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COUNTY OF INYO
WATER DEPARTMENT

DEPTH TO GROUNDWATER BENEATH VEGETATION REINVENTORY PARCELS

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INTRODUCTION

To determine the relationship between vegetation conditions and shallow groundwater levels, it is desirable to have collocated measurements of vegetation conditions and depth to groundwater (DTW). In the Owens Valley, copious data exist for both vegetation conditions and DTW, but because they are generally not collocated, DTW measurements from shallow monitoring wells must be used to estimate DTW at areas where vegetation conditions have been measured. Owens Valley vegetation conditions in selected vegetation parcels have been monitored for the years 1984-1987 and 1991-1999 (Inyo County Water Dept., 1999). Conditions during 1984-1987 were measured by the Los Angeles Department of Water and Power (LADWP) and represent the baseline vegetation condition to which current conditions are compared. Conditions during 1991-1999 were measured by the Inyo County Water Department (ICWD) as part of an ongoing program of annual reinventory of vegetation conditions in a subset of the parcels inventoried by LADWP. In support of ICWD's vegetation reinventory program, DTW maps have been developed by interpolating observations of water levels in shallow wells (Zdon and Jackson, 1991; Zdon, 1992; Puskar and Jackson, 1994; Jackson, 1994; Jackson, 1996).

As an alternative to interpolation, one could rely on the hydrograph of single monitoring wells to represent DTW beneath nearby vegetation parcels. This strategy arbitrarily uses partial information (a single well, rather then a weighted average of all nearby wells), and lacks a quantitative scheme for assessing uncertainty of the estimate within the parcel.

During the course of these previous DTW mapping efforts, several methodological questions have arisen, including: (1) what are the geostatistical properties of the data used to develop DTW maps, (2) how should information from dry wells be incorporated into DTW estimates, (3) should the primary data set of shallow well observations be supplemented with surface water data, and (4) what is the uncertainty of the estimated DTW beneath vegetation parcels? This report addresses these methodological questions, and presents hydrographs for the mean April water levels beneath 138 vegetation reinventory parcels.

METHODS

Data. This report is based on data collected by LADWP from their monitoring well network. LADWP periodically measures DTW in monitoring wells throughout the Owens Valley, and a complete digital set of these data was transmitted to ICWD in November, 1999 (E. Coufal, written communication). The data consist of LADWP's monthly well reports, which contain DTW, water table elevations (WTE), well reference point (RP) elevations, land surface elevations, and dry-well indicators. The data exist for intermittent months for years 1971-1999. LADWP also provided all total-depth information for monitoring wells from their database. LADWP's total-depth information was supplemented with well soundings conducted by ICWD (data on file, ICWD). The monthly well reports were imported into a Microsoft Access database and merged with the UTM coordinates (zone 11, NAD 27) of the wells (McGhie, 1997). For wet wells, DTW was computed as land surface elevation minus water table elevation. For dry wells, because the water table elevation was not explicitly in the raw data files, depth to the bottom of the well was computed as depth from RP minus RP elevation plus ground surface elevation.

Each well was examined to determine if it should be used for estimation of DTW. The criteria used for this determination were:

1. Any well less than 40 ft deep was considered a candidate for DTW mapping.
2. If a well was deeper than 40 ft, but nearby lithologic logs indicate that it did not penetrate any significant confining layers, it was considered useful for DTW mapping.

If the above two criteria were met, data were extracted from the data base at a resolution of 0.1 ft for April of each year 1985-1999, with each record consisting of UTM easting, UTM northing, April WTE (feet msl), April DTW (feet below land surface), and station ID. Dry wells were flagged and exported as separate data sets, with each record consisting of UTM easting, UTM northing, elevation of the bottom of well (feet msl), depth of the bottom of well below land surface (feet), and station ID. A listing of wells deemed suitable for DTW mapping is given in Appendix I.

Several sources of error are present in the monthly well reads. Wells reads made by e-tape and RP elevations generally are given with a resolution of 0.01 ft. It is unknown how accurately the RP's were surveyed with respect to mean sea level, but it should be noted that the differential nature of DTW measurements means that only the error in the e-tape measurement is imparted to the DTW measurement. The land surface corrections used to determine land surface elevation from RP elevation are accurate to 0.1 ft. WTE mapping would require an evaluation of the absolute accuracy of the RP elevations in relation to a digital elevation model (DEM). For wells deemed suitable for DTW mapping, any water level measurement made during the month of April was used. DTW mapping procedures implicitly assume that all measurements were made simultaneously; therefore, there is some error due to using measurements spanning an entire month. Examination of well hydrographs suggests that this error may be as much as a few tenths of a foot. Well locations were taken from LADWP global positioning system measurements (McGhie, 1997), which have a horizontal resolution of 3.28 ft (1 m). In general, as will be shown later, the uncertainty in DTW estimates due to measurement error is small compared to the standard deviation of the kriging errors in DTW estimates; therefore, measurement error was not incorporated into the assessment of uncertainty of DTW estimates.

Interpolation using kriging. Kriging performs interpolation of spatial data by computing linear combinations of observations:

$$z^* = \sum_{i=1}^{n} w_i z_i \tag{1}$$

where z^* is the interpolated estimate, w_i are the weights given to each observation, and z_i are the observations. Kriging uses the spatial covariance of the data to compute weights that minimize the error variance of the estimate. The spatial covariance structure of the data is expressed in an experimental variogram derived from the data, and, to assure mathematical stability, a model variogram is fit to the experimental variogram. Kriging is an optimal interpolator in the sense that it is unbiased with respect to the mean and it minimizes the error variance of the estimates, which has resulted in the widespread use of kriging for interpolating geophysical data (Journel and Huijbregts, 1978; de Marsily, 1986; Isaaks and Srivastava, 1989; Kitanidis, 1992).

Variogram development. Experimental variograms were calculated using the standard form of the experimental semivariogram (Deutsch and Journel, 1998), given by

$$\gamma(h) = \frac{1}{2N(h)} \sum_{h_{ij} \in h}^{N(h)} (z_i - z_j)^2 \qquad (2)$$

where h is the separation (lag) of the data pairs in the summation. The pronounced topographic anisotropy of the Owens Valley and the close relationship between topography and DTW suggest that the DTW field may be statistically anisotropic (i.e., the spatial variance depends on the orientation of the data). Isotropic and anisotropic variograms were developed from the wet well data sets for each year, using a lag interval of 820 ft (250 m) and a lag tolerance of 410 ft (125 m). For anisotropic variograms, the direction of maximum variogram range was assumed to correspond to the axis of the Owens Valley (true azimuth 345°), and the experimental variogram was developed using a 45° half-window (see Deutsch and Journel, 1998). These parameters produced experimental variograms with well-defined ranges and sills (Appendix II).

Spherical variograms of the form

$$\gamma(h) = c_0 + c\left(\frac{3}{2}\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right) \text{ if } h < a \tag{3a}$$

$$\gamma(h) = c_0 + c \text{ if } h \geq a \tag{3b}$$

where c_0 is the nugget, c is the sill, and a is the range of the variogram, were fit to the experimental variograms (Table 1 and Appendix II). Experimental variograms and model variograms were developed using the GMS groundwater modeling system (Boss International Inc. and Brigham Young University, 1999) as an interface to the GSLIB geostatistical software (Deutsch and Journel, 1998).

Several subjective judgements enter into the modeling of variograms. The experimental variograms sometimes exhibited parabolic near-field behavior; however, because of the reputed instability of variogram models possessing parabolic near-field behavior (Isaaks and Srivastava, 1989), spherical variogram models were used throughout. Search radii for kriged estimates were limited to 1.55 miles (2.5 km); therefore, in fitting the variogram models more consideration was given to lags less than 1.55 miles. Examination of the experimental variograms in Appendix I suggests hole-effect models or anisotropic sills could be considered for some of the variograms (see Deutsch and Journel, 1998). In the interest of simplicity and in the absence of a physical basis for the hole-effect in these data, spherical variograms and isotropic sills were used throughout, i.e., only the range parameter, a, was treated as anisotropic. Experimental variograms in the 75° direction were much more variable than those in the 345° direction because fewer data pairs contribute to the 75° direction. General information on fitting variogram models to experimental variograms can be found in any of the geostatistical texts cited in this report.

Table 1. Parameters for spherical variograms. Parameter values are in m^2 for c_0 and c, m for a, and r is the ratio of the minimum range to the maximum range (unitless).

	Isotropic variograms			Anisotropic variograms			
Year	c_0	c	a	c_0	c	a	r
1999	5.1	174.0	2435.0	7.7	178.5	3101.0	0.59
1998	6.6	137.5	1873.6	6.0	139.2	2829.3	0.76
1997	12.3	166.8	2528.3	6.8	175.8	3169.0	0.69
1996	3.8	114.6	1830.8	5.8	123.3	2724.3	0.70
1995	6.2	138.8	3048.4	6.0	134.0	3343.2	0.71
1994	6.1	137.9	2560.3	2.6	154.0	2774.5	0.86
1993	3.6	166.9	2612.1	4.8	161.6	3165.0	0.69
1992	3.6	157.9	2405.4	2.3	153.5	2829.1	0.75
1991	5.2	150.8	2538.9	2.5	150.7	3056.9	0.64
1990	5.7	156.0	2226.9	5.4	160.7	2997.1	0.67
1989	2.2	157.6	2163.4	4.9	152.8	3111.0	0.66
1988	3.8	134.6	2267.6	4.5	136.0	3170.1	0.61
1987	5.3	121.9	2351.3	2.2	128.0	3223.8	0.68
1986	6.1	54.8	1561.5	7.0	46.7	2146.5	0.56
1985	0.7	44.6	1664.9	1.2	47.8	2825.7	0.69

Dry wells. Dry wells have the potential to improve DTW maps by providing additional information that would be lost if the dry wells were simply discarded. However, because of the censored nature of dry well data, they must be handled separately from the wet well data. Using the anisotropic variograms given in Table 1, the wet wells were used to estimate DTW at the locations of dry wells, thus providing an estimate of DTW at each dry well as if the DTW there was unknown. An operation such as this, where one set of observations (here, the wet wells) is used to estimate another set of observations (the dry wells) is generically referred to jackknifing in the applied statistics literature (Efron, 1982). For each dry well, if the estimated DTW was greater than the depth of the dry well, the well was not added to the kriging data set. Conversely, if the estimated DTW was less than the depth of the dry well, then the dry well was added to the kriging data set. This amounts to adding dry wells only at locations where the kriged estimate would otherwise clearly conflict with the observed minimum DTW in the dry well.

