that the additional thickness of relatively permeable units in the deeper models (especially SC6) has a significant effect on predicted drawdowns. Given the great uncertainty as to actual hydrologic properties at depth (especially Kmsf, which is relatively high in SC6) it was decided to truncate the model, and remove the bottom three layers. This resulted in some degradation of the model calibration, but this was considered acceptable.

The OSE modified model simulation of Albuquerque area hydrographs (as shown in Appendix A) is as good as that of the original Tiedeman SC6 model.

As another option, SC5 (which is similar to SC6, but with 6 rather than 9 layers) was tested, but it was found that when Kusf1, ANIV and Ss were adjusted as described above, this model performed significantly worse. Additional adjustment could probably produce an acceptable version of SC5, but time constraints, and the considerable uncertainty that would result in any case, led us to choose the modified SC6 model as our interim model. In addition, SC5 was difficult to work with because Tiedeman did not create a version of that configuration with convertible layers.

Jemez River Boundary Condition: The Jemez River and the other tributaries to the Rio Grande are treated as specified-flux recharge boundaries in the Kernodle and Tiedeman models. (The Rio Grande and associated canals and drains are simulated by head-dependent boundaries using the RIV package). The average estimated infiltration into the aquifer from these tributaries is applied along the length of these features in layer 1 at a constant rate. This is a reasonable way to treat intermittent streams, especially if they are perched above the main water table, but this may not be the best way to simulate the Jemez River.

There is a dam on the Jemez River shortly above its confluence with the Rio Grande. Water has been impounded since the early 1980's, providing opportunity for a connection between groundwater and surface water. In addition, piezometer nests along the Jemez River at Zia and Santa Ana Pueblos show upward hydraulic gradients between depths of 750 and 200 feet, which are difficult to reconcile with recharge and downward flux from the surface. Water levels from these piezometers and other wells in the vicinity of the Jemez are close to the river bed elevation, suggesting that the river and the groundwater may well be in hydrologic connection in some reaches. Further investigation of the stream-aquifer connection at this location is needed.

In the mean time, OSE staff decided to modify the Albuquerque Groundwater model by converting the Jemez River from a specified flux boundary to head-dependent flux boundary. This will allow calculation of stream depletion to the Jemez River caused by groundwater pumping. In the absence of data that would allow us to determine exactly which parts of the Jemez River are likely to be connected with the groundwater, and which are not, it was decided to make the entire length of the Jemez River within the model a head-dependent-flux boundary. The GHB package was selected to simulate the Jemez River. Use of the GHB package has two advantages:

1. GHB fluxes are automatically segregated from RIV fluxes in model output, which allows us to easily separate the predicted effects on the Jemez River from the effects on the Rio Grande.

2. GHB cells do not become disconnected, and therefore the seepage from these cells does not become independent of groundwater levels, as occurs with RIV cells when groundwater levels drop below a certain level. This is advantageous for the northern part of the model where groundwater levels are, at present, poorly simulated. If the RIV were used for the Jemez, disconnection might result accidentally due to inaccuracy in water level simulation in that area.

To accomplish this conversion, the RCH package was modified by removing the recharge due to the Jemez River. A GHB package was created consisting of the cells in layer 1 along the Jemez River. Each GHB head is set equal to the average topographic elevation of each cell, estimated by eye from a topographic map. GHB conductance is roughly proportional to the length of the Jemez River reach occurring in each cell, assuming a river-width:bed-thickness ratio of 50:1, and a vertical hydraulic conductivity of approximately 0.5 ft/day (consistent with the value used for the Rio Grande). The GHB conductances for the Jemez River cells are comparable, but generally somewhat smaller than the conductance of the Rio Grande RIV cells.

The Jemez River boundary condition changes with time: Jemez dam was built in 1953, but significant amounts of water were not impounded until 1980. To roughly simulate this, two different GHB's were applied for two different time intervals. For early times, GHB heads and conductances simulate the Jemez River as an intermittent, shallow stream. For later times, after 1980, the heads and some of the conductances in the cells corresponding to the Jemez reservoir were changed to reflect the larger area and greater surface water elevation of the impounded water. GHB heads at the reservoir were set at the average elevation of impounded water, and GHB conductances were increased to roughly simulate a larger area of surface water. Considerable uncertainties remain in the simulation of this boundary, but this modification is physically reasonable, and will allow an estimate of effects to this tributary.

The conversion of the Jemez River to a GHB boundary produced a slight improvement in the model calibration in the vicinity of the Jemez River. Simulated heads and drawdowns in the Albuquerque area were not changed noticeably.

Summary of Revised Model

The OSE revised model (OSEMRG) is based upon Tiedeman's SC6, with the following modifications:

Table 3
Comparison of Tiedeman SC6 and OSEMRG Models

Parameter or Quantity	**Original SC6**	**OSE Modified SC6**
Kusf1 (ft/day)	38.65	15.0
Sy	0.20	0.20
Ss (1/ft)	2.0E-06	1.0E-06
ANIV	1203	750
Number of Layers	9	6
Treatment of Jemez River	Specified Flux: RCH	Head-dependent Flux: GHB
Model Results:		
Sum of Squared Head Weighted Residuals (includes new piezometer data for a total of 1167 observations)	16,409	19,043
Baseflow Loss in Albuquerque Reach: (Observed: 29,000 AF/yr equivalent)	39,800 AF/yr	33,900 AF/yr
Weighted Flow Residuals	-0.374	-0.168
1993 Stream Depletion Caused by Historical COA Pumping:	70,617 AF/yr	63,589 AF/yr

Miscellaneous Modifications: A number of other modifications were made to simplify model use, save computer space, and reduce model run time. The model input files have been modified so that the parameter estimation package of MODFLOWP is no longer required. In addition, a version of the model has been created that will perform future prediction runs without rerunning the calibration period. This version starts from initial heads generated by the last time step of an extended (1901-2000) calibration run. This version of the model should run with standard MODFLOW or MODFLOW96.

Although the model runs with standard MODFLOW or MODFLOW96 source code, the user may encounter problems when pumping wells are completed in (or withdraw water from) multiple layers. If a well is designated to withdraw some of its water from a shallow layer that goes dry in that location during the course of the simulation, the pumping of that well will be automatically reduced when the shallow cell becomes inactive. In order to prevent this occurrence, the OSE uses a modified version of MODFLOW (after Balleau, 1998) which takes the pumping from a shallow dry cell and places it in the next deepest layer. Model runs made with this version of MODFLOW will maintain the pumping rates set in the WEL file. This modification must be used with caution, however, to ensure that well withdrawals are not deepened beyond reasonable limits. In the case of most water rights uses in the Albuquerque Basin, however, this should not be a problem. Instead, accurate estimates of the effects of multi-layer pumping wells require that pumping rates be maintained in the face of deepening water levels. Conservative estimates of the effects of water rights associated with shallow wells also require that pumping rates be maintained even if the well owner would have to deepen his wells to maintain production.

Future Prediction Scenario

The first application of the OSE Modified model has been to predict what drawdowns could occur over the next 40 years due to the full exercise of existing permits. This run was made by first repeating the calibration run (1901-1995), then adding another stress period to simulate pumping from 1995-2000, and then an additional stress period to simulate the next 40 years: 2000-2040.

Pumping for the 1995-2000 period: Pumping in the period 1995-2000 is assumed to be approximately equal to the pumping in the last stress period of the calibration run (1994-1995). The 1994-95 well stresses were used as a base for the 1995-2000 well stress, and modified as deemed necessary. These modifications are difficult because the USGS well input file is not annotated, and thus it is difficult to determine which well or permit is simulated by which lines in the well file. Nevertheless, modifications were made when information became available to the OSE that indicated such a change was necessary. These modifications include: addition of INTEL wells at historical rates, modification of Rio Rancho pumping and NMU pumping to match historical distributions.

Baseline pumping for the future period: Pumping for the period 2000-2040 was set at a constant rate (217,600 AF/yr) which was calculated to represent full exercise of existing non-domestic permits, plus reasonable use of domestic wells. No quantitative information is available concerning Pueblo groundwater withdrawals, which do not require permits from the OSE, and these are not included in the Historical or Baseline Future pumping scenarios. Historical use of Pueblo wells is probably relatively small, and neglect of that amount should not unduly effect model calculations.

Domestic water use in the future prediction scenario was set equal to that used in the last stress period (1994-1995) of the USGS Tiedeman model's historical simulation. These domestic water withdrawals were applied to cells located outside municipal water system area. The quantity of water withdrawn in each of these cell was calculated based upon a consumption rate of 100 gallons per day per person and population density data obtained from the 1990 census. We did not attempt to modify this pumping distribution or amount to reflect projected population growth; any other projection of domestic pumping would be laborious and probably also inaccurate. Domestic use is a sufficiently small component of the Albuquerque Basin water budget that inaccuracy in this distribution should have little impact on model predictions.

The Water Rights Division tabulated all permits of greater than 50 AF/yr, and many of the smaller permits as well. Pumpage representing full exercise of each permit was applied to the model at the location of the permitted wells. Domestic pumpage was included as in the Kernodle and Tiedeman models: the domestic pumpage magnitude and distribution from the Tiedeman model's last time step (1994-1995) was used for the 2000-2040 period.

Table 4 is a tabulation of the pumpage included in the future prediction scenario, listing many large permittees (greater than approximately 1000 AF/yr) separately.

Table 4
Pumpage included in Baseline Future Pumping Scenario
OSE Modified Albuquerque Basin Model
***Note: This list does not constitute an official tabulation of water rights, and should not be used for such a purpose.

Type of Pumping or Permittee	Pumpage (AF/yr)
DomesticPumpage	7,063 (estimated by the USGS based on demographic data for 1990)
City of Albuquerque	132,000
Rio Rancho	14,420 (Includes RG-06745 and RG-26259)
Los Lunas	2,250
Belen	4,190
Bernalillo	1,174
Kirtland AFB	4,500
PNM	6,720
Rio Grande Utilities	10,800
Sandia Peak Utility	1,010
New Mexico Utilities	10,000
National Utility Co.	1,920
INTEL	3,250
UNM	2,685
Albuquerque Academy	1,412
All other tabulated permittees	14,206
TOTAL:	**217,600**

The distribution of permitted pumping among more than one well under a given permit was based upon the present pumping distribution for those wells. Pumping was distributed among layers for each well in accordance with the 1995 pumping distribution in the USGS model. These methods of pumping distribution may result in some excessive pumping at particular sites, where in reality the permittee would bring other supplemental wells on line, but the pumping distribution should be an acceptable approximation in most cases.

The City of Rio Rancho and the City of Albuquerque are treated the same as the other non-domestic permittees. The pumpages of these entities were set at constant amounts, equal to their presently permitted amounts: 14,420 AF/yr (RG-06745 and RG-26259) and 132,000 AF/yr respectively, distributed among their active wells in accordance with present pumping practices. While the COA may not pump at these rates for the next 40 years (given their plan for direct diversion of Rio Grande water), it was decided to use these pumpages for the baseline future scenario rather than speculate about other pumping schemes.

In a few cases, adjustments to the pumping distribution were made. The historic and future pumping distribution resulted in a few cases in which large pumping amounts were placed on cells representing faults, that have very low K, and the model simulated unrealistic, extremely large drawdowns (100's - 1000's of feet). Part of the problem is that the model simulates faults as low-K zones at least one model cell (750 meters) wide, while, in reality, low K zones associated with faults are probably much narrower. In these cases, tests were run in which the pumpage was moved over by one cell to get it off the fault, or redistributed among other wells under the same permit. If these adjustments produced a more moderate drawdown distribution, this new distribution was used.

Model Predicted Drawdowns for Baseline Future Scenario

Drawdowns were calculated for each layer by subtracting year 2040 model predicted heads from model heads in the base year (either 2000 or 1901). These drawdowns varied at each location from layer to layer: typically the greatest drawdowns occurred in the most heavily pumped layer. In order to make simple two-dimensional representations of drawdown, a postprocessor was written which, at each row and column location, selected and saved the maximum drawdown in any layer. These were tabulated and contoured, and can be used as a basis for administration.

Two drawdown maps are shown. The first (Figure 6) illustrates drawdowns predicted to occur over the next 40 years: from 2000 to 2040. It is predicted that water levels in wells will decline by more than 100 feet in the next 40 years in a large area east of the Rio Grande, and a smaller area west of the Rio Grande. The area east of the Rio Grande is largely associated with the COA's future pumping of their fully permitted amount. Since the City is planning to reduce groundwater pumping in the future as they switch to surface water diversions, these drawdowns may not be realized, but still should be considered in administering the basin at this time. The small area west of the Rio Grande is associated with a large, under-utilized right owned by New Mexico Utilities.

The second drawdown map, Figure 7, shows the total drawdowns which will have occurred in 2040 since predevelopment times (1901). A fairly large zone of 200+ feet drawdowns is shown east of the Rio Grande, which illustrates the sum of historical drawdowns (already exceeding 100 feet in some areas) and future drawdowns that could theoretically be caused by the pumpage of the City of Albuquerque and other groundwater users in that area. These drawdowns are especially troubling when one considers the possibility of land subsidence which large water level declines can create. Our best, although highly uncertain estimate is that land subsidence may start when water levels drop more than 250 feet below predevelopment levels (Haneberg, 1995; and Haneberg, personal communication, 1998).

Use of the Model

It is proposed that the OSE Modified SC6 model be used to estimate stream depletions caused by changes in groundwater pumping, and drawdowns when appropriate. Local drawdowns, at short distances from the pumping well, should be calculated using the Theis equation or other methods appropriate to the scale of the problem. Other problems may still require analytical methods, such as calculating the effects of very small stresses, or calculating the effects of pumping outside of the useful boundaries of the model.

The OSE Modified SC6 model is non-linear, especially in the Albuquerque where historic drawdowns have caused one of more model layers to go dry over a large area, and changed the transmissivity significantly in those areas. In some parts of the model, cells representing drains, canals and a few of the cells representing the Rio Grande have become disconnected from the groundwater system, which affects both drawdowns and stream depletion calculations.

While individual applications are unlikely to cause non-linear behavior, the fact that the model behaves non-linearly over its calibration and future prediction period, makes it advisable to use the model carefully. For the time being I propose that each pumping change be evaluated by the following process, which involve comparison of two runs of the model and postprocessors presently being developed:

1) A future model run should be made using a future baseline pumping distribution. This future baseline pumping distribution should be based upon the future pumping distribution described above for 2000-2040, but should also include full exercise of any permits which were approved since this report was issued.