Kriging search radii were set to 2.5 km (1.55 miles), and the number of wells used to make an estimate was constrained to be between 4 and 12, with no more than 3 wells from each quadrant (see Deutsch and Journel, 1998). Because of these constraints, jackknifing operations such as described above often result in points where no estimate was made due to an absence of nearby data. For dry wells where this was the case, judgements were made on a case by case basis as to whether or not including a well in the data set would improve the final kriging product. Generally, dry wells for which no estimate was made were situated on the margins of the valley floor with no nearby wells, and unless these were very shallow wells, they were included in the data set (e.g. wells 107T, 431AT, 483T, 579T, 665T, 698T,V154 were dry most years, but still provide useful information). In cases where dry wells of different depths were in close proximity, only the deepest well was added to the data set (e.g. 312AT, 605T, and 606T are all dry in 1992 and are within 150 ft lateral distance from one another, therefore only well 606T, the deepest of the three, was added to the data set).

Surface water data. A cross validation study was done to determine the efficacy of supplementing the shallow well data set with surface water data. The rationale behind using supplementary surface water data was that in areas where surface water is connected to the water table, this connection could be represented by data points of

DTW=0 corresponding to locations of surface water. This strategy has been used in previous Owens Valley DTW mapping efforts (e.g., Jackson, 1996) on the assumption that the additional information provided by the surface water points improved DTW estimates. In these previous efforts, 4681 points were digitized along the wet reaches of the Owens River and various valley-floor water bodies, and these points were added to the kriging data set to supplement the shallow well observations.

Cross validation is a widely used method of testing kriging estimates by comparing them to known data. Cross validation proceeds as follows:

1. Remove one point from the data set.
2. Use the remaining data to compute an estimate at the location of the removed point.
3. Determine the difference between the estimate and the observation (the residual).
4. Repeat this process for all points in the data set, thus generating a residual for each point in the data set.
5. Examine the set of residuals to compare the accuracy and bias of the estimates with respect to the observed data. It is useful to examine both the residuals, $z_i^* - z_i$, and the normalized residuals, $(z_i^* - z_i)/\sigma_z$, where σ_z^2 is the error variance predicted by the kriging procedure. The residuals provide an assessment of error in terms of the same units as the data, whereas the normalized residuals also have the property that they should have unit variance, which provides an assessment of how closely the kriging variance represents the actual variability of the errors.

The following criteria are useful for judging the performance of kriging strategies:

The mean residual should be close to zero:

$$\frac{1}{n}\sum_{i=1}^{n}(z_i^{\ *} - z_i) \cong 0 \qquad 4$$

The standard deviation of the residuals should be small:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_i^{*} - z_i)^2} \cong \text{ some acceptably small number} \qquad 5$$

The mean normalized residuals (S_1) should be close to zero:

$$\frac{1}{n}\sum_{i=1}^{n}\frac{z_i^{*} - z_i}{\sigma_z} \cong 0 \qquad 6$$

The variance of the normalized residuals (S_2) should be close to 1:

$$\frac{1}{n}\sum_{i=1}^{n}\left(\frac{z_i^{*} - z_i}{\sigma_z}\right)^2 \cong 1 \qquad 7$$

The relative merit of different kriging strategies can be determined by comparing their cross validation statistics.

Assessment of uncertainty. Kriging provides an estimate of error variance for each estimate; however, it can only be used as an assessment of uncertainty if the kriging variance represents the actual errors when estimates are compared to reality. The mathematical derivation of kriging assumes that the data are second order stationary (the variance does not have a spatial trend) and the data are homoscadastic (the variance does not depend on the magnitude of the data). When these assumptions are not met, kriging can still produce useful estimates, but the kriging variance will not be a good indicator of the uncertainty of the estimate (Deutsch and Journel, 1998; Isaaks and Srivastava, 1989). For the current application, use of the kriging variance is justified by the homoscadasticity and slowly varying nature of DTW. Deutsch and Journel (1998) caution that the kriging variance is largely an index of the spatial configuration of the data used to produce an estimate. In the case of DTW estimates, the proximity of the wells used to produce an estimate is a good index of the uncertainty of the estimate. In terms of cross validation statistics, use of the kriging variance as an assessment of uncertainty is justified only if the variance of the normalized residuals is close to 1.0. As shown below, this condition is best achieved for the DTW estimates made with anisotropic variograms and without surface water points.

DTW grids and parcel hydrographs. A DTW grid was produced for each year,1985 through 1999, for each vegetation reinventory parcel. The grids had 440 columns and 1130 row, and each grid cell was 100 X 100 m (328 ft X 328 ft). For each DTW grid, a grid of cell kriging standard error was also produced as described above. The average DTW for each parcel was computed by averaging all cells whose centroids were within the boundary of a parcel. The standard error of the DTW estimate has two components of variance: (1) variance due to changes in DTW across the parcel, and (2) the uncertainty of each gridded DTW estimate. Thus, the standard error of the parcel mean DTW was calculated

$$\sigma_p = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((z_i^* - \bar{z}_p)^2 + \sigma_i^2)} \qquad 8$$

where σ_i^2 is the kriging variance of grid cell *i*, z_i^* are the gridded estimates within the parcel, $\bar{z}_p$ is the mean of the gridded estimates within the parcel, and *N* is the number of grid cells in the parcel.

To produce a hydrograph for each parcel, the mean DTW was plotted for each parcel for all years. The resulting time series of mean DTW was examined for anomalies due to changes in the wells present in the data set for different years, and consistency with nearby well hydrographs. Anomalies due to interannual changes in wells used for estimation were identified and removed from the hydrograph. The parcel standard errors were averaged over the time series to produce a general estimate of the uncertainty of the DTW hydrograph.

RESULTS

Dry wells. The jackknifing procedure suggested that a substantial number of dry wells should be included in the DTW data sets (Table 2). Appendix I indicates which dry wells were included. Inclusion of dry wells is especially important considering that the DTW maps are to be used for assessing changes in vegetation, because the bottom of many of the dry wells is substantially below the root zone. Thus, if the water table data were being treated as categorically within or below the plant root zone, the dry well data would be uncensored and below the root zone. As shown in Table 2, this procedure added a significant number of wells to the kriging data sets, especially during the drought years 1990-1993.

Table 2. Number of wells available for DTW map development.

Year	Wet wells used for kriging	Total dry wells	Dry wells used for kriging	Total wells used for kriging
1999	253	24	11	264
1998	316	51	21	337
1997	307	61	30	337
1996	264	59	30	294
1995	282	87	54	336
1994	287	85	48	335
1993	265	103	62	327
1992	258	109	67	325
1991	248	108	69	317
1990	251	108	72	323
1989	236	93	59	295
1988	249	74	48	297
1987	237	12	10	247
1986	220	14	10	230
1985	148	5	4	152

Anisotropy and surface water points. In order to assess the utility of anisotropic variograms and supplemental surface water points, cross validations were performed on three cases for each year 1985-1999: (1) isotropic variograms (Table 1) and surface water points were used; (2) anisotropic variograms (Table 1) were used and surface water point were used; and (3) anisotropic variograms (Table 1) were used and no surface water points were used. Table 3 shows the resulting cross validation statistics.

Table 3. Mean and standard deviation of cross validation residuals (estimate minus observed, feet). S_1 and S_2 are mean and variance of standarized residuals.

Year	Isotropic variogram with surface water points		Anisotropic variogram with surface water points		Anisotropic variogram without surface water points	
	mean residual	SD of residuals	mean residuals	SD of residuals	mean residuals	SD of residuals
1999	-2.33	7.84	-2.23	7.84	-0.16	7.35
1998	-2.52	8.45	-2.31	8.15	-0.23	7.78
1997	-2.68	8.54	-2.43	8.37	-0.23	7.99
1996	-2.89	8.30	-2.76	7.92	-0.32	7.60
1995	-2.79	7.96	-2.66	7.89	-0.27	7.34
1994	-2.98	7.71	-2.82	7.61	-0.18	6.91
1993	-2.80	7.70	-2.64	7.74	-0.07	6.99
1992	-2.90	7.97	-2.79	7.84	0.08	7.37
1991	-3.23	8.24	-2.94	8.04	-0.19	7.40
1990	-3.13	8.79	-2.88	8.59	0.23	8.15
1989	-3.21	8.90	-3.04	8.59	-0.24	7.62
1988	-2.99	8.50	-2.76	8.28	-0.21	7.67
1987	-2.99	7.75	-2.77	7.50	-0.46	6.86
1986	-3.31	7.37	-3.26	7.42	-0.33	6.87
1985	-3.91	7.66	-3.82	7.60	-0.77	6.76
Mean	**-2.98**	**8.11**	**-2.81**	**7.89**	**-0.23**	**7.35**
Year	S_1	S_2	S_1	S_2	S_1	S_2
1999	-0.32	1.51	-0.24	0.77	-0.01	0.64
1998	-0.31	1.17	-0.29	1.18	-0.01	0.97
1997	-0.32	1.08	-0.31	1.24	-0.02	1.02
1996	-0.38	1.38	-0.36	1.26	-0.02	0.98
1995	-0.42	1.59	-0.39	1.51	-0.00	1.10
1994	-0.44	1.40	-0.43	1.56	-0.01	0.93
1993	-0.38	1.08	-0.36	1.00	-0.00	0.66
1992	-0.43	2.31	-0.40	1.54	0.01	1.02
1991	-0.42	1.67	-0.40	1.78	-0.01	1.37
1990	-0.41	1.42	-0.39	1.42	0.03	1.01
1989	-0.41	1.29	-0.40	1.26	-0.02	0.82
1988	-0.38	1.46	-0.35	1.58	-0.02	1.06
1987	-0.40	1.10	-0.40	1.22	-0.04	0.85
1986	-0.50	1.39	-0.50	1.46	-0.04	0.99
1985	-0.77	2.25	-0.78	2.32	-0.07	1.10
Mean	**-0.42**	**1.47**	**-0.40**	**1.41**	**-0.02**	**0.97**

The cross validation results suggest that the use of anisotropic variograms provides a modest improvement in the results. The anisotropic case is slightly less biased with respect to the mean than the isotropic case for all years, and has a slightly smaller standard deviation of the residuals for all but two years. These statistics suggest that an improvement in predictive capability is achieved through use of anisotropic variograms.

Cross validation residuals are customarily calculated as the difference between the estimate and the observation; therefore, the pronounced negative bias of the residuals suggests that the DTW was generally being modeled as too small, i.e., the water table was predicted to be closer to the land surface than it actually was. The negative bias led to the investigation of the third case, where supplemental surface water points were removed from the data set. Removal of the surface water points gave clearly superior results. Without the surface water points, the negative bias disappeared almost entirely, and a greater decrease in the standard deviation of residual is achieved than was achieved between isotropic and anisotropic models (Table 3). Furthermore, the variance of the normalized residuals was much closer to 1.0 than in either of the cases that included the surface water points, indicating that the kriging variance is a more reliable estimate of error variance in the case where surface water points were not used. When the variance of the normalized residuals is greater than 1.0, the variance of the cross validation residuals is greater than the kriging variance, indicating that the kriging variance is likely underestimating the true error of the estimates when surface water points are included.

Comparison of the spatial pattern of cross validation residuals reveals regions where the supplemental surface water points result in erroneously shallow estimated water tables. Figure 1A shows cross validation results for 1992 for the region between Tinemaha Reservoir and George Creek when surface water points are included in the data. When supplemental surface water point are used, clusters of underestimated DTW appear between Tinemaha Reservoir and the aqueduct intake, in the area between Black Rock Spring and Thibaut Ponds, and along the Owens River south of Mazourka Canyon. These clusters are all near supplemental surface water points, suggesting that the surface water points are biasing the water table upward. Figure 1B shows cross validation results for the same region and year as Figure 1, but the supplemental surface water points have been removed from the kriging data. Without the surface water points, the cross validation errors are less biased, and the spatial distribution of positive and negative errors is more homogeneous (Table 3). Figures 2A and 2B show a similar comparison of cross validation results for the Bishop-Laws area. When surface water points are used, a cluster of negative residuals is aligned with the Owens River. When the surface water points are removed from the data set, the cluster disappears and the residuals are less biased (Table 3). The example given above is typical. When cross validation results for each year were examined, and a pattern of underestimated DTW near supplemental surface water data was evident in every case. This does not mean that surface water bodies are not in hydraulic communication with the shallow groundwater; it simply means that assigning a DTW of 0 at surface water bodies is not representative of the DTW in the nearby subsurface.

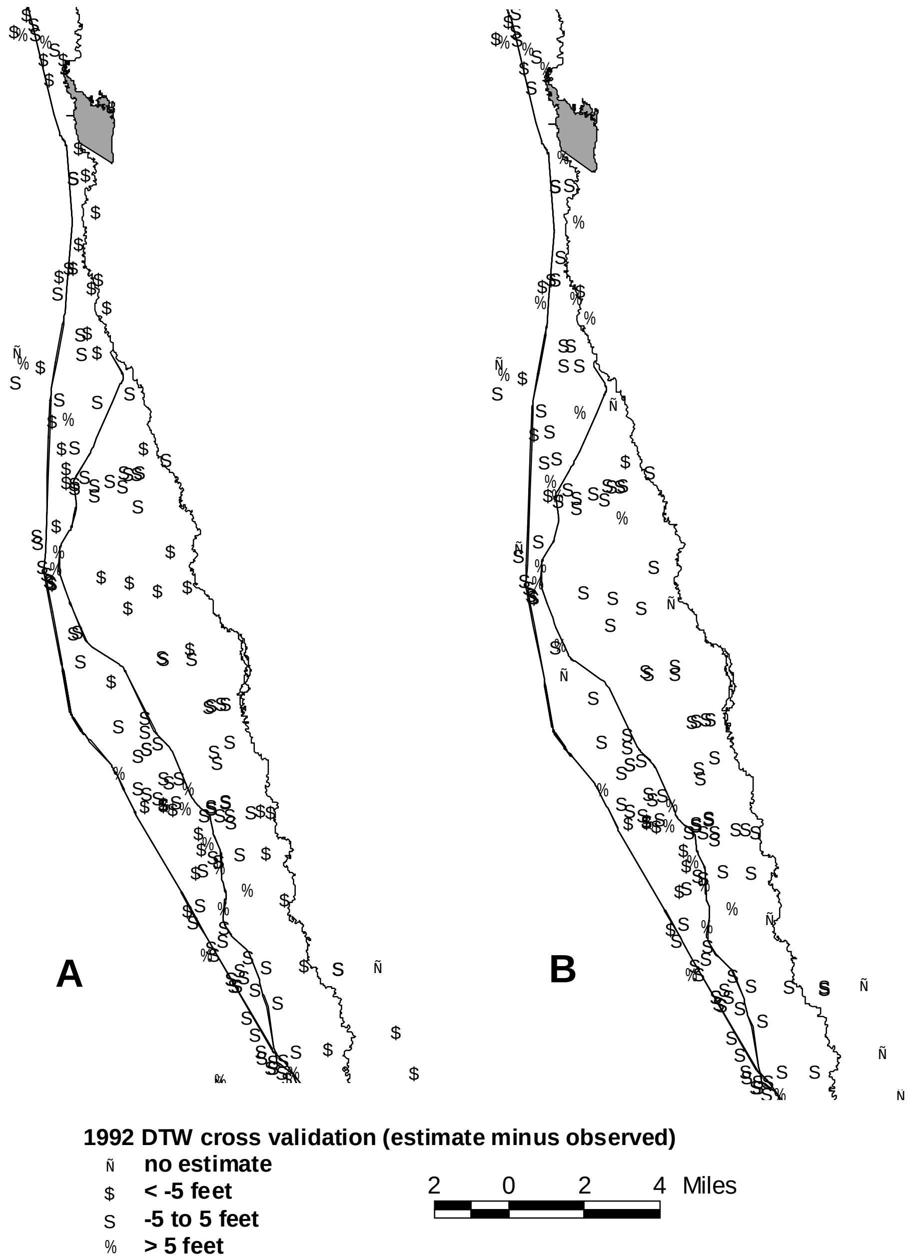

Figure 1. Cross validation (estimate minus observed) results for April 1992, Tinemaha Resevoir to George Creek area. Figure A was developed with supplemental surface water points; Figure B was developed without supplemental surface water points.