2) A second future model run should be made with the same future baseline pumping as the first run **plus** the proposed pumping change.

3) The effect of the pumping change on the surface water system will be calculated by a postprocessor which will calculate the difference in the model water budget between the two runs.

4) The drawdowns caused by the change in pumping will be calculated by a postprocessor that will calculate the difference in heads between the two runs.

Significant changes in pumping by the City of Albuquerque may occur in the future, and may need special model adjustment. If the City reduces their groundwater pumpage significantly, then water levels may actually rise in an area east of the Rio Grande. To simulate this properly, the model may have to allow some cells to "rewet", which the present model set-up does not permit.

The model presented in this report is intended to be an interim administrative model for the MRGB. Significant hydrogeologic data is now being collected that is not yet incorporated into the model. The proposed guidelines for the MRGB acknowledge that the administrative model may be revised as water uses change, or as deemed necessary by the agency.

Geographic Limits of Model Use

The model should provide reasonable and useful predictions for most of the Albuquerque Basin. The Hydrology Bureau recommends, however, that the model not be used for the parts of the model that lay beyond major low-K zones associated with major faults, as shown in Figure 8. The modeled hydraulic conductivity of these features is so low that the Rio Grande is effectively shielded from any well placed beyond them. The actual hydraulic conductivity of these features is highly uncertain, and in some areas the exact location of these features is not well constrained. Therefore, it is not conservative to use the model to estimate stream depletion effects of wells located beyond the features. We recommend that stream depletion of wells located east of the Sandia Fault and west of the Cat Mesa/West Atrisco fault complex be treated on a case-by-case basis. Two possible treatments are described below:

1. The stream effects of a well located within the active model grid but outside of the fault boundaries shown in Figure 8 could be conservatively estimated by simulating that well at an adjusted location, just within the fault boundary,

2. The stream effects of a well located beyond the fault boundaries (west of the West Mesa Fault or east of the Sandia Fault) shown in Figure 8 could be estimated employing the Glover-Balmer method, using appropriate hydrogeologic parameters consistent with the past use of Glover-Balmer by this office. (For list of affected cells, see Appendix B.)

Discretization and Coordinates

The model consists of 6 layers. The top of Layer 1 is the water table, and that layer is 40 feet thick near the Rio Grande. Away from the river, Layer 1 is more variable in thickness. Initially (in predevelopment conditions) Layer 1 thickened on either side of the river as the elevation of the water table rises. In later simulation times, parts of Layer 1 has gone dry due to groundwater development. The next 5 layers are of constant thickness, except where groundwater development has either caused layers 2 or 3 to go dry, or to convert to water table layers. The initial (predevelopment) thicknesses of these layers is as follows:

Layer 2: 40 feet;
Layer 3: 120 feet;
Layer 4: 200 feet;
Layer 5: 400 feet;
Layer 6: 800 feet.

In plan view, the model consists of 113 rows and 60 columns. The cells vary in size. The smallest cells are 2461 ft by 2461 ft (750 m by 750 m). The largest cells are 16,404 ft by 8202 ft (5 km by 2.5 km).

The coordinates of the corners of the grid, as obtained from the USGS, are as follows:

	State Plane-Central (feet)		Lambert Conformal Conic (meters)	
Corner:	X	Y	X	Y
Upper Left	353502.7609	1741628.5692	-67000.00	642300.0
Upper Right	524818.1401	1688162.0910	-15022.43	625911.6
Lower Left	193022.0449	1226359.3015	-116315.70	485890.4
Lower Right	364090.4102	1173099.4328	-64338.17	469502.0

The Y axis is oriented 17.5 degrees east of North.

REFERENCES

Balleau Groundwater, Inc., 1998, Hydrologic Model of the Estancia Basin: Report prepared for Entranosa Water and Wastewater Cooperative.

Bjorklund, L. J., and Maxwell, B. W., 1961, Availability of ground water in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer Technical Report 21, 117 p.

Glover, R. E., and Balmer, G. G., 1954, River depletion resulting from pumping a well near a river: American Geophysical Union Transactions, v. 35, p. 468-470.

Hawley, J. W., and Haase, C. S., 1992, Hydrogeologic framework of the northern Albuquerque Basin: New Mexico Bureau of Mines and Mineral Resources Open-File Report 387, Socorro, variously paged.

Haneberg, W.C., 1995, Depth-porosity relationships and virgin specific storage estimates for the upper Santa Fe Ground aquifer system, central Albuquerque Basin, New Mexico: New Mexico Geology, November 1995, p. 62-71.

Hawley, J. W., Haase, C. S., and Lozinsky, R. P., 1995, An underground view of the Albuquerque Basin, *in* Ortega-Klett, C. T., ed., The water future of Albuquerque and Middle Rio Grande Basin: Proceedings of the 39th Annual New Mexico Water Conference, November 3-4, 1994, New Mexico Water Resources Research Institute WRRI No. 290, P. 37-55.

Hill, M. C., 1992, A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression: U. S. Geological Survey Open-File Report 91-484, 358 p.

Kernodle, J. M., 1998, Simulation of Ground-Water Flow in the Albuquerque Basin, Central New Mexico, 1901-95, with Projections to 2020, (Supplement Two to U. S. Geological Survey Water Resource Investigations Report 94-4251): U. S. Geological Survey Open-File Report 96-209, 54 p., Model Revision.

Kernodle, J. M., McAda, D. P., and Thorn, C. R., 1995, Simulation of Ground-Water Flow in the Albuquerque Basin, Central New Mexico, 1901-1994, with Projections to 2020: U. S. Geological Survey Water Resources Investigation Report 94-4251, 114 p.

McAda, D. P., 1998 &1999, unpublished data, personal communication.

McDonald, M. G., and Harbough, A. W., 1988, A modular three-dimensional finite-difference ground-water flow model: U. S. Geological Survey, Techniques of Water-Resource Investigations book 6, chap. A1, 586 p. (MODFLOW)

Thorn, C. R., McAda, D. P., and Kernodle, J. M., 1993, Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, central New Mexico: U. S. Geological Survey Water Resources Investigation Report 93-4149, 106 p.

Tiedeman, C. R., Kernodle, J. M. and McAda, D.P., 1998: Application of Nonlinear-Regression Methods to a Ground-Water Flow Model of the Albuquerque Basin, New Mexico: U. S. Geological Survey, Water Resources Investigation Report 98-4172, 90 p.

Todd, D. K., 1980, Groundwater Hydrology: New York, John Wiley & Sons, 535 p.

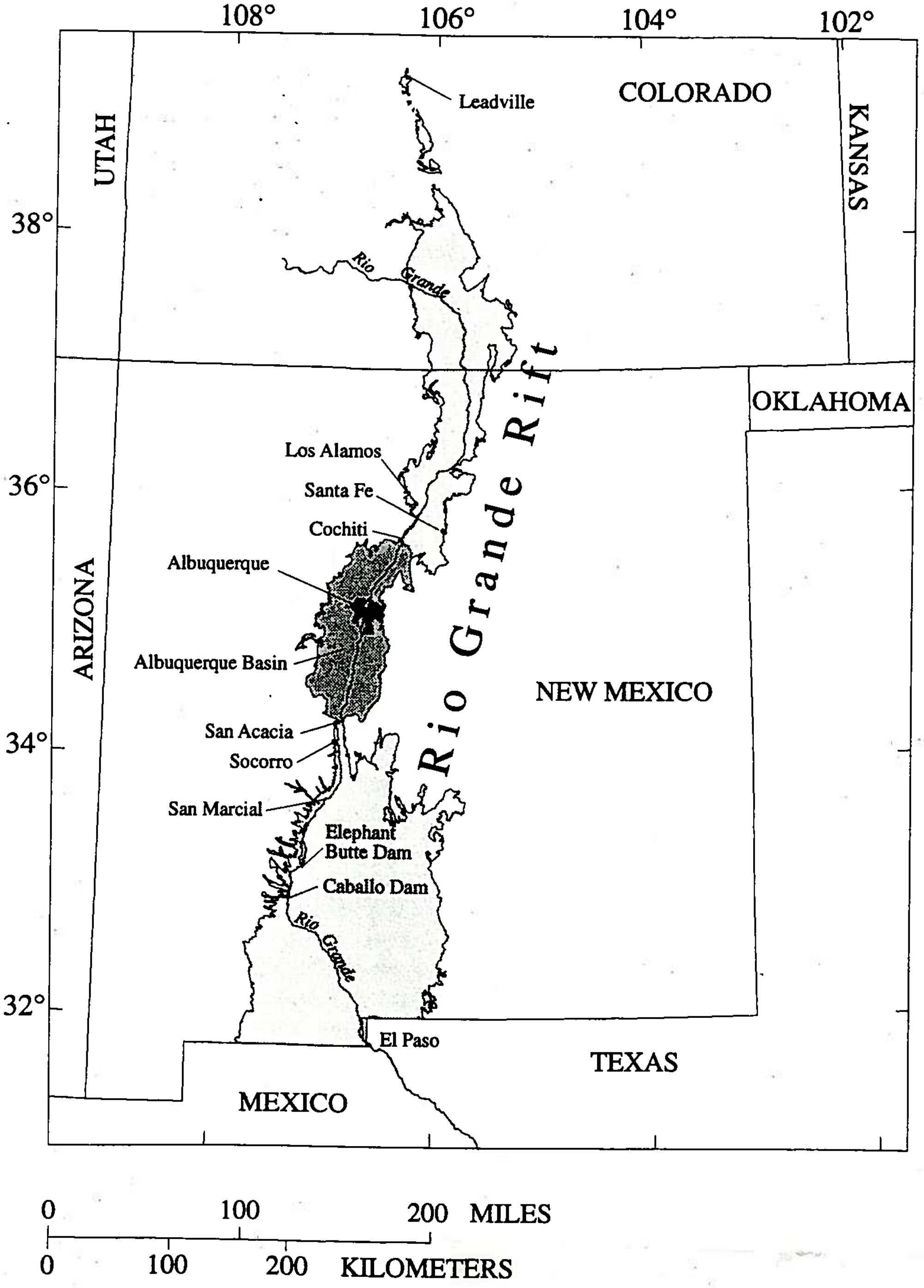


Figure 1. Location of the Middle Rio Grande Basin (MRGB) or Albuquerque Basin in central New Mexico. (From Tiedeman et al., 1998)

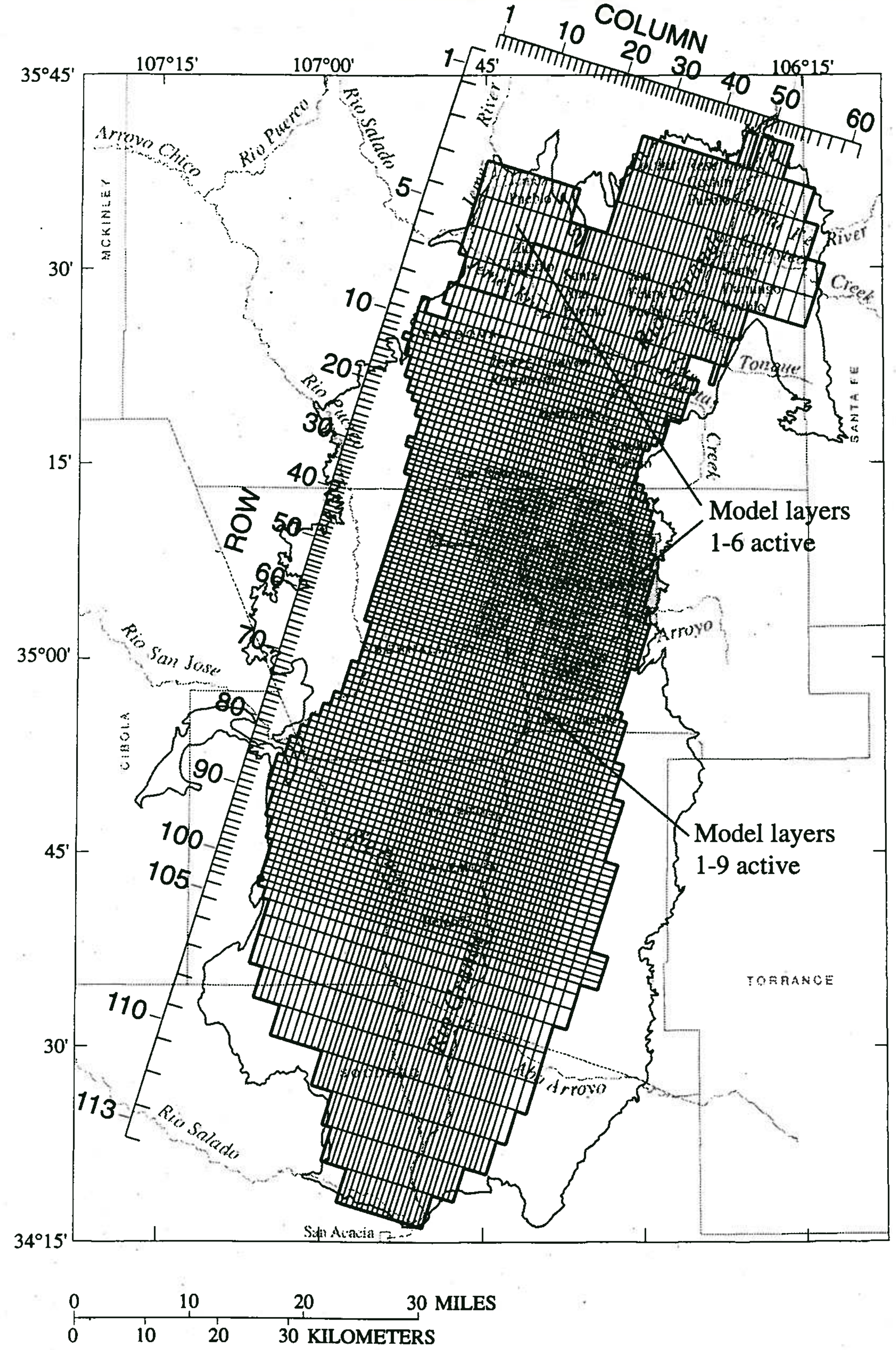


Figure 2. Plan view of the finite difference grid of the Tiedeman groundwater model and the OSE modified groundwater model. (From Tiedeman et al. 1998)