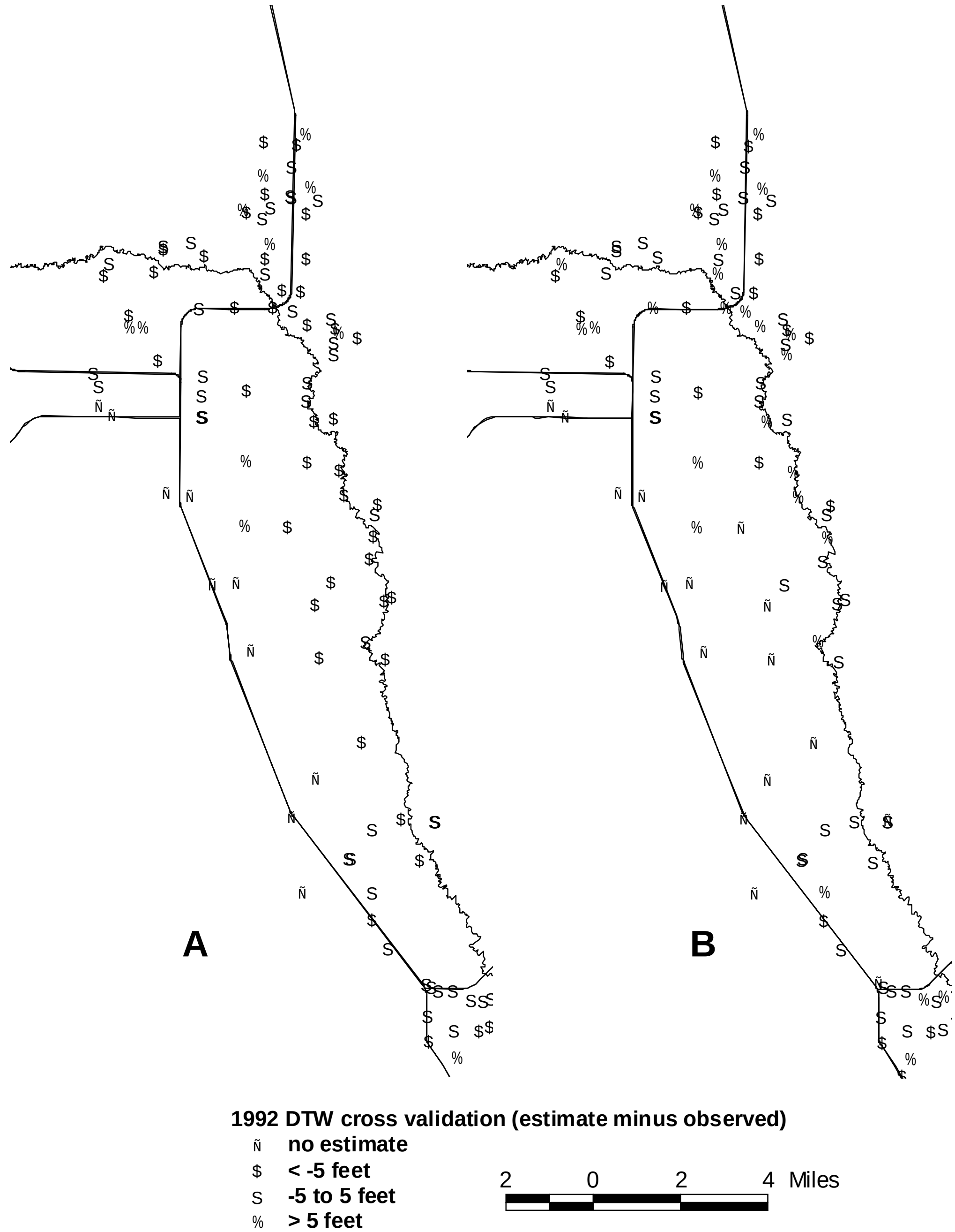

Figure 2. Cross validation (estimate minus observed) results for April 1992, Laws and Bishop area. Figure A was developed with supplemental surface water points; Figure B was developed without supplemental surface water points.

Parcel hydrographs. Baseline mean DTW for each parcel was calculated from the 1985, 1986, and 1987 parcel mean DTW, and is given in Table 3 (refer to Inyo County Water Dept., 1999 for parcel locations). DTW standard error for each parcel was calculated from the 1987 through 1999 standard errors. 1985 and 1986 data had anomalously low global variances, as reflected in the variograms for those years (Appendix II); therefore, the standard errors from 1985 and 1986 were not used in this calculation. Also given in Table 3 are DTW for 1999, which provides a comparison between baseline and current conditions.

Figures 3 through 43 show the resulting hydrographs for each vegetation reinventory parcel. Anomalies in specific hydrographs are discussed in the figure captions. When a particular parcel hydrograph is said to be “consistent” with a particular nearby well, it means that trends in the parcel hydrograph parallel trends in the monitoring well hydrograph.

Table 3. Baseline DTW, 1999 DTW, and standard error of the parcel mean for each vegetation reinventory parcel. Baseline depth to water (BDTW) is the mean April DTW for 1985 through 1987 (m). SE is the standard error of the parcel means (Equation 8) plotted in Figures 3 through 35, averaged over 1987 through 1999 (m).

Parcel	BDTW	1999	SE	Parcel	BDTW	1999	SE	Parcel	BDTW	1999	SE
LAW030	6.74	8.29	2.52	PLC111	3.04	2.87	2.82	BLK115	1.37	1.83	3.64
LAW040	5.94	5.01	2.12	PLC113	3.79	3.69	2.08	BLK142	2.42	1.75	2.44
LAW052	2.92	2.79	2.29	PLC121	1.22	1.24	2.54	IND011	0.92	0.78	2.08
LAW062	3.93	3.45	2.03	PLC125	2.59	2.08	3.12	IND019	1.27	1.15	2.95
LAW063	4.06	3.75	2.29	PLC136	-----	1.82	3.54	IND021	0.95	0.80	2.39
LAW065	3.14	3.91	2.67	PLC137	-----	1.67	2.96	IND035	1.40	2.22	2.57
LAW076	2.73	2.80	3.20	PLC187	2.66	2.29	3.47	IND064	1.23	2.21	1.93
LAW078	2.28	2.24	1.93	PLC193	2.75	3.12	3.58	IND066	1.11	1.99	2.38
LAW082	3.95	3.28	2.65	PLC220	2.66	2.82	2.67	IND067	1.25	1.86	3.74
LAW085	4.21	3.71	2.51	PLC223	4.37	4.26	2.13	IND087	1.50	1.40	2.61
LAW104	4.87	5.16	2.38	PLC239	1.96	2.16	2.55	IND096	0.78	0.45	2.43
LAW107	1.98	1.82	1.71	PLC240	1.89	2.09	3.46	IND099	0.28	0.73	2.38
LAW109	2.82	3.28	3.06	PLC241	1.91	2.09	4.02	IND106	2.90	4.32	2.59
LAW110	2.80	3.14	3.29	PLC246	1.93	2.35	3.65	IND111	2.91	3.02	2.92
LAW112	3.80	3.82	1.74	PLC251	-----	-----	-----	IND119	1.34	2.26	3.10
LAW120	4.17	4.79	2.05	PLC263	-----	-----	-----	IND122	1.99	1.07	2.30
LAW122	2.96	2.82	2.60	BGP013	-----	1.19	3.00	IND132	2.66	3.84	2.74
LAW137	4.96	5.68	4.36	BGP031	2.51	2.91	3.63	IND139	1.94	3.56	3.11
LAW154	2.89	2.60	3.54	BGP047	1.80	2.11	2.89	IND151	2.28	1.74	3.61
LAW167	3.01	3.01	3.44	BGP086	3.24	2.58	3.85	IND156	1.68	1.36	3.20
LAW187	2.51	2.48	3.11	BGP088	3.54	2.71	3.59	IND163	2.22	1.70	3.05
FSL051	2.94	3.29	2.90	BGP154	4.63	4.28	1.70	IND205	2.46	2.61	2.46
FSL065	1.34	1.91	2.83	BGP157	4.10	2.58	2.31	IND231	2.77	7.14	2.84
FSL116	2.42	3.65	3.14	BGP162	5.93	6.21	2.56	MAN006	1.58	2.01	1.99
FSL118	4.21	5.45	2.37	BGP204	-----	1.91	4.08	MAN007	2.90	3.32	2.40
FSL122	2.11	1.88	2.88	BGP205	-----	1.92	4.55	MAN014	1.97	2.10	3.01
FSL123	2.21	2.10	2.99	UHL052	5.24	5.98	3.24	MAN017	3.24	3.69	2.66
FSL133	5.96	5.82	2.70	TIN006	2.81	3.47	1.63	MAN034	2.87	2.12	2.84
FSL179	-----	----	-----	TIN028	3.60	3.79	2.41	MAN037	3.43	2.31	2.11
FSL187	-----	----	-----	TIN050	3.66	3.23	2.77	MAN042	4.47	4.23	3.89
FSP004	4.06	4.88	2.00	TIN064	6.08	5.88	2.45	MAN060	-----	-----	-----
FSP006	3.18	3.72	2.00	TIN068	3.79	4.18	2.77	UNW029	2.21	2.35	3.69
BIS019	-----	----	-----	BLK002	5.77	9.06	3.35	UNW039	1.71	1.12	2.93
BIS068	1.99	2.03	3.09	BLK006	2.06	2.50	1.61	UNW072	3.97	3.24	4.51
BIS085	4.27	5.24	3.43	BLK009	2.74	2.91	2.26	UNW073	5.58	4.60	4.33
PLC007	3.54	3.87	3.22	BLK016	2.03	2.01	2.16	UNW079	6.28	5.92	3.70
PLC024	2.39	2.70	2.26	BLK021	1.95	2.55	2.69	LNP018	6.57	5.71	3.83
PLC028	2.95	3.10	3.25	BLK024	3.54	4.24	2.81	LNP019	5.48	4.35	3.51
PLC055	2.69	2.73	3.25	BLK029	12.03	12.99	2.59	LNP045	4.11	2.79	3.42
PLC056	2.20	1.98	2.88	BLK033	3.54	3.50	2.62	LNP050	3.89	2.86	4.21
PLC059	3.34	3.54	3.63	BLK039	3.06	2.98	2.85				
PLC064	3.62	3.69	2.76	BLK040	2.33	2.77	2.82				
PLC065	3.40	3.60	3.40	BLK044	4.43	3.70	2.10				
PLC069	3.61	3.49	3.38	BLK069	1.68	2.00	2.16				
PLC072	3.50	3.46	3.60	BLK074	1.58	1.90	2.04				
PLC092	-----	-----	3.32	BLK075	1.70	1.89	2.16				
PLC097	-----	-----	3.80	BLK077	2.68	3.79	2.08				
PLC106	3.26	2.78	2.06	BLK094	1.14	3.73	2.53				
PLC110	3.05	2.53	2.71	BLK099	0.88	1.80	2.04				

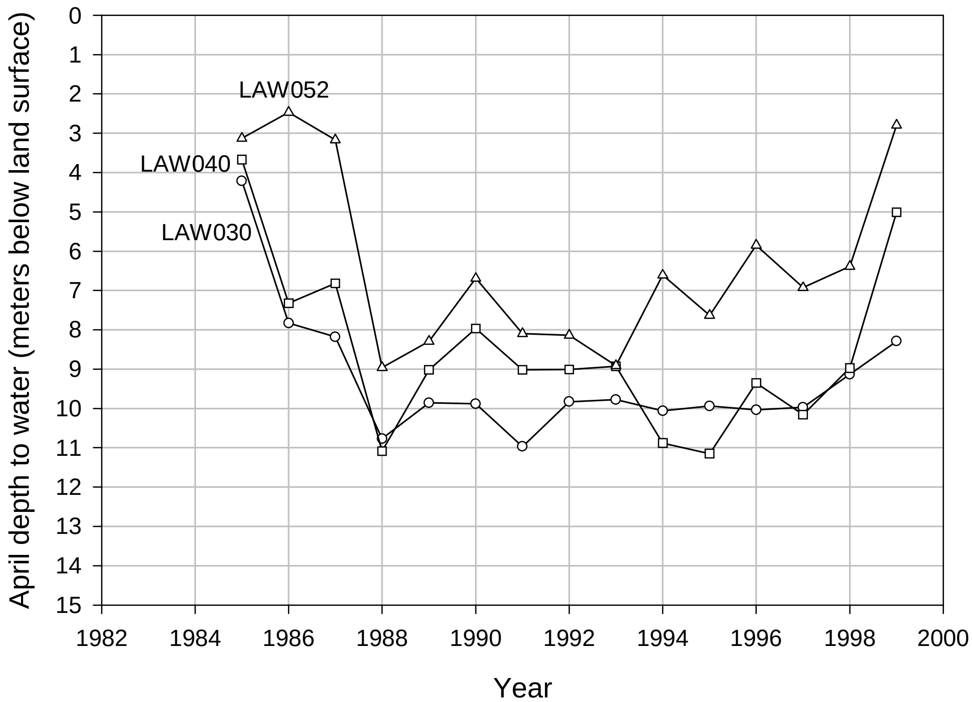

Figure 3. The shallow DTW in 1985 in LAW030 and LAW040 is consistent with well 577T. LAW052 is consistent with wells 493T, 494T, and 577T. Estimates during the drought of the early nineties use many dry wells; hence, the actual DTW was probably deeper during the drought.

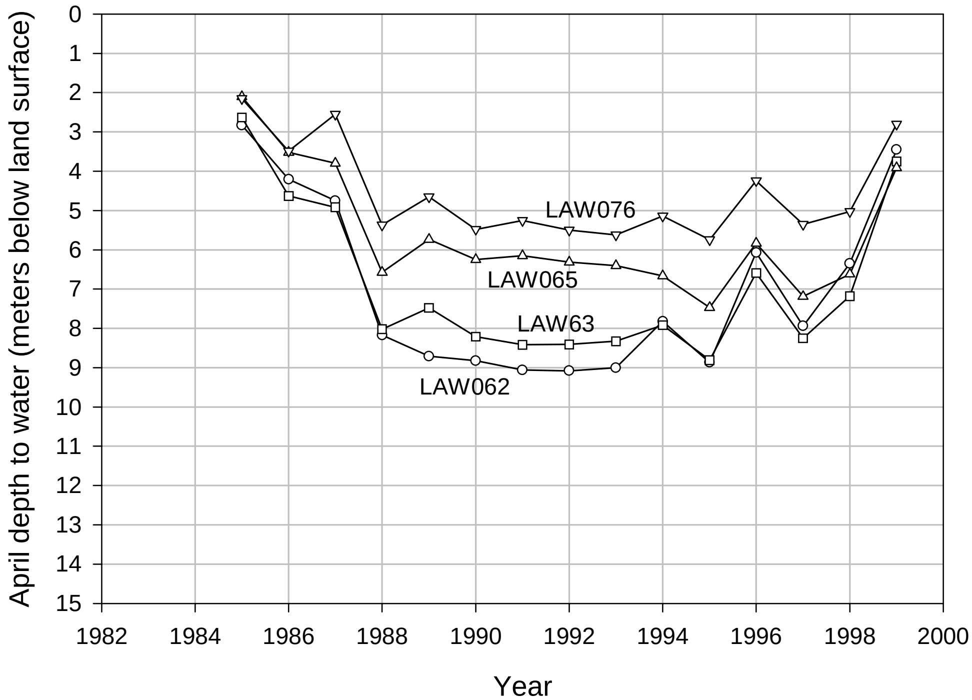

Figure 4. Anomaly in 1996 is consistent with wells 577T and 702T. LAW076 is consistent with 436T and shows greater recovery than 435T. Estimates during the drought of the early nineties were based on many dry wells; hence, the actual DTW during drought was probably greater.

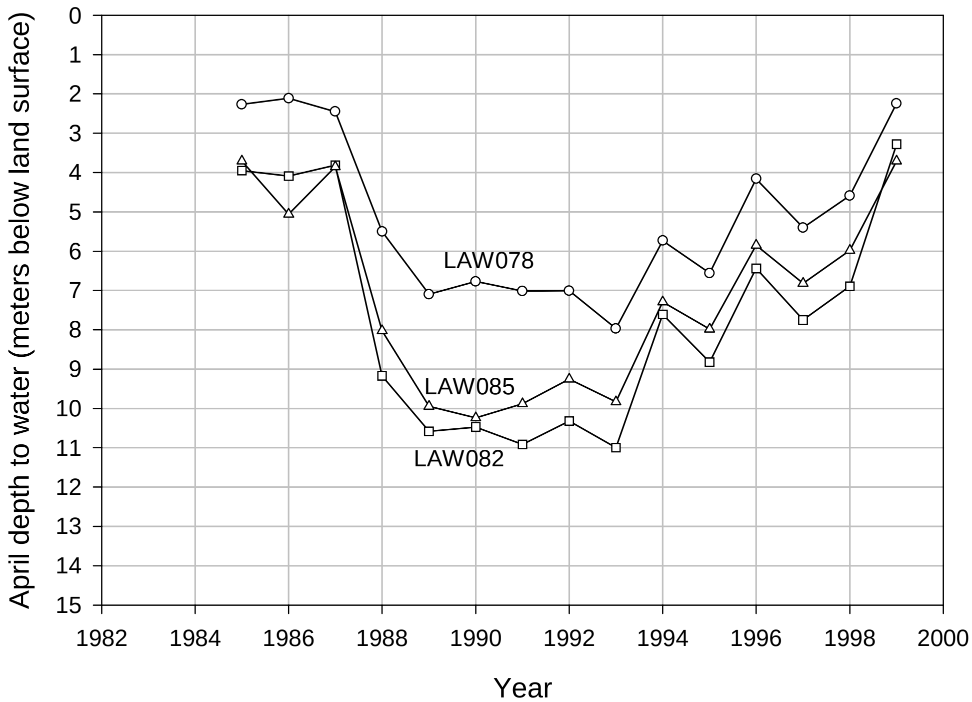

Figure 5. Oscillations from 1991 to 1997 are consistent with 435T. LAW 078 shows more recovery than well 435T. LAW 082 and LAW 085 show more recovery than 001G. The drought years of the early nineties are based on many dry wells; hence, the actual DTW during the drought was probably greater.

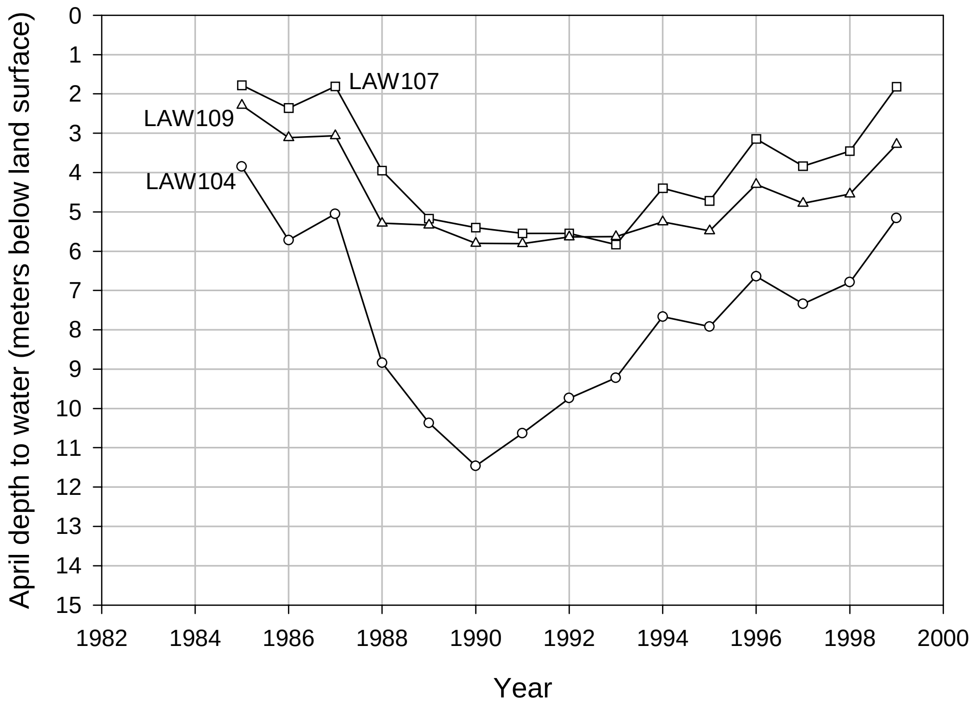

Figure 6. LAW104 is consistent with well 503T; LAW107 is consistent with well 436T; LAW109 is consistent with wells 438T and 576T. Estimates during the drought were based on many dry wells; actual depth to water was probably greater.