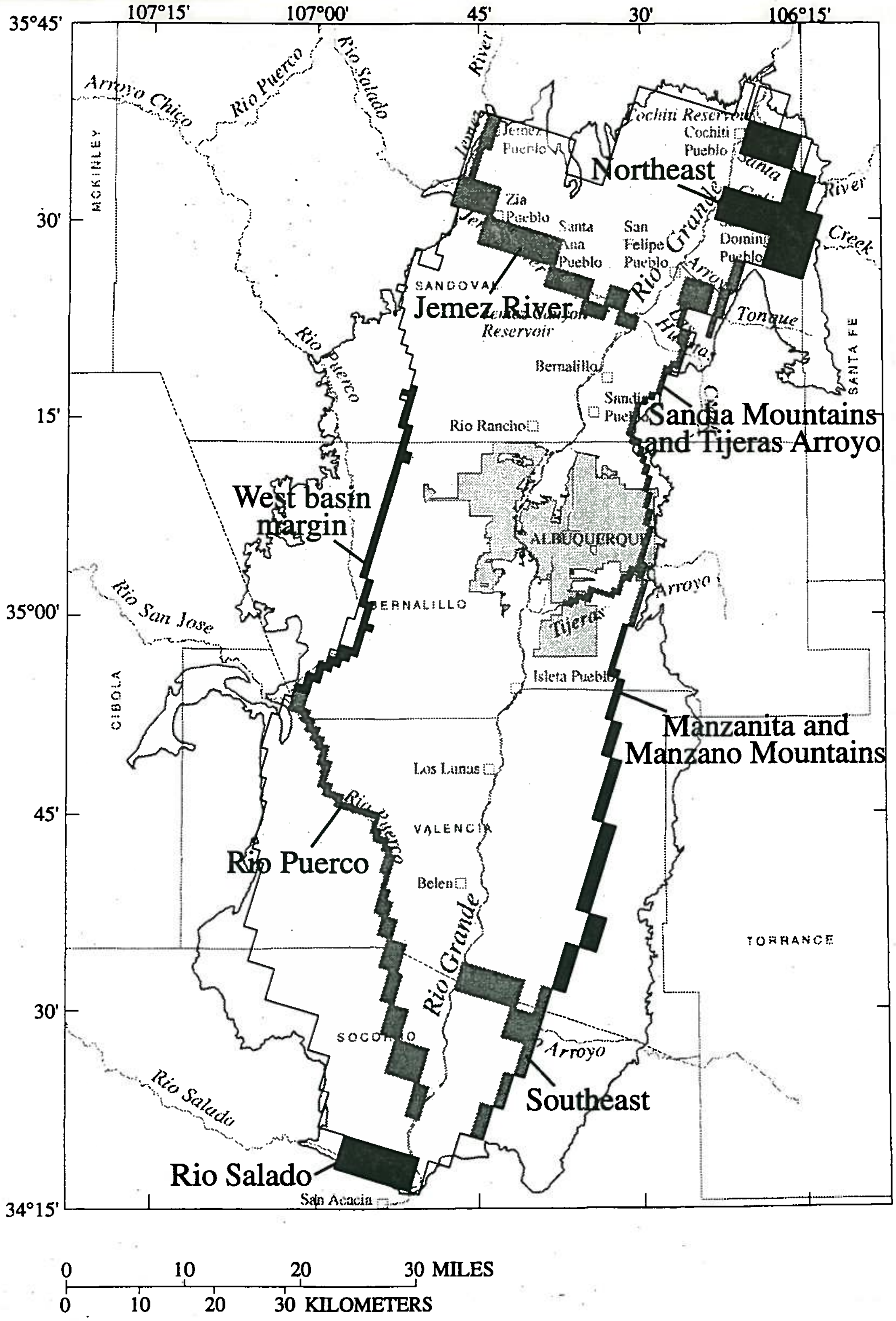


Figure 3. Locations of tributary and mountain-front recharge zones in the Tiedeman groundwater flow model. These correspond with recharge zones in the OSE modified groundwater model, except for the Jemez River which has been modified by the OSE, and to be simulated by a GHB boundary. (From Tiedeman et al., 1998)

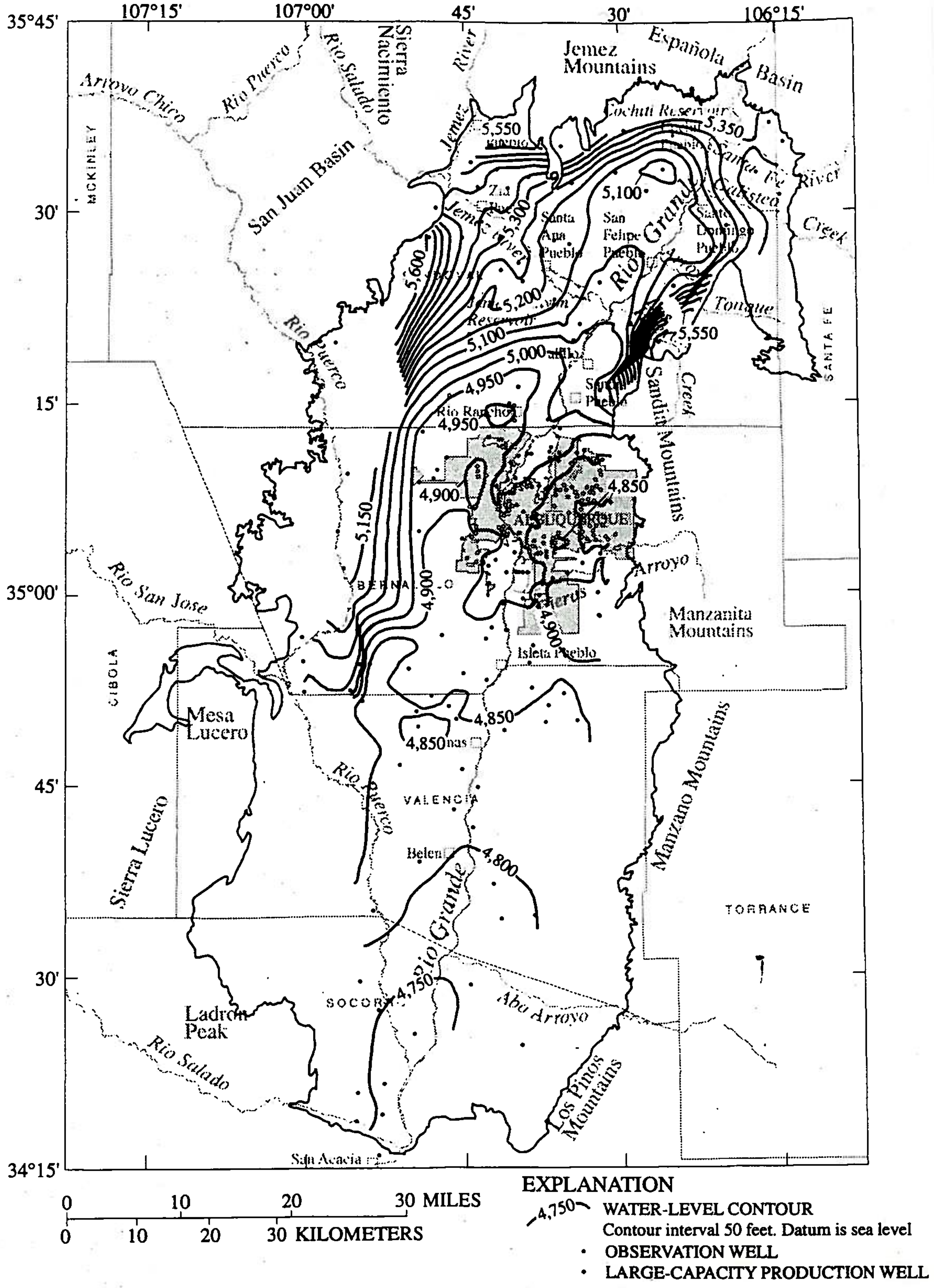


Figure 4. Contours of groundwater levels that represent winter 1994-1995 conditions in the Santa Fe Group aquifer group system in the Albuquerque Basin and locations of wells used to construct contours (from Tiedeman et al., 1998).

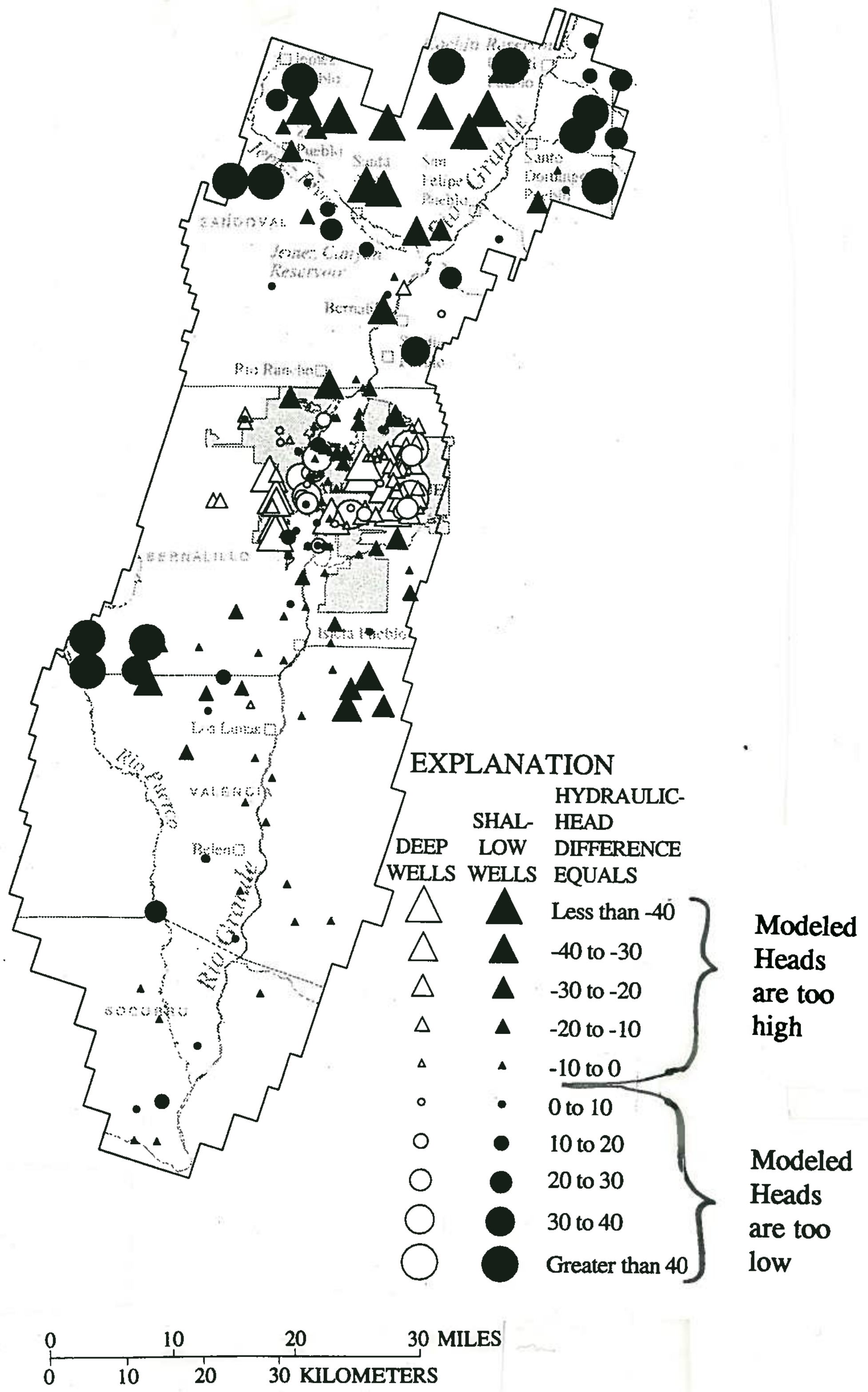


Figure 5 Tiedeman model differences between simulated and observed heads for 1994, Subsurface Configuration 6. Units: feet. (From Tiedeman et al., 1998).

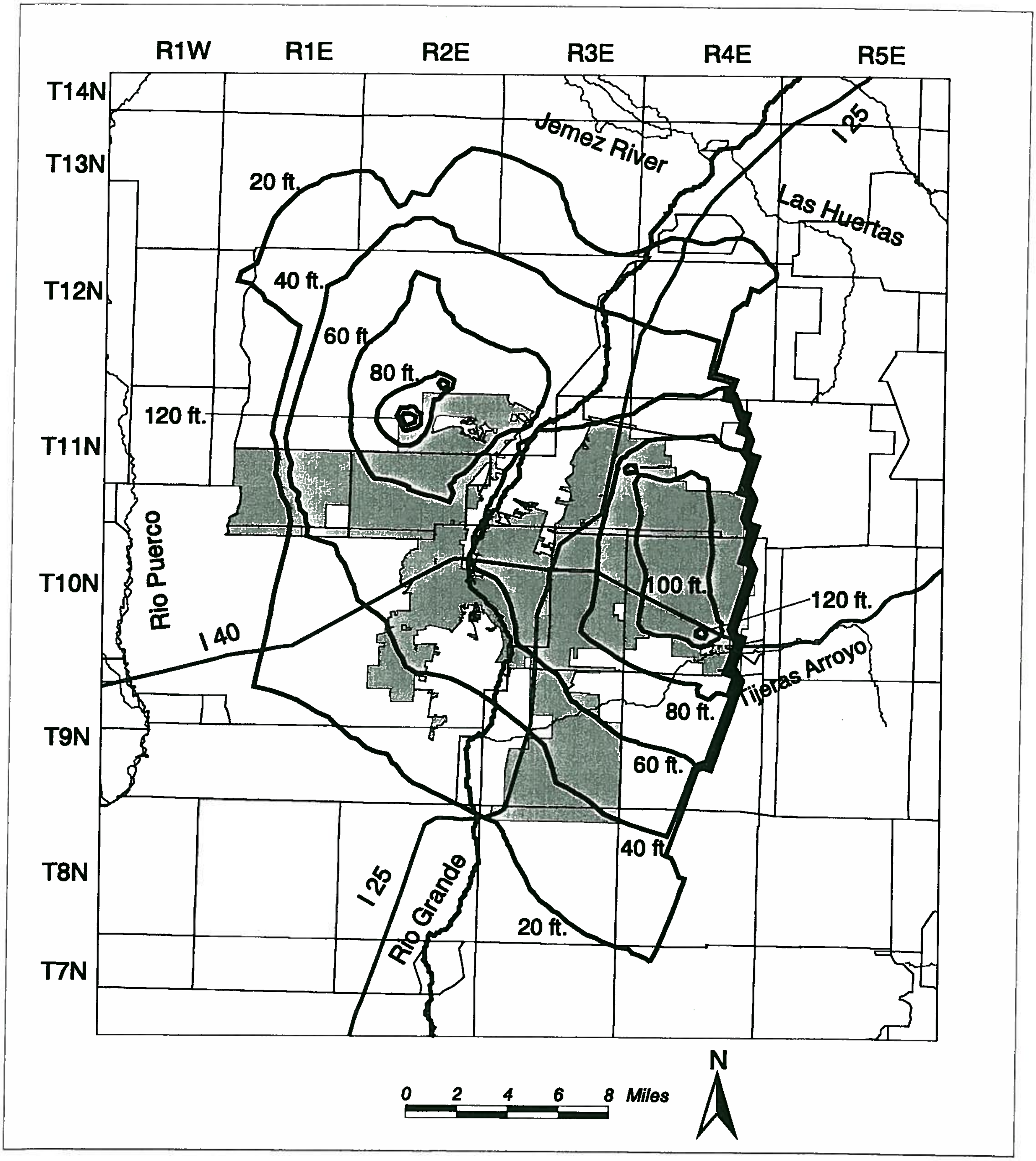


Figure 6
Model Calculated Drawdowns
2000 - 2040
Contour Interval 20ft.