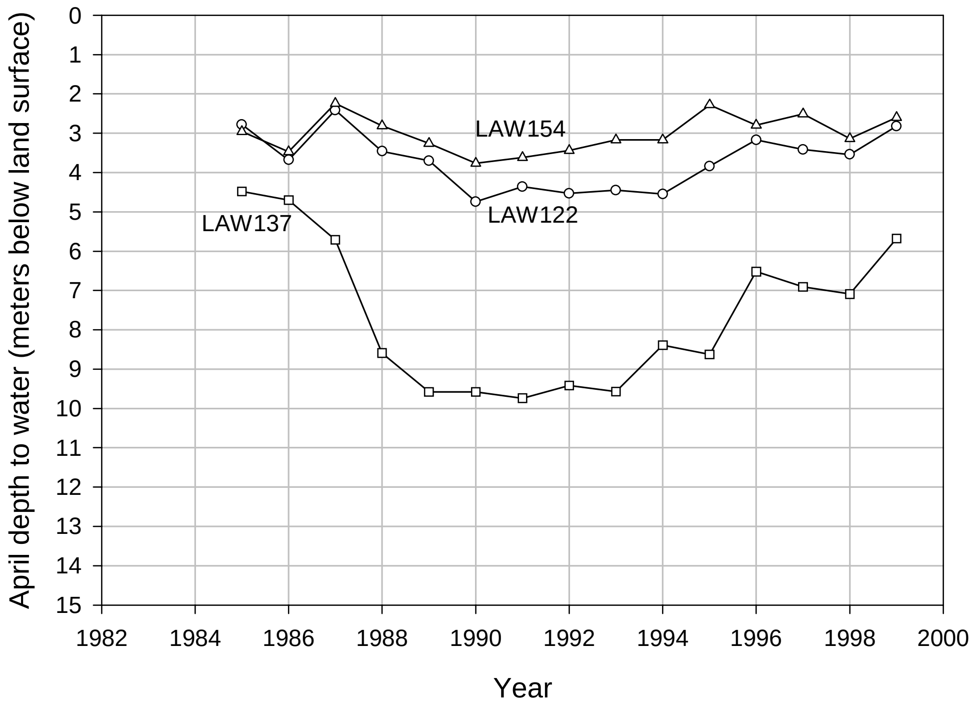

Figure 7. LAW122 is consistent with wells 573T and 574T, but shows more recovery than 490T. LAW137 is consistent with 490T and has a rather high standard error due to the distance to the nearest monitoring wells. LAW154 is consistent with wells 573T and 574T, but shows more recovery than well 490T. This parcel has a rather high standard error due to the distance from the nearest monitoring wells (Table 3). Estimates of DTW during the drought of the early nineties rely on many dry wells; it is likely that actual DTW was greater during the drought.

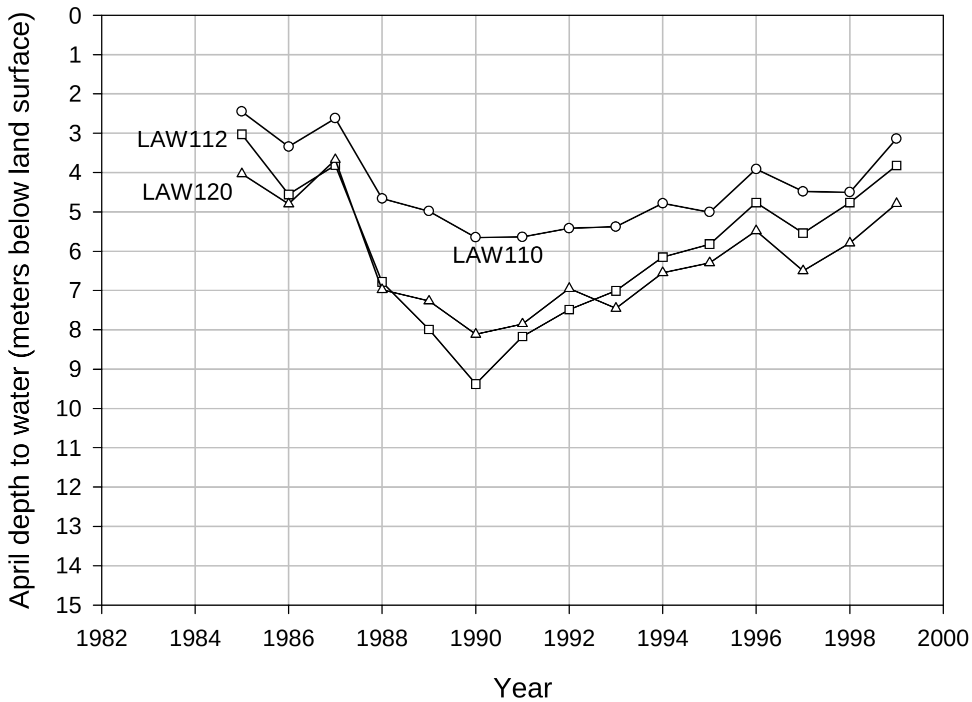

Figure 8. LAW110 is adjacent to Owens River, suggesting that this parcel may be strongly connected to surface water; hydrograph is consistent with 436T and 576T, but these wells are too distant to assess connectivity to surface water. It is likely that DTW is overestimated for this parcel. LAW112 and LAW120 are consistent with 503T and 574T. Estimates during drought of the early nineties rely on dry wells; actual DTW during the drought was probably deeper.

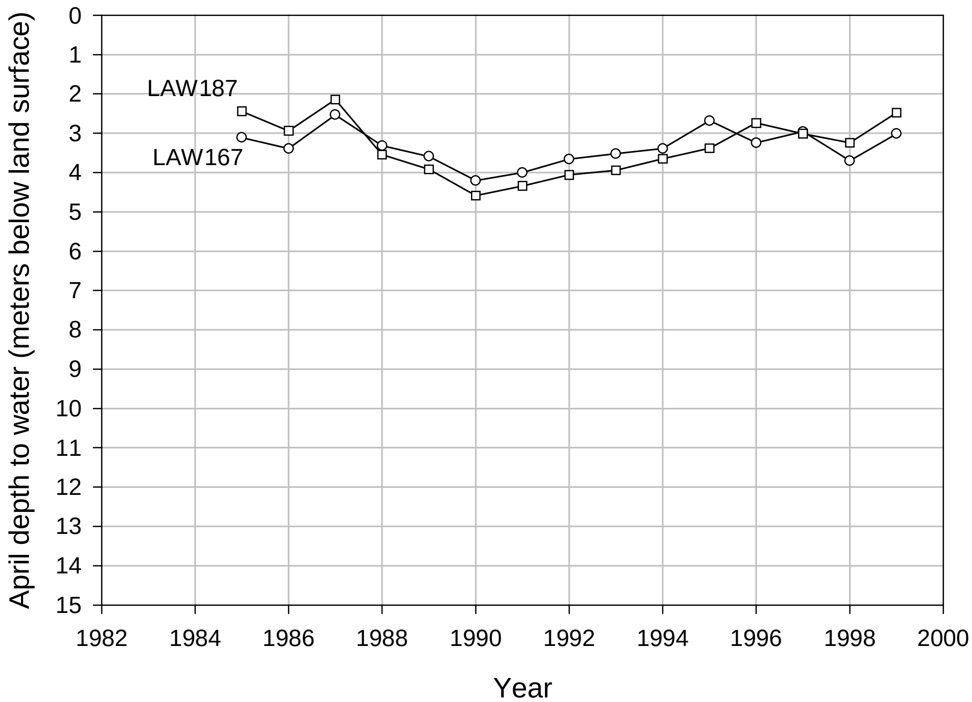

Figure 9. LAW167 has no wells nearby, similar to LAW154. LAW187 is adjacent to Owens River, similar to LAW110. Both of these parcels are subject to greater uncertainty than suggested by their standard errors in Table 3 due topographic variability and surface water between the parcels and the closest wells.

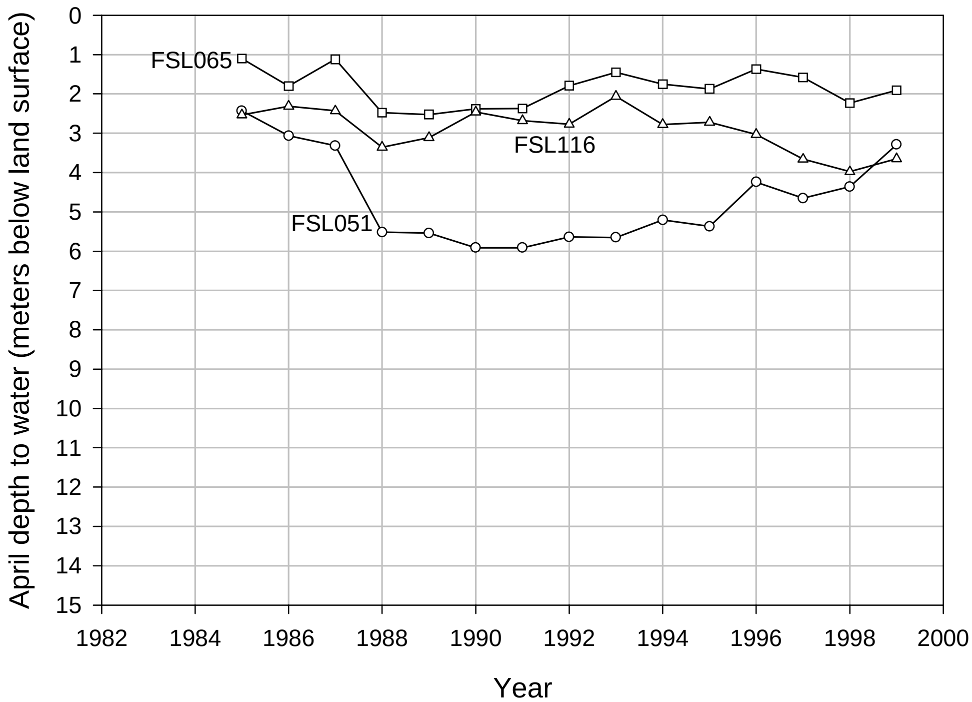

Figure 10. The actual FSL051 hydrograph is may be shallower than shown due to proximity to Owens River. Anomaly in FSL065 for 1985 is consistent with 498T. FSL116 is consistent with 498T and 384T.

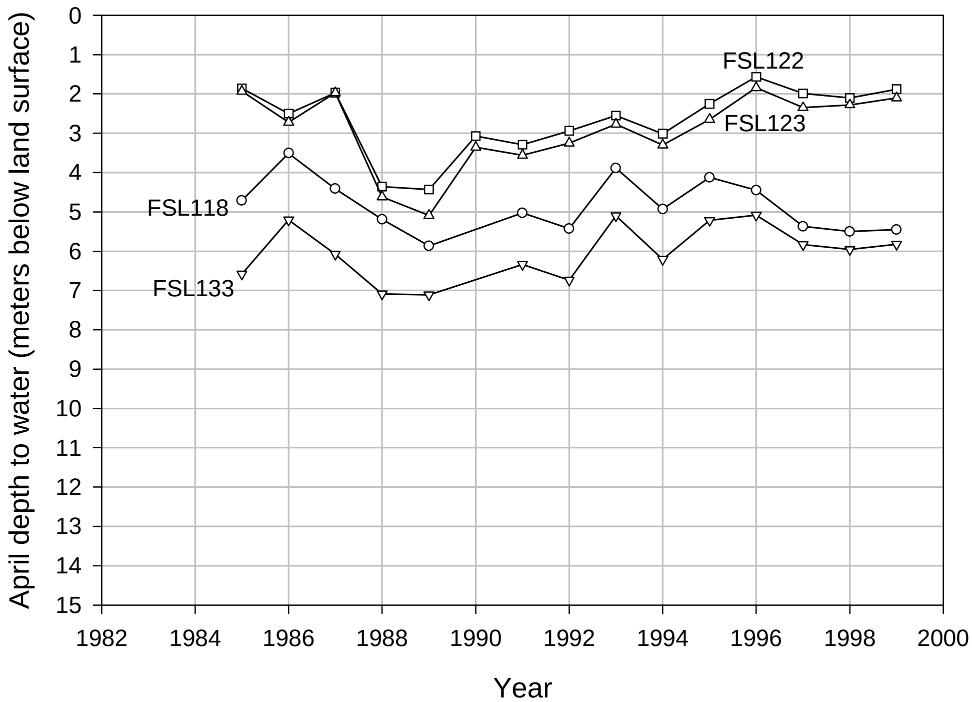

Figure 11. FSL122 and FSL123 are on a terrace south of Owens River, and trends are consistent with nearby wells. FSL118 is consistent with nearby wells. The anomaly in FSL118 and FSL133 for 1985 is likely real; nearby wells show similar fluctuations during 1985 and 1986.

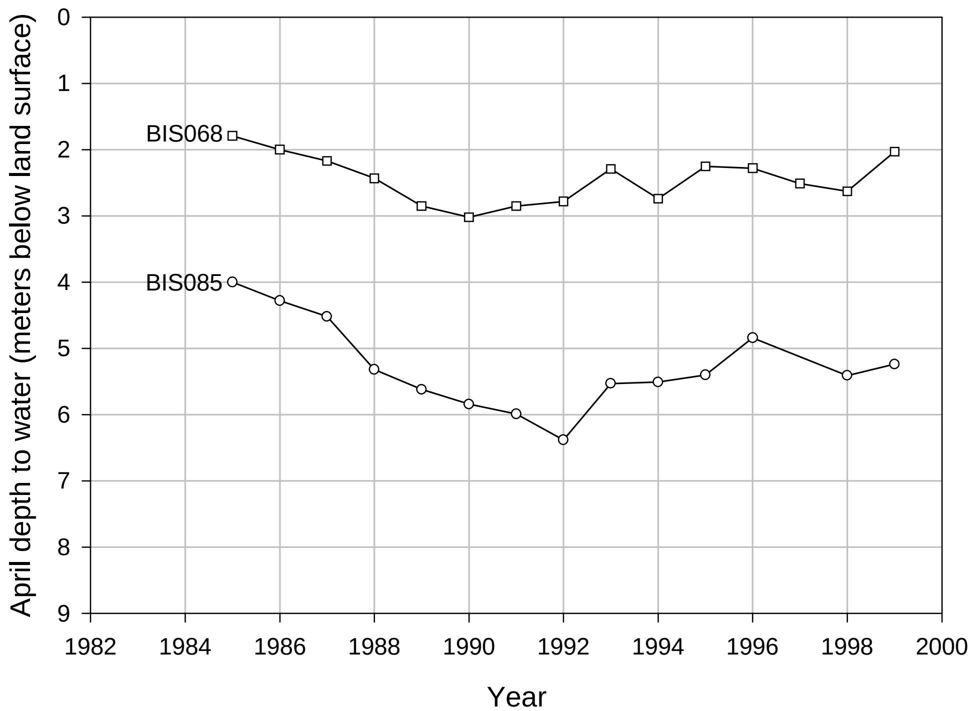

Figure 12. 1997 estimate for BIS085 was anomalous due to the absence of 336T from the data set. Both parcels are consistent with 430T.

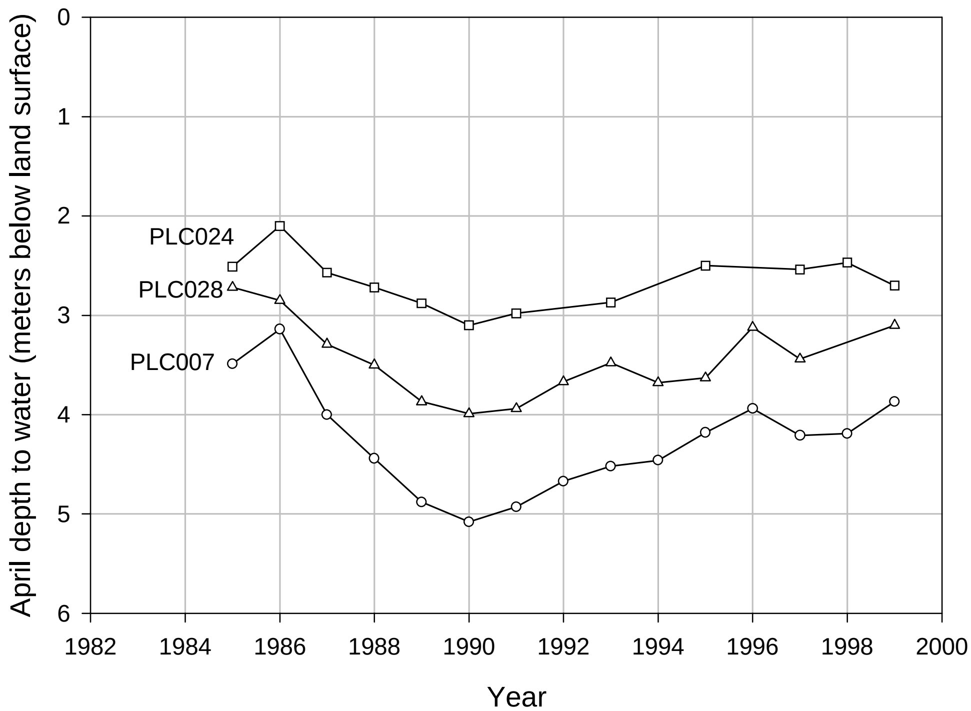

Figure 13. PLC007 is consistent with 499T and 501T. Wells near river (323AT and 324AT) may bias PLC024 too shallow, as the wells are in the Owens River flood plain and the parcel is on an adjacent elevated terrace. PLC024 had anomalies in 1992, 1994, and 1996 due to the absence of 323AT. PLC028 was anomalous in 1998 due to the absence of 499T, otherwise, PLC028 is consistent with 499T.

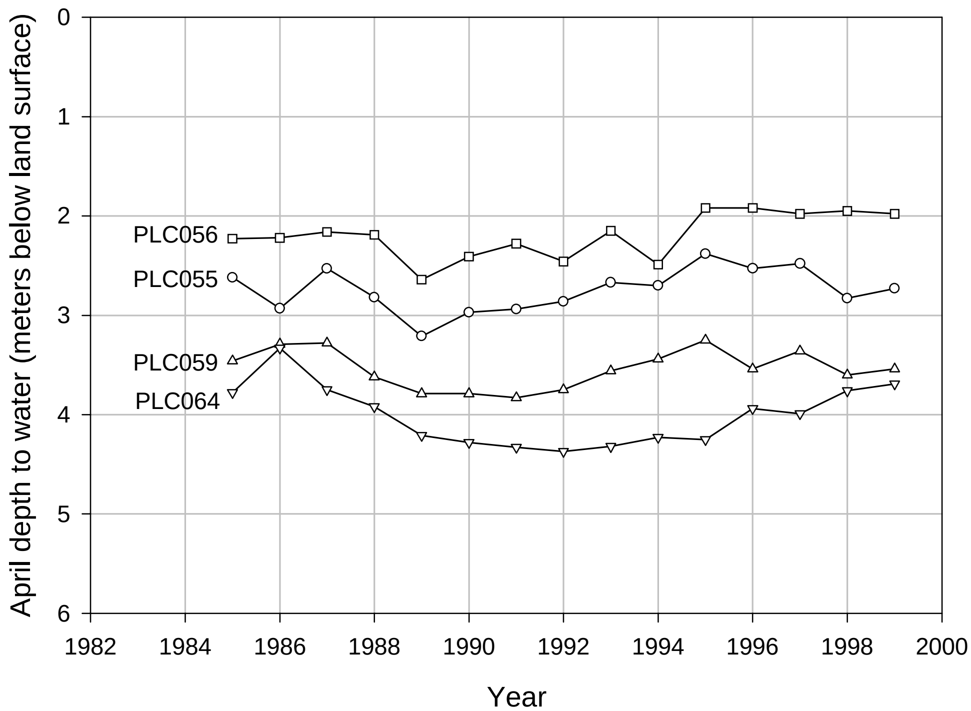

Figure 14. Wells near the Owens River (319AT and 320AT) may bias PLC055 and PLC056 too shallow and reduce drawdown during drought, because the wells are in the flood plain and the parcel on the adjacent elevated terrace. Hydrographs are not consistent with 485T. PLC059 and PLC064 are consistent with 485T.