- Drawdowns
- ▨ Albuquerque Municipality

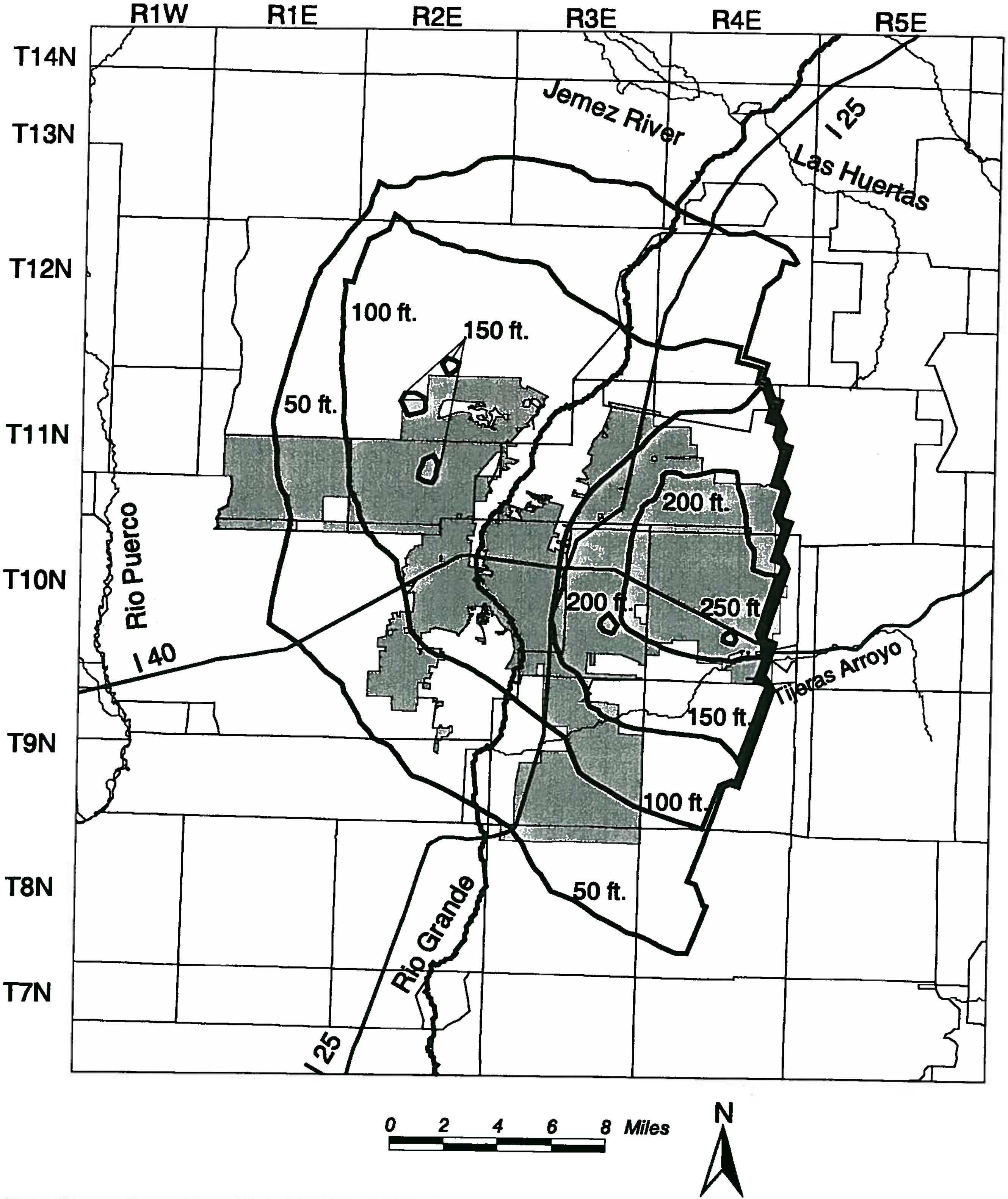


Figure 7
Model Calculated Drawdowns
1901 - 2040
Contour Interval 50ft.

Drawdowns
▨ **Albuquerque Municipality**

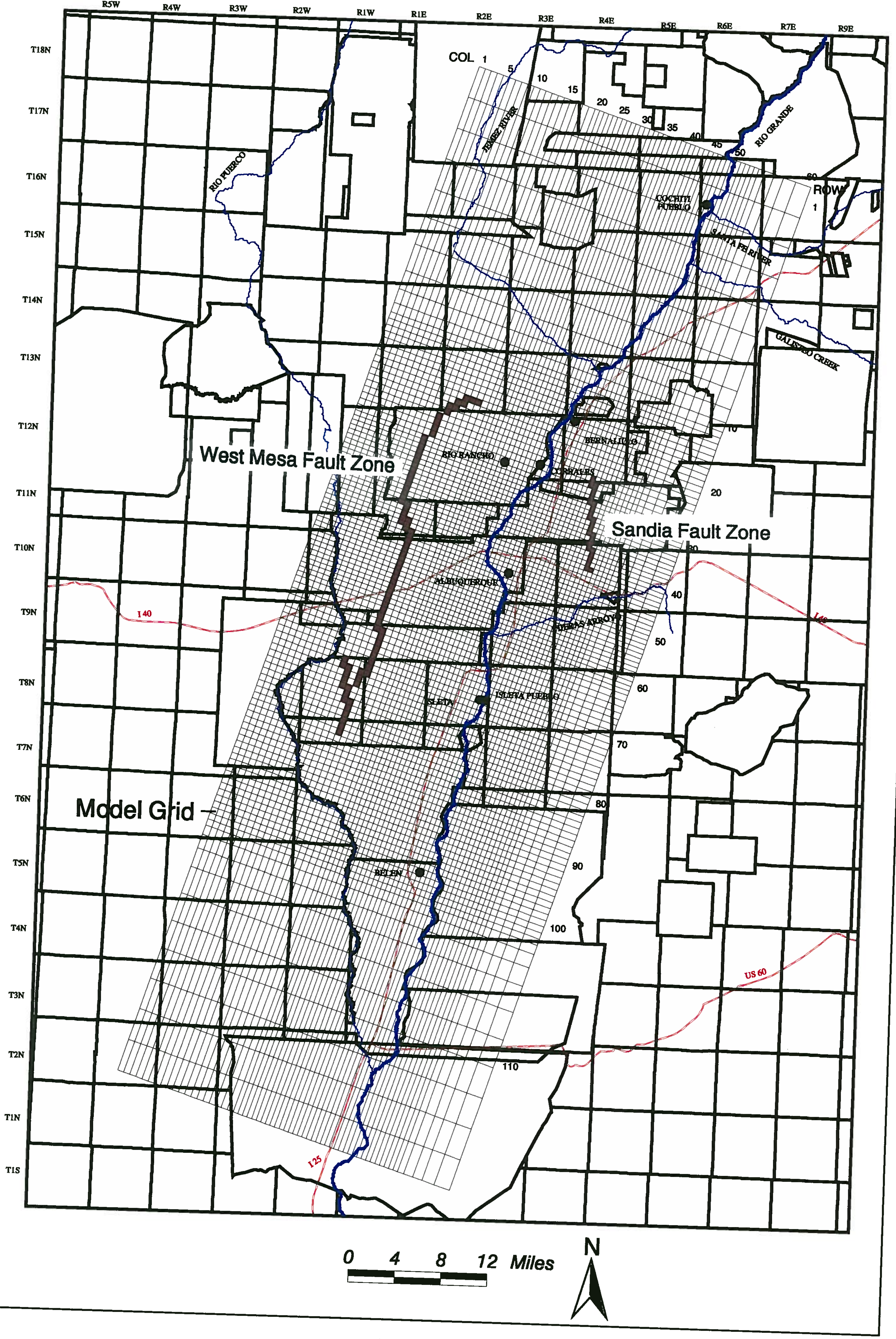


Figure 8

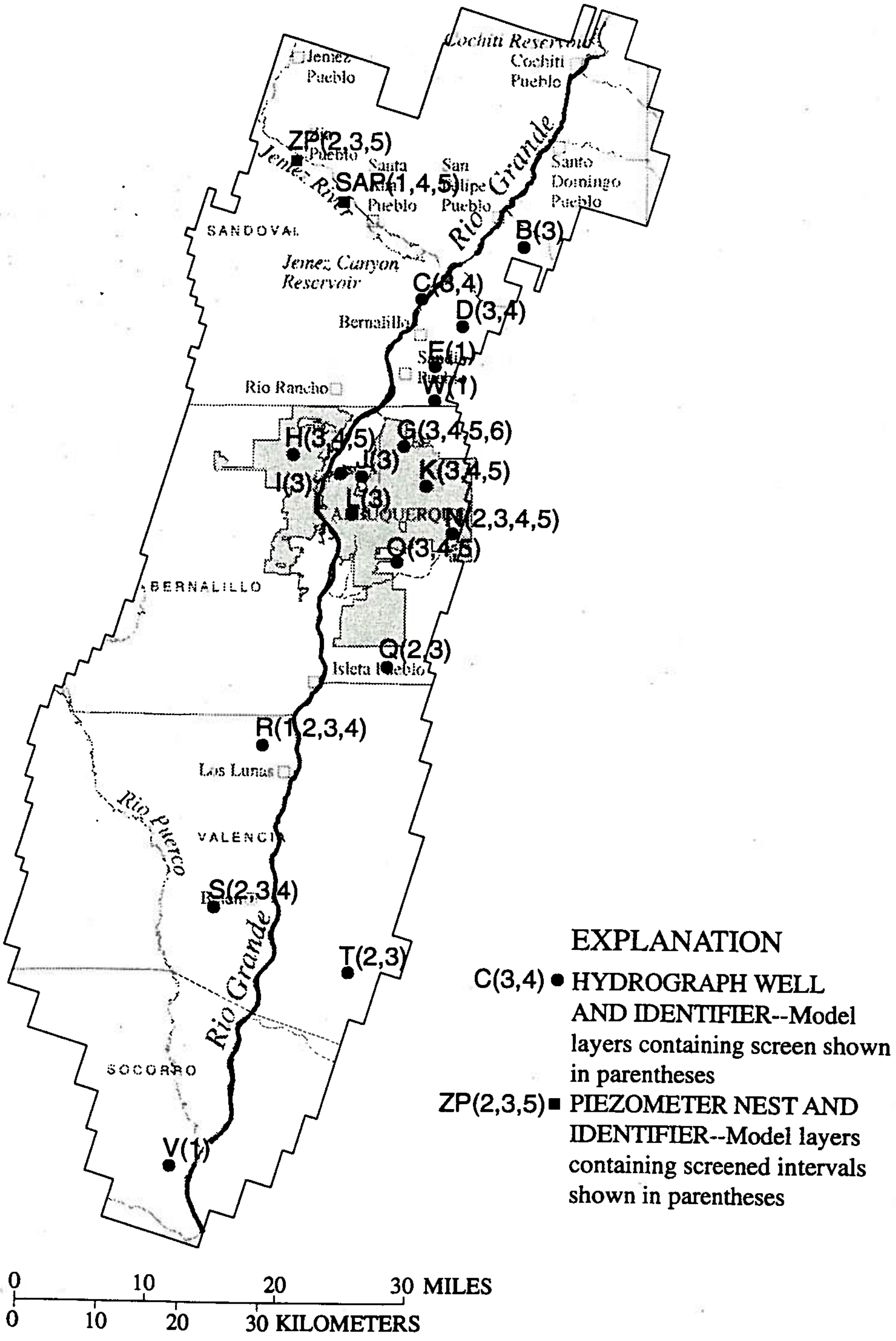
Location of Critical Fault Zones
Albuquerque Basin Model
OSE Modified

▨ Sandia Fault Zone and West Mesa Fault Zone

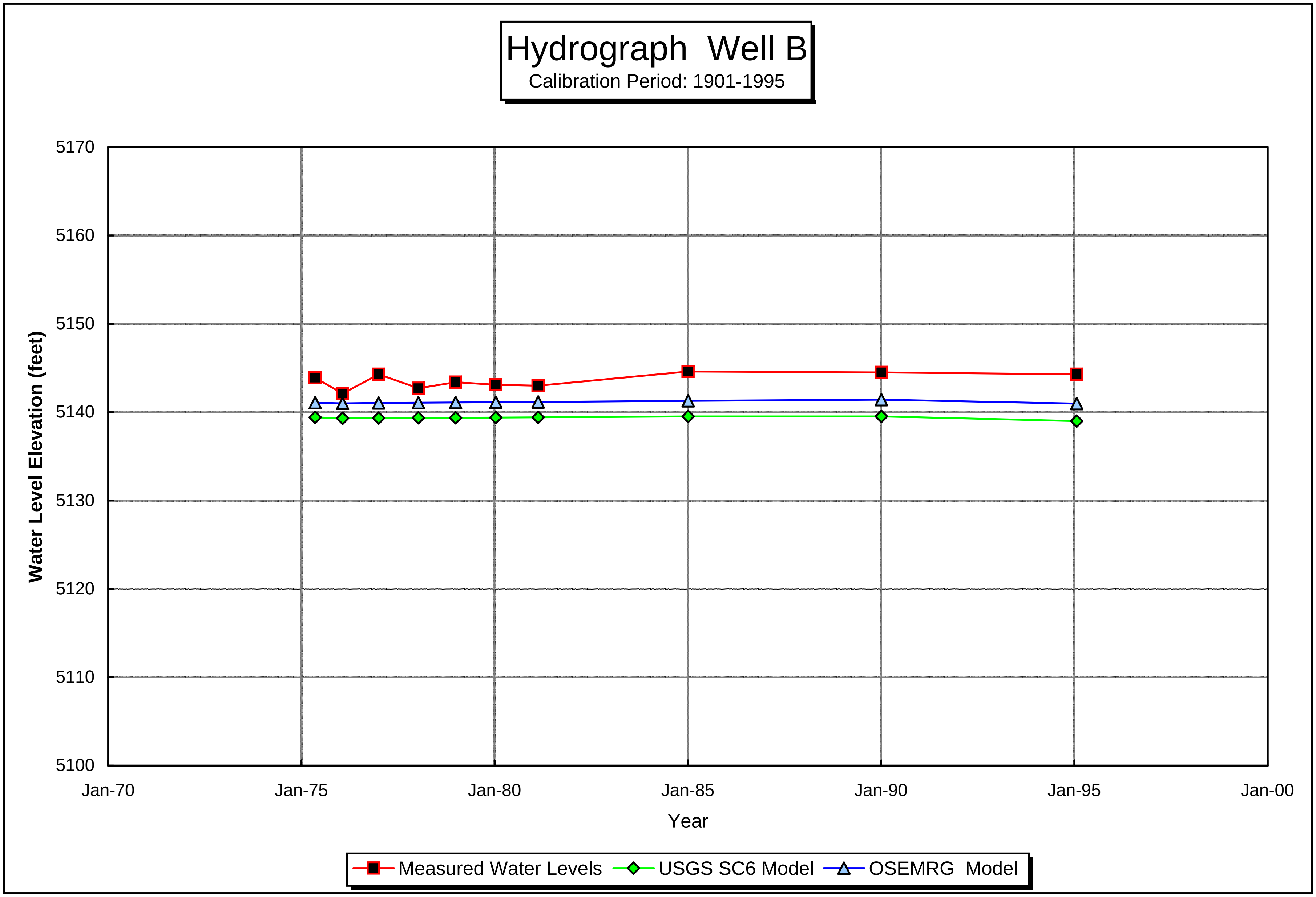
Appendix A

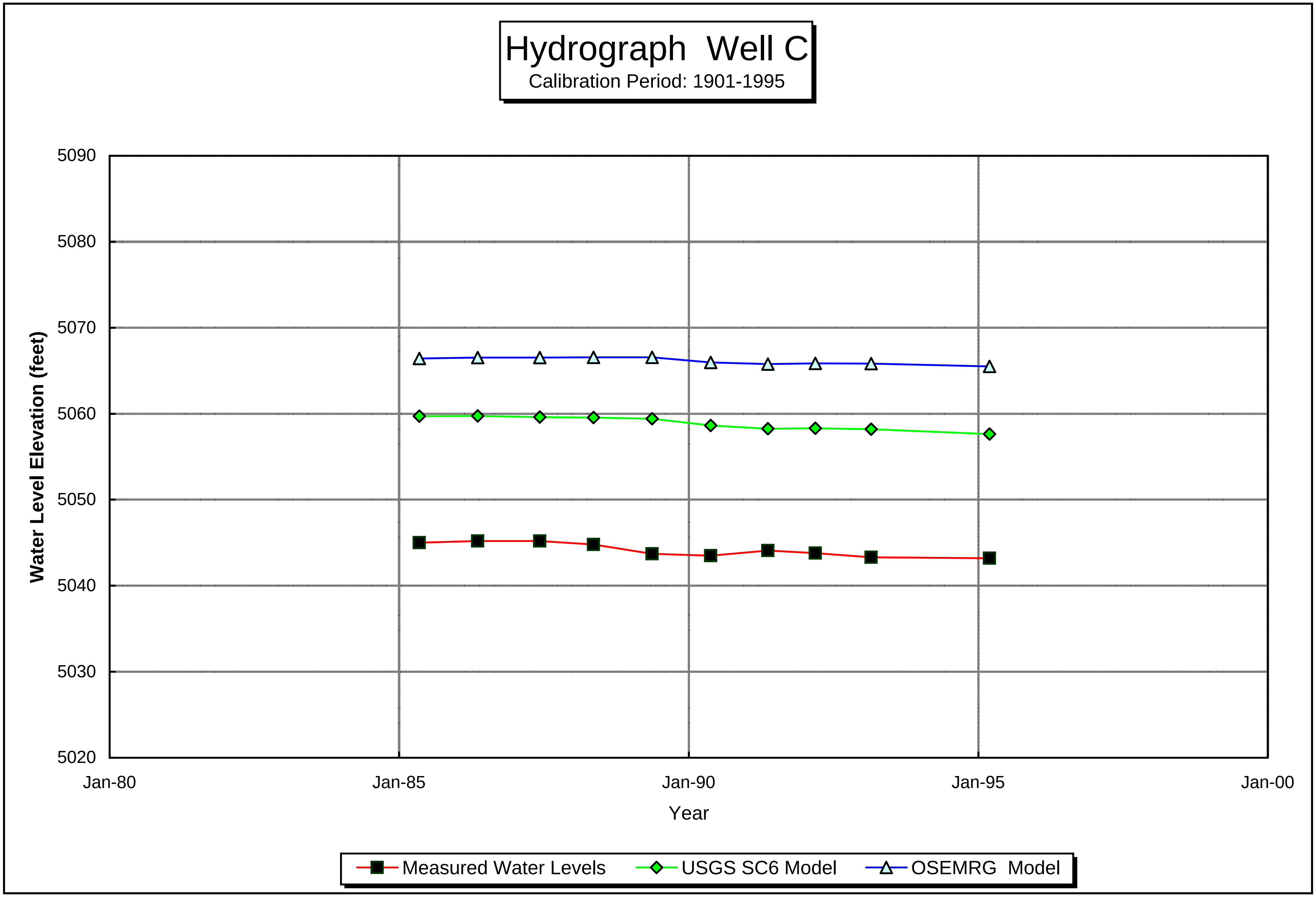
Observed and Model Simulated Hydrographs From the Albuquerque Basin

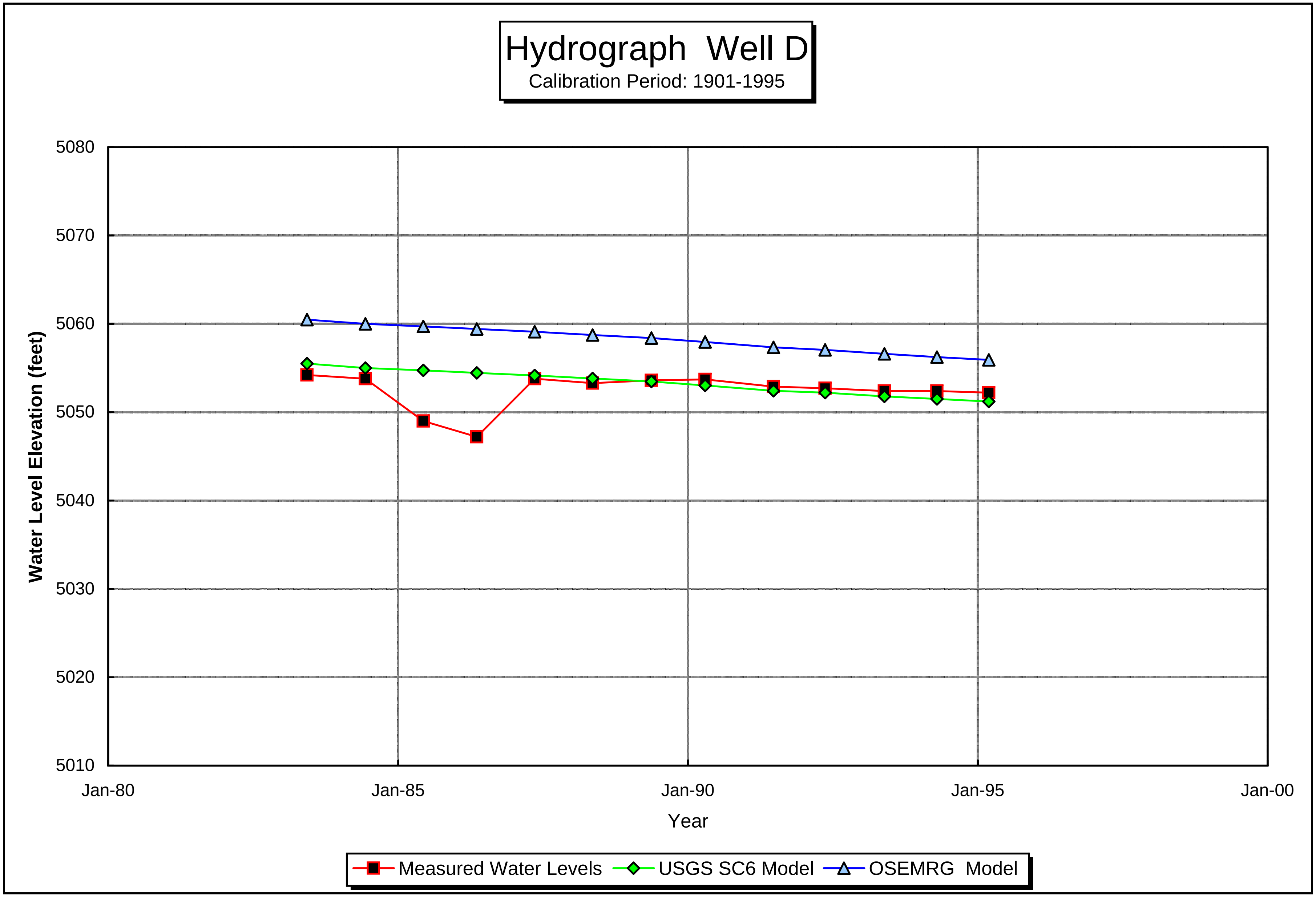
Observed water-level hydrographs from selected wells in the Albuquerque Basin are plotted with modeled water levels from the Original Tiedeman SC6 model and from the Modified OSEMRG model. All hydrographs from Tiedeman et al. 1998 from the Albuquerque area are included.

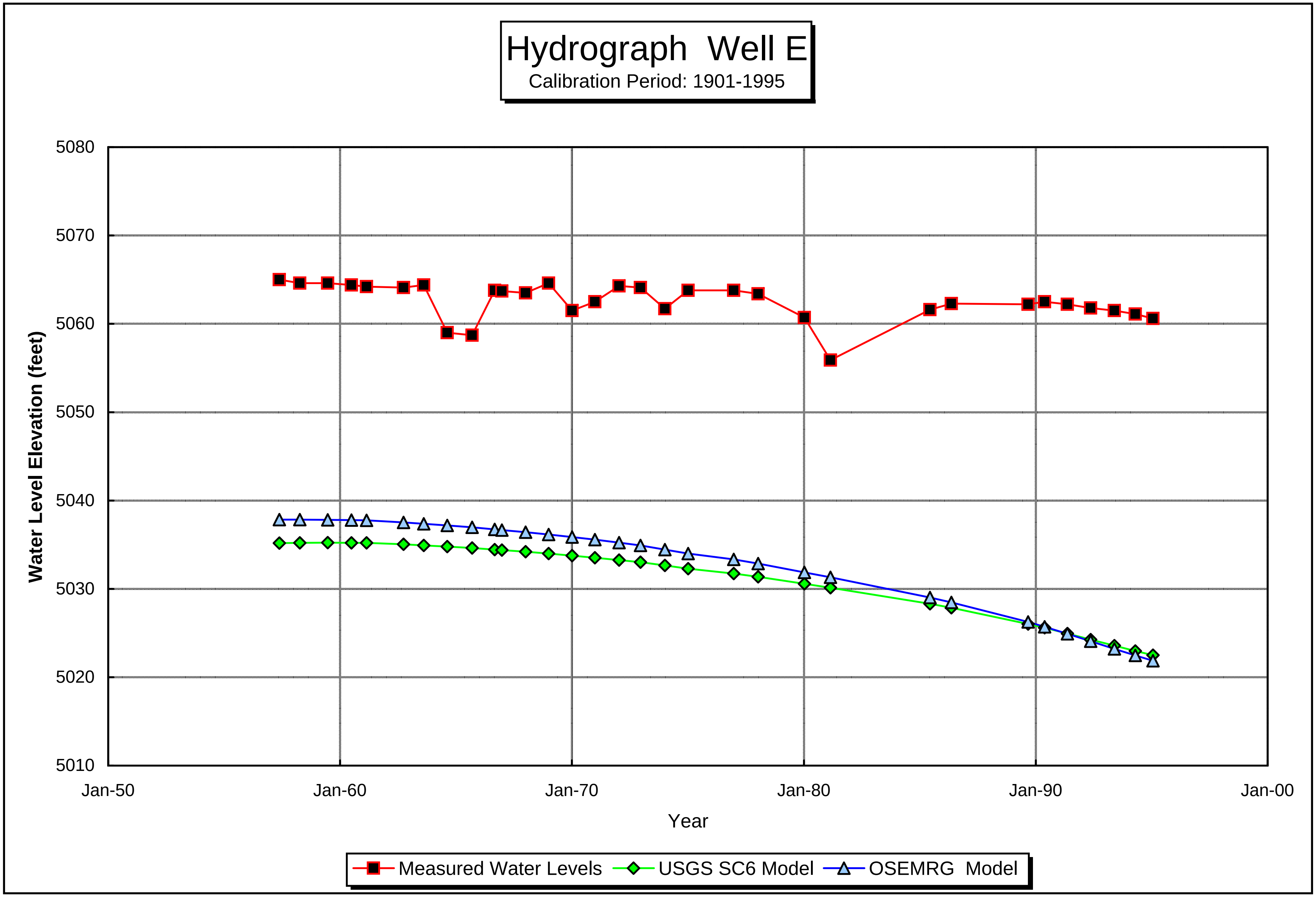


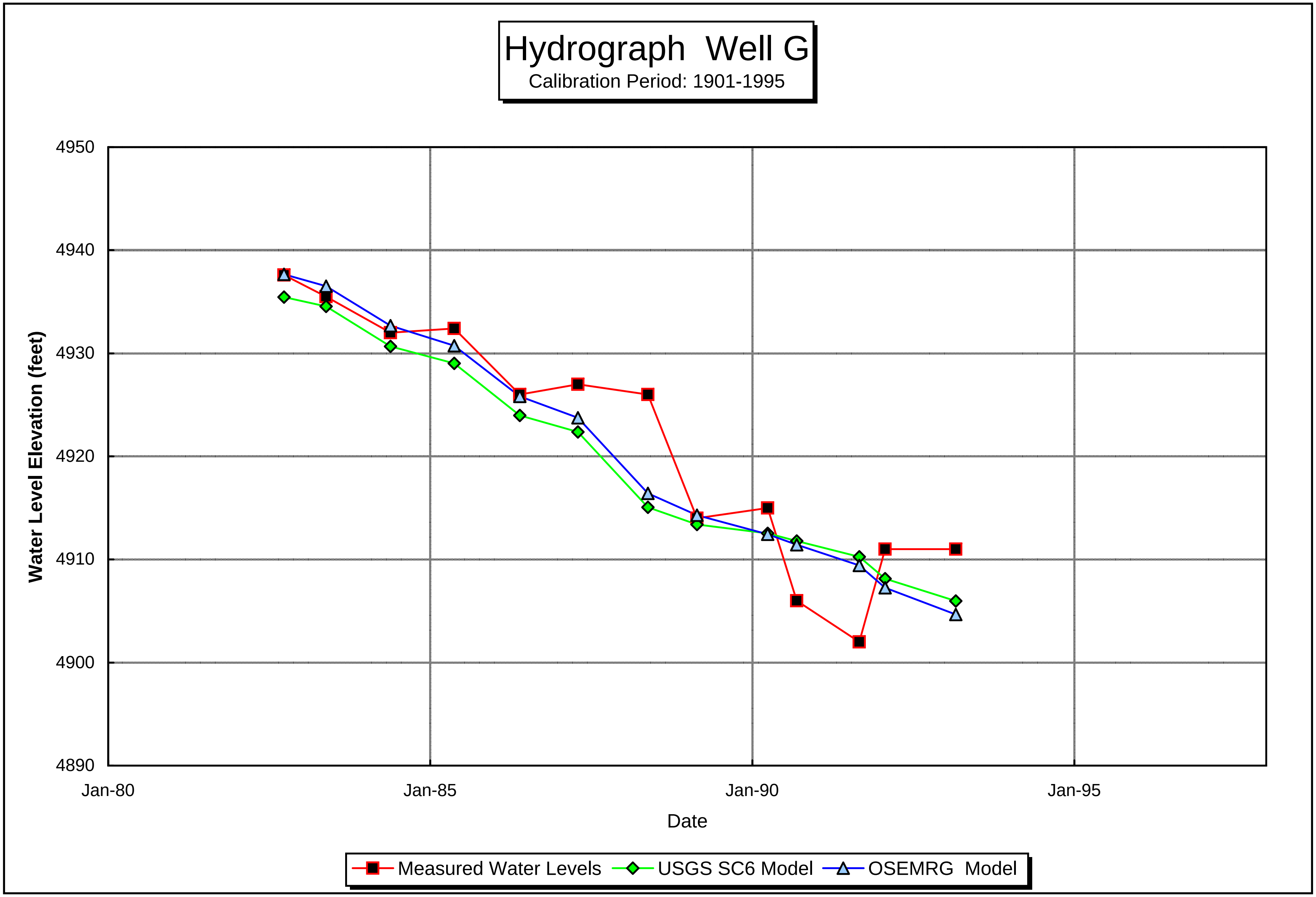
Location Map for hydrograph wells in the Albuquerque Basin. (Also includes the locations of piezometer nests near the Jemez River: ZP and SAP.) From Tiedeman et al. 1998.

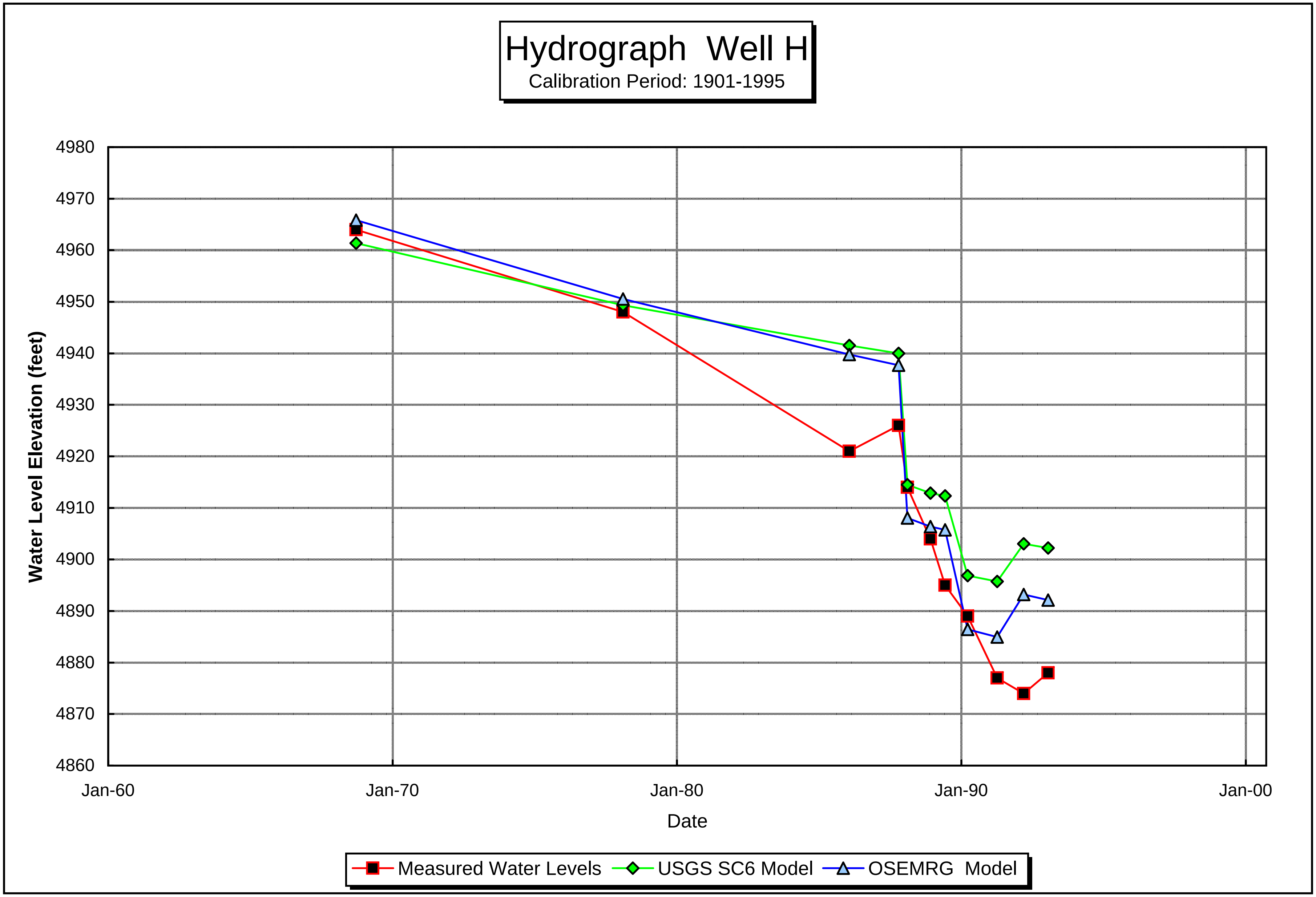

Hydrograph Well B
Calibration Period: 1901-1995
Water Level Elevation (feet)
5170
5160
5150
5140
5130
5120
5110
5100
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Year
Measured Water Levels
USGS SC6 Model
OSEMRG Model

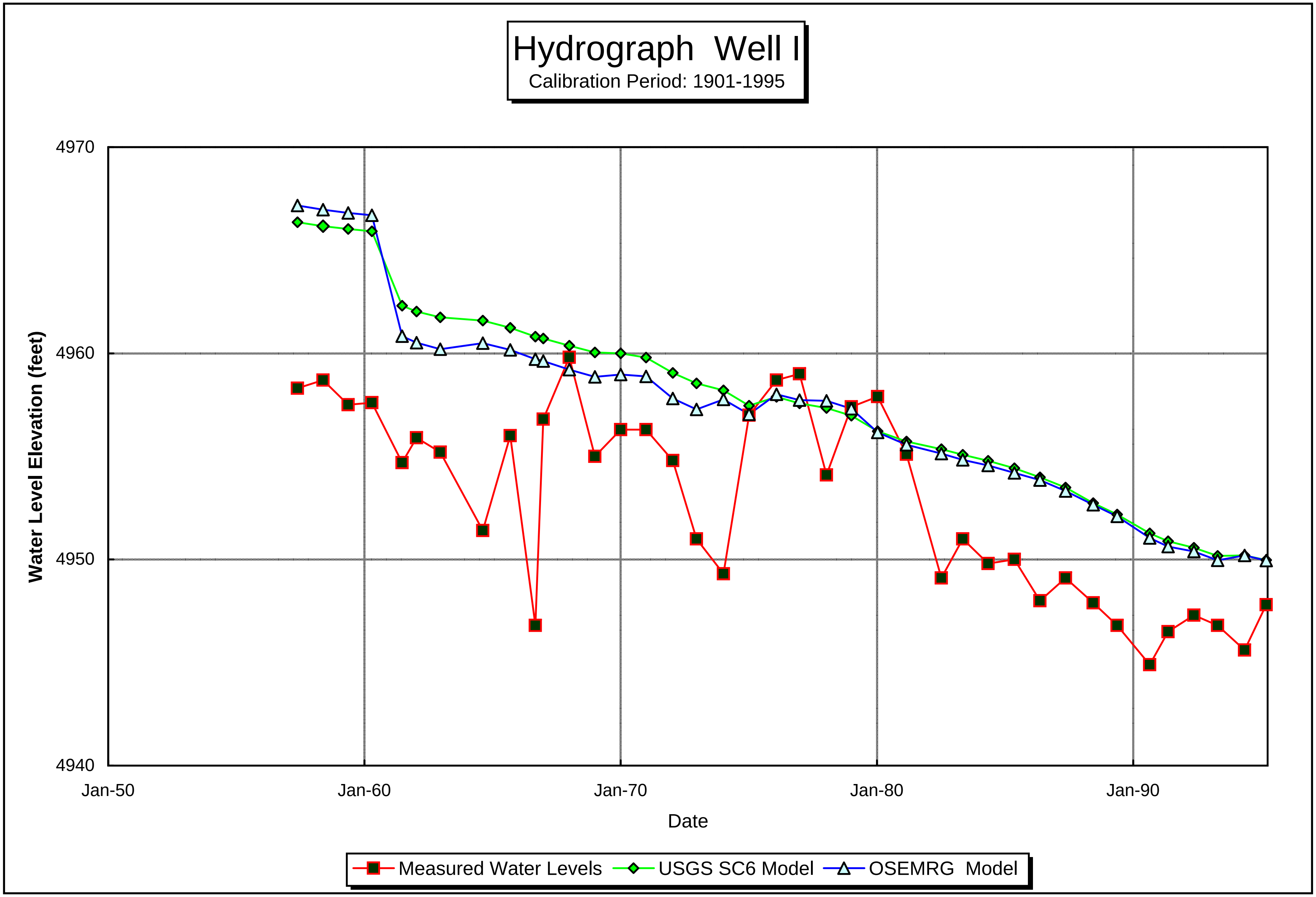

Hydrograph Well C
Calibration Period: 1901-1995
5090
5080
5070
5060
5050
5040
5030
5020
Water Level Elevation (feet)
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Year
Measured Water Levels
USGS SC6 Model
OSEMRG Model

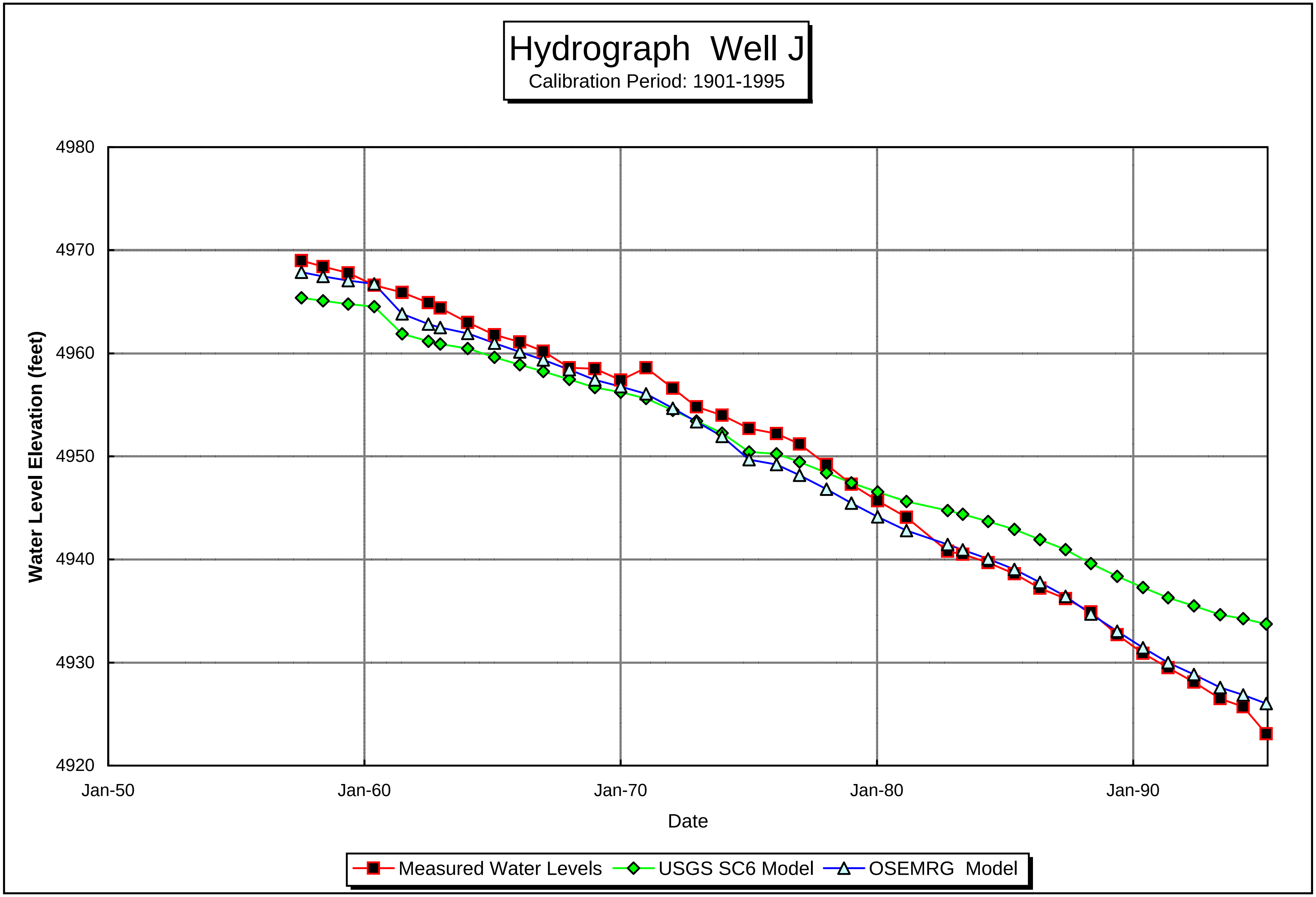

Hydrograph Well D
Calibration Period: 1901-1995
5080
5070
5060
5050
5040
5030
5020
5010
Water Level Elevation (feet)
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Year
Measured Water Levels
USGS SC6 Model
OSEMRG Model

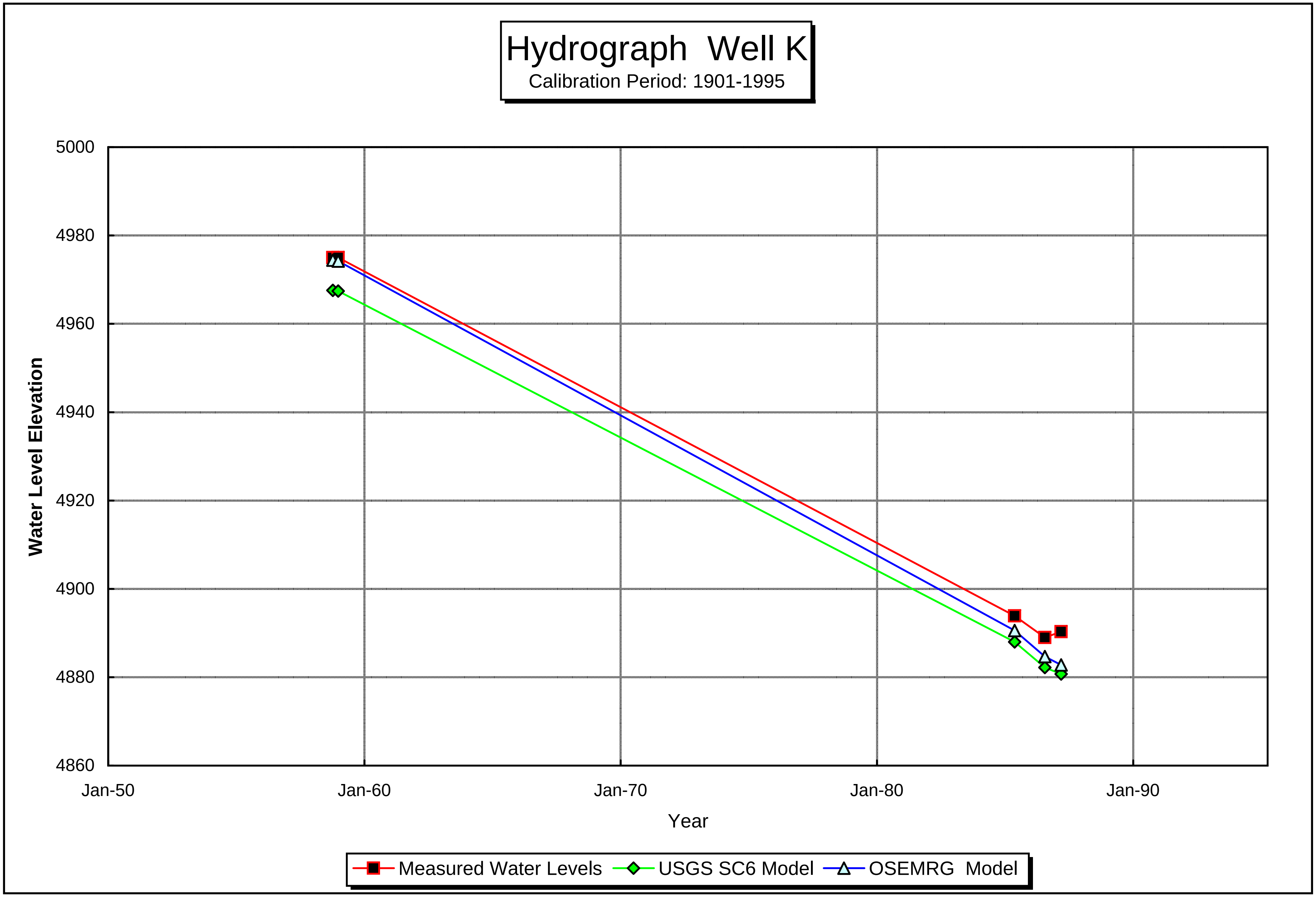

Hydrograph Well E
Calibration Period: 1901-1995
Water Level Elevation (feet)
5080
5070
5060
5050
5040
5030
5020
5010
Jan-50
Jan-60
Jan-70
Jan-80
Jan-90
Jan-00
Year
Measured Water Levels
USGS SC6 Model
OSEMRG Model

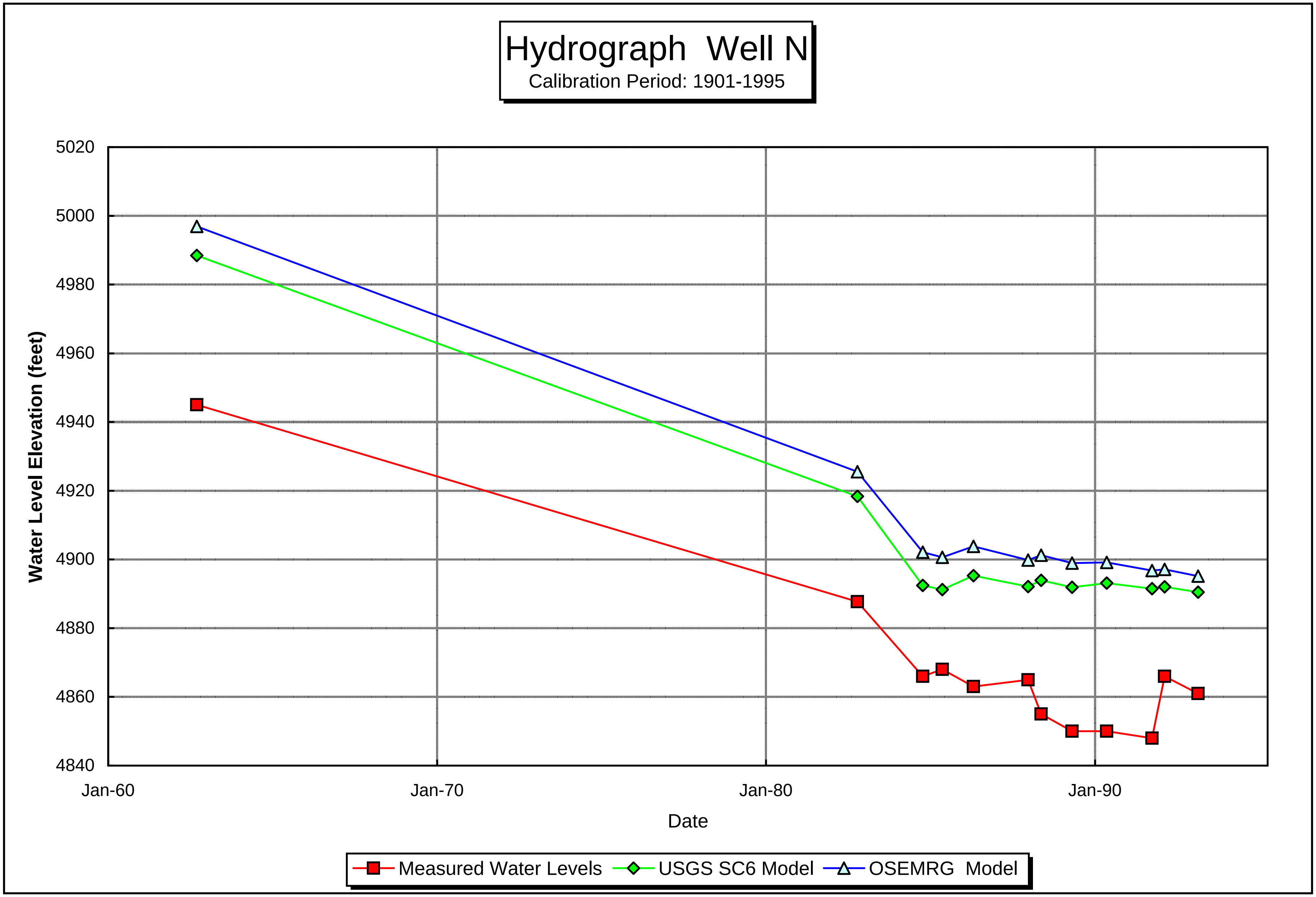

Hydrograph Well G
Calibration Period: 1901-1995
Water Level Elevation (feet)
4950
4940
4930
4920
4910
4900
4890
Jan-80
Jan-85
Jan-90
Jan-95
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model

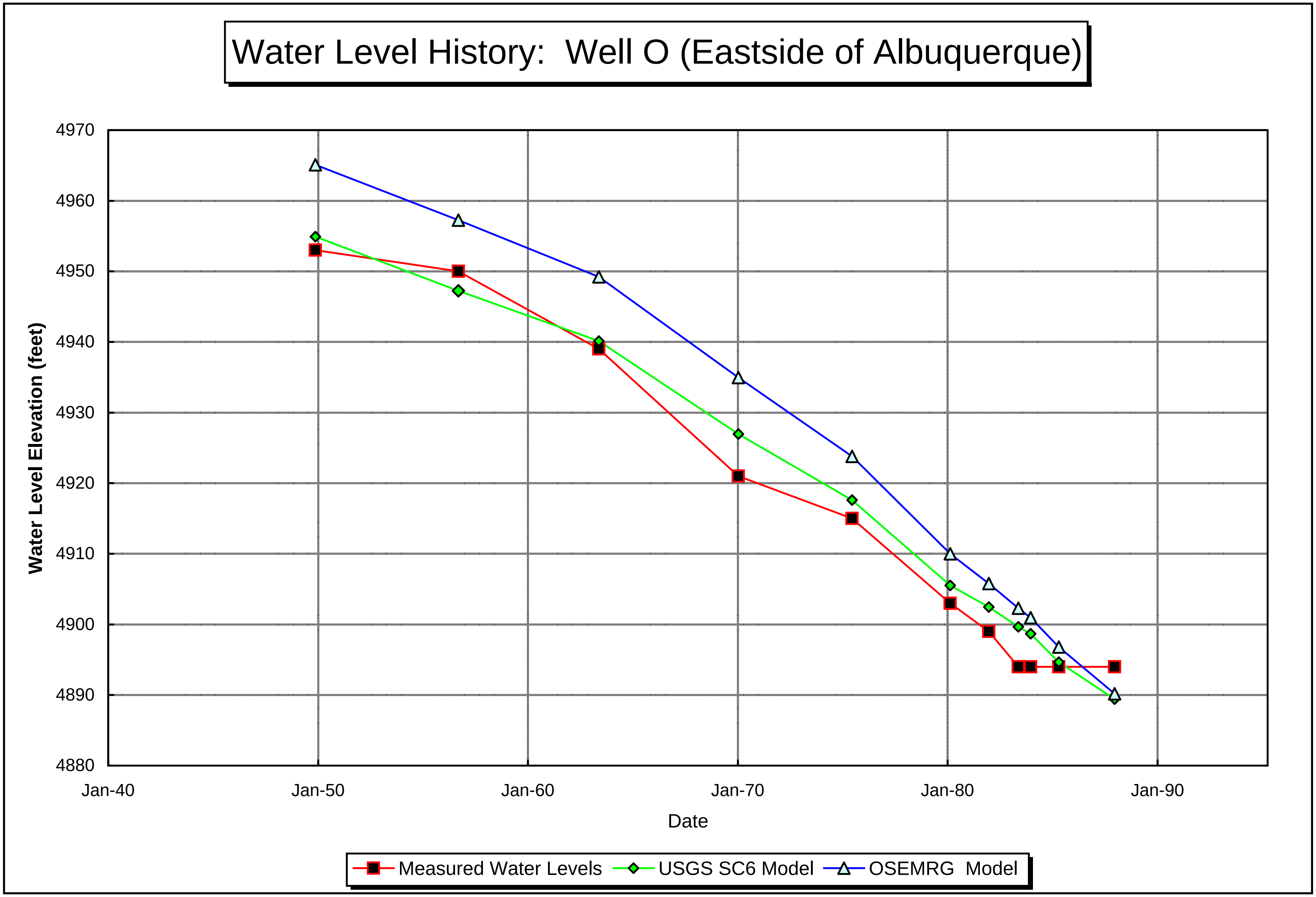

Hydrograph Well H
Calibration Period: 1901-1995
4980
4970
4960
4950
4940
4930
4920
4910
4900
4890
4880
4870
4860
Water Level Elevation (feet)
Jan-60
Jan-70
Jan-80
Jan-90
Jan-00
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model

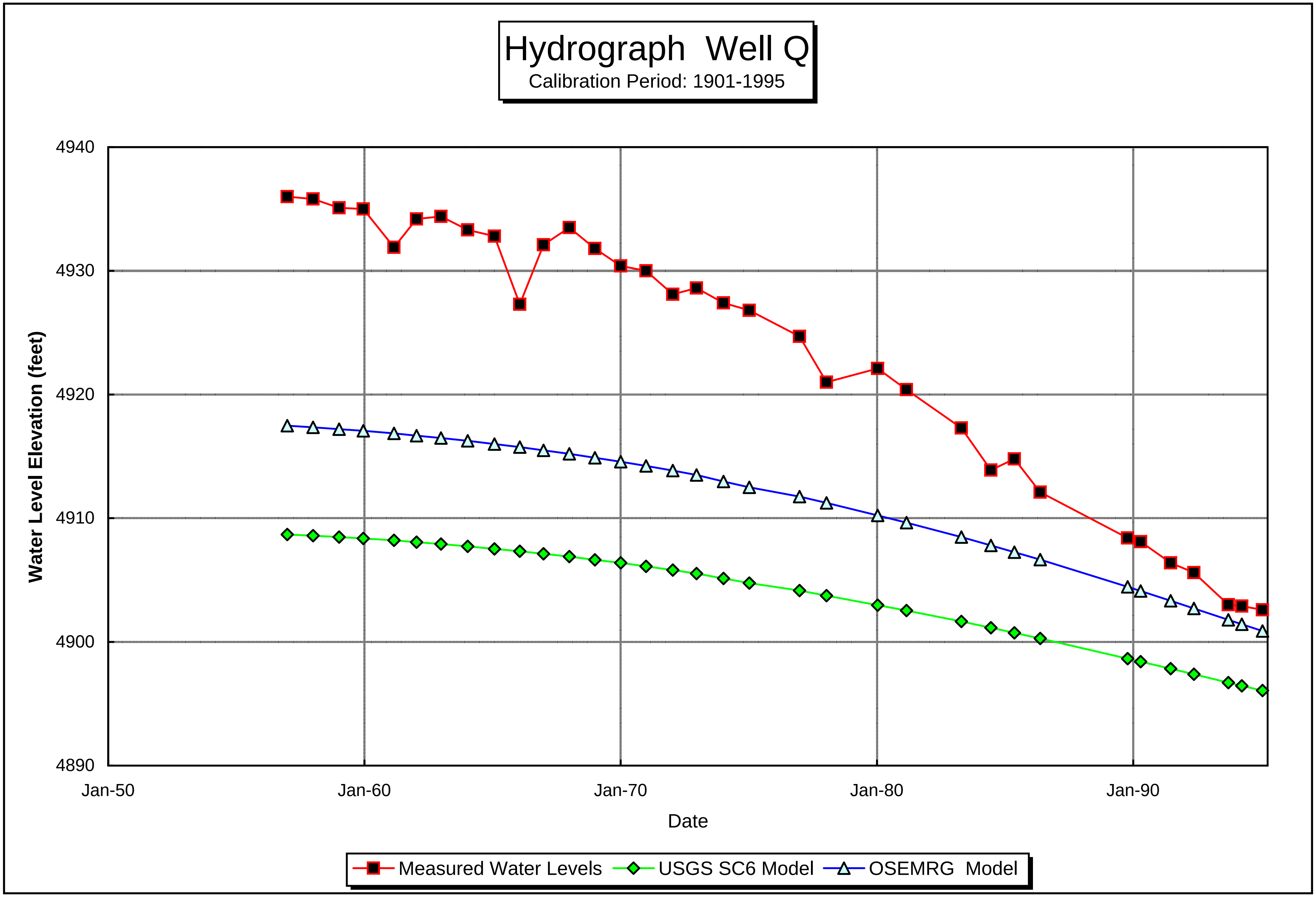

Hydrograph Well I
Calibration Period: 1901-1995
4970
4960
4950
4940
Water Level Elevation (feet)
Jan-50
Jan-60
Jan-70
Jan-80
Jan-90
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model

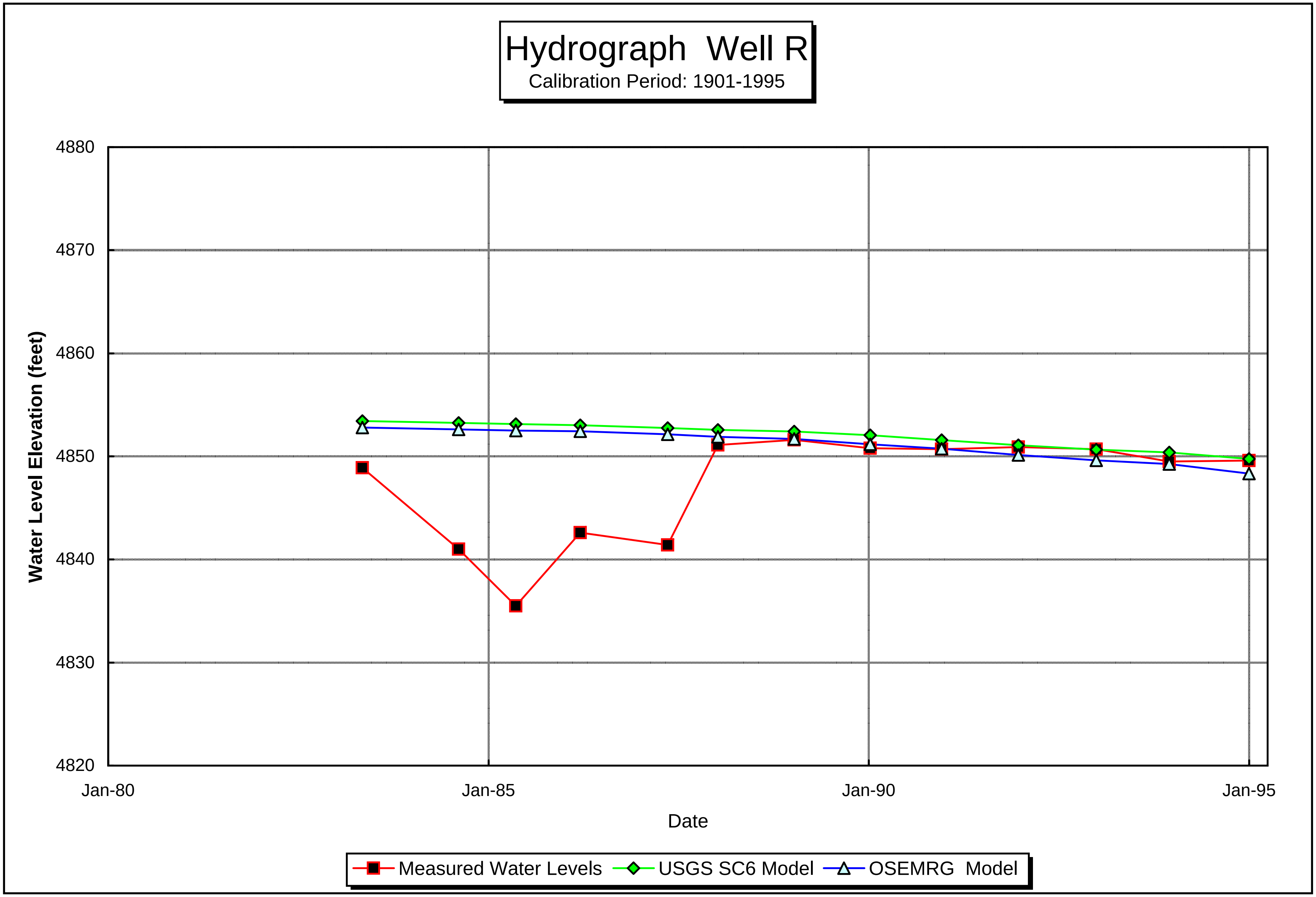

Hydrograph Well J
Calibration Period: 1901-1995
Water Level Elevation (feet)
4980
4970
4960
4950
4940
4930
4920
Jan-50
Jan-60
Jan-70
Jan-80
Jan-90
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model

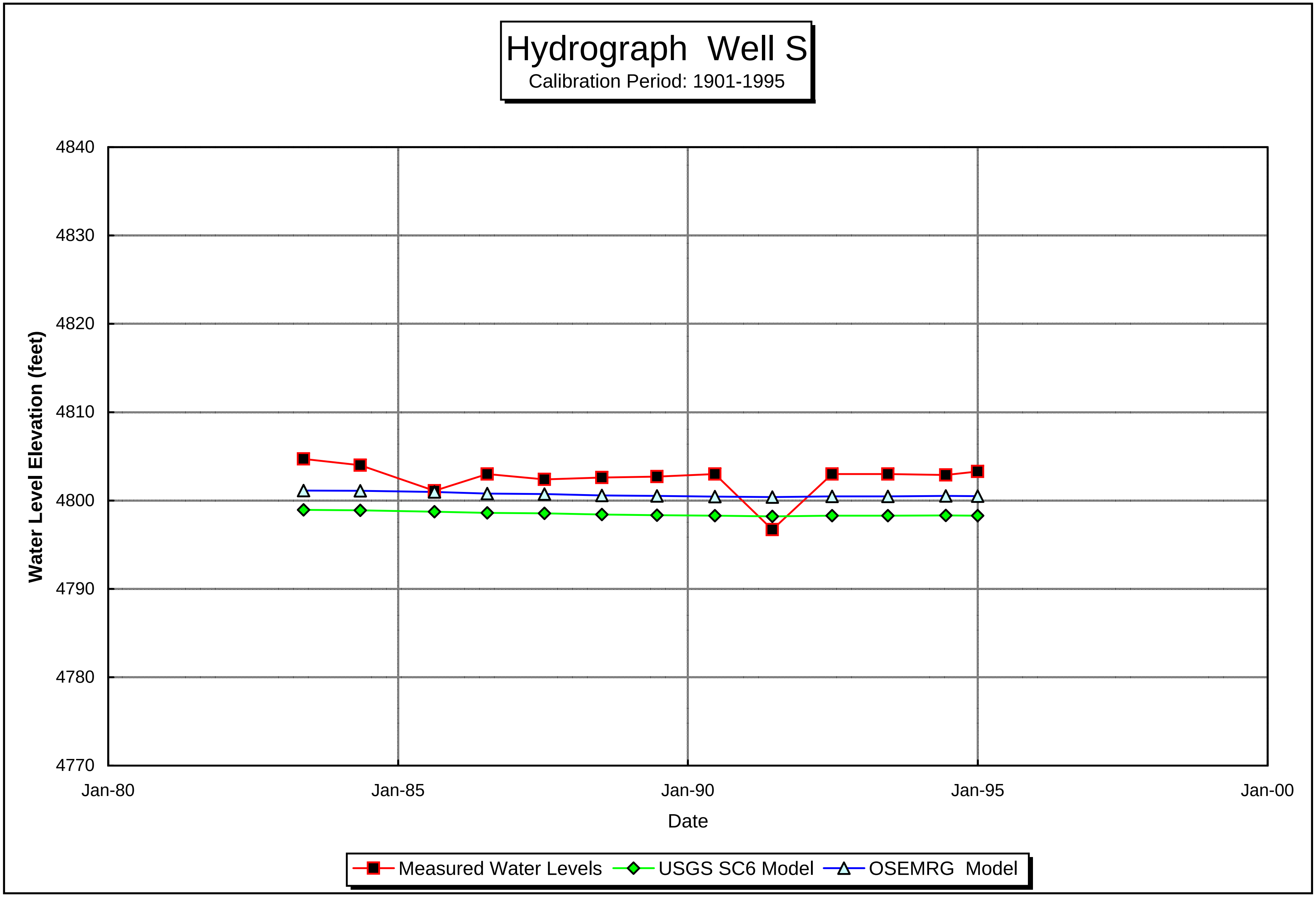

Hydrograph Well K
Calibration Period: 1901-1995
5000
4980
4960
4940
4920
4900
4880
4860
Water Level Elevation
Jan-50
Jan-60
Jan-70
Jan-80
Jan-90
Year
Measured Water Levels
USGS SC6 Model
OSEMRG Model


Hydrograph Well N
Calibration Period: 1901-1995
Water Level Elevation (feet)
5020
5000
4980
4960
4940
4920
4900
4880
4860
4840
Jan-60
Jan-70
Jan-80
Jan-90
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model


Water Level History: Well O (Eastside of Albuquerque)
Water Level Elevation (feet)
4970
4960
4950
4940
4930
4920
4910
4900
4890
4880
Jan-40
Jan-50
Jan-60
Jan-70
Jan-80
Jan-90
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model


Hydrograph Well Q
Calibration Period: 1901-1995
Water Level Elevation (feet)
4940
4930
4920
4910
4900
4890
Jan-50
Jan-60
Jan-70
Jan-80
Jan-90
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model


Hydrograph Well R
Calibration Period: 1901-1995
Water Level Elevation (feet)
4880
4870
4860
4850
4840
4830
4820
Jan-80
Jan-85
Jan-90
Jan-95
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model


Hydrograph Well S
Calibration Period: 1901-1995
4840
4830
4820
4810
4800
4790
4780
4770
Water Level Elevation (feet)
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Date
Measured Water Levels
USGS SC6 Model
OSEMRG Model

Appendix B

List of cells located on or beyond major fault zones

Cells located on or beyond major fault zones, for which model prediction of stream depletions may not be accurate, and for which Glover-Balmer, or other modified calculations are recommended instead:

West Side of Model

Row	Columns	Row	Columns
17	3-15	52	8-15
18	3-16	53	8-15
19	4-18	54	8-15
20	4-16	55	8-15
21	5-15	56	8-15
22	6-14	57	8-15
23	6-14	58	8-15
24	7-13	59	8-15
25	7-13	60	8-15
26	7-13	61	8-15
27	6-12	62	8-15
28	6-12	63	9-15
29	7-12	64	9-15
30	7-12	65	9-15
31	7-12	66	9-16
32	7-12	67	9-16
33	7-12	68	9-16
34	8-12	69	8-16
35	8-12	70	8-16
36	8-12	71	8-16
37	8-12	72	8-16
38	8-12	73	8-16
39	8-12	74	7-15
40	8-12	75	7-15
41	8-13	76	6-14
42	8-13	77	6-14
43	8-13	78	5-15
44	8-14	79	5-15
45	8-14	80	4-15
46	8-15	81	4-15
47	8-15	82	3-15
48	8-15	83	3-15
49	8-15	84	3-14
50	8-15	85	2-13
51	8-15		

East Side of Model:

Row	Columns
24	45-46
25	45-47
26	46-48
27	46-49
28	46-49
29	47-50
30	47-50
31	47-50
32	48-51
33	48-51
34	48-51
35	49-52
36	49-52
37	49-52
38	50-53
39	50-53
40	50-53
41	50-53