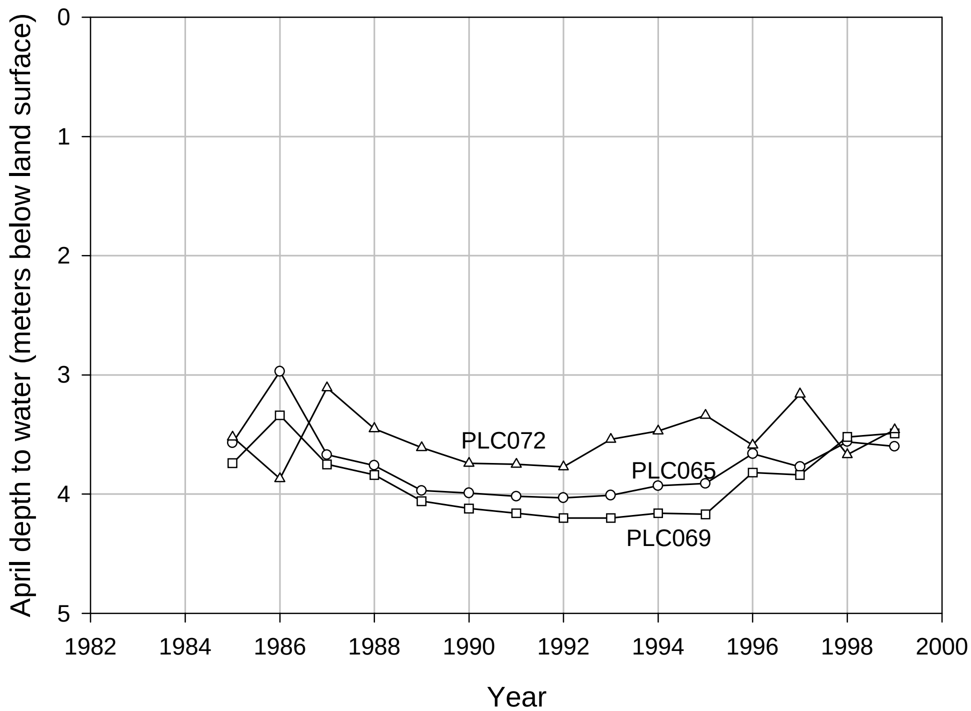

Figure 15. PLC065 and PLC069 are consistent with 485T, including the increase in 1986. PLC072 is consistent with 484T and 485T.

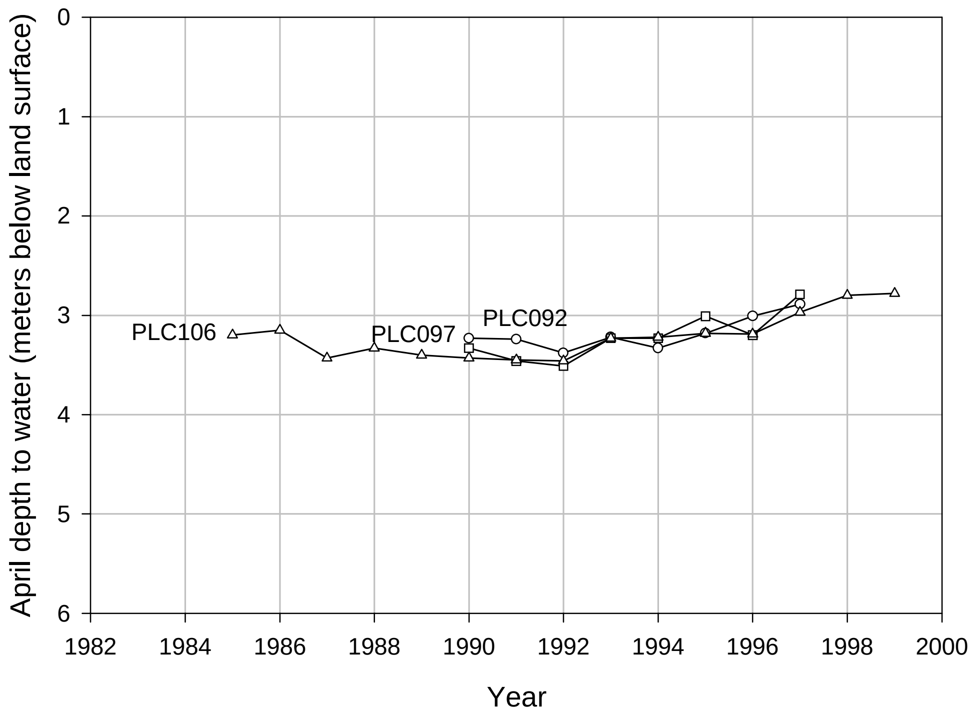

Figure 16. PLC092 and PLC097 had anomalies in 1985 through 1989, prior to the installation of 797T, and an anomaly in 1998 and 1999 due to the absence of 335T in the record. PLC106 is consistent with V002G.

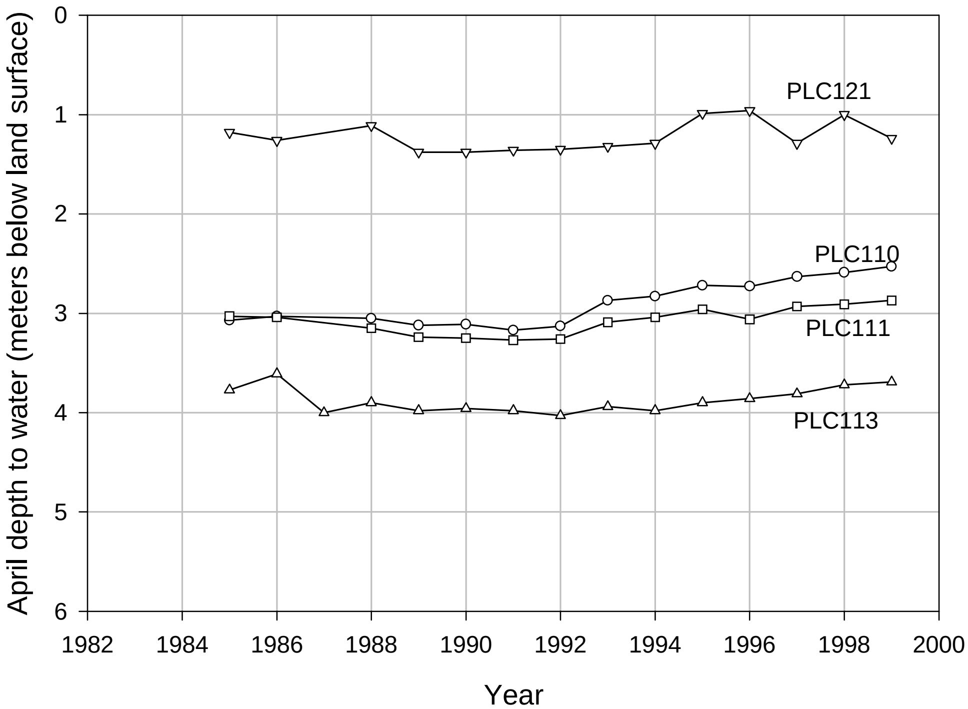

Figure 17. Anomaly in 1986 in PLC110, PLC111, and PLC121 due to the absence of 314T; consistent with 481T. Trends are consistent with 480T.

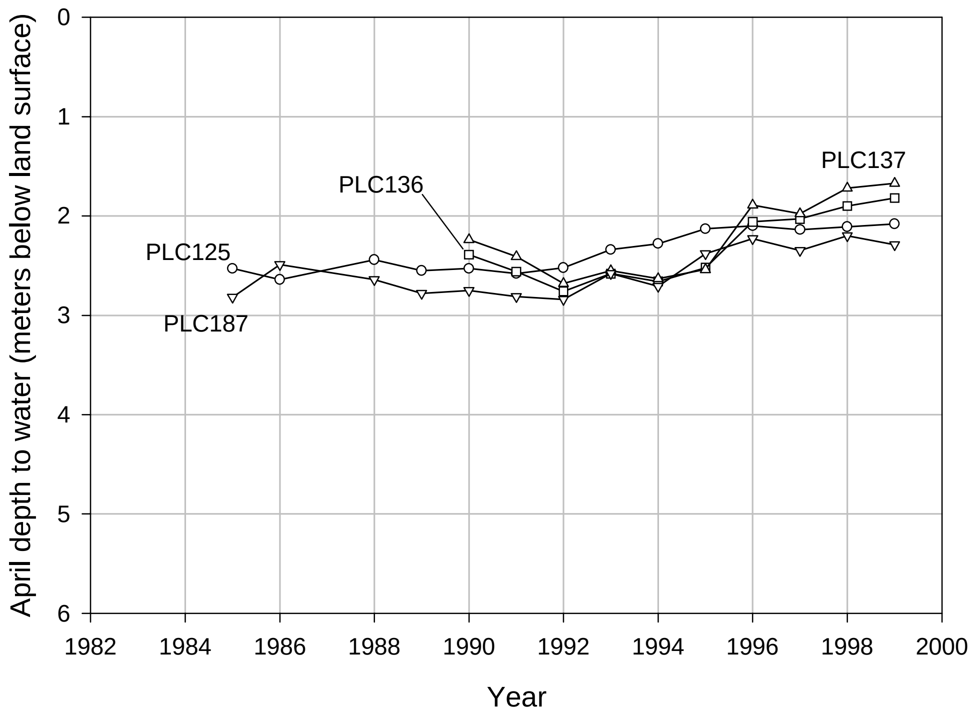

Figure 18. An anomaly in 1987 in PLC125 and PCL187 due to absence of 314T in record was removed. PLC136 and PLC137 anomalous prior to 1990 when 797T was installed (similar to PLC125). Post-1990 trend for all hydrographs is consistent with 797T.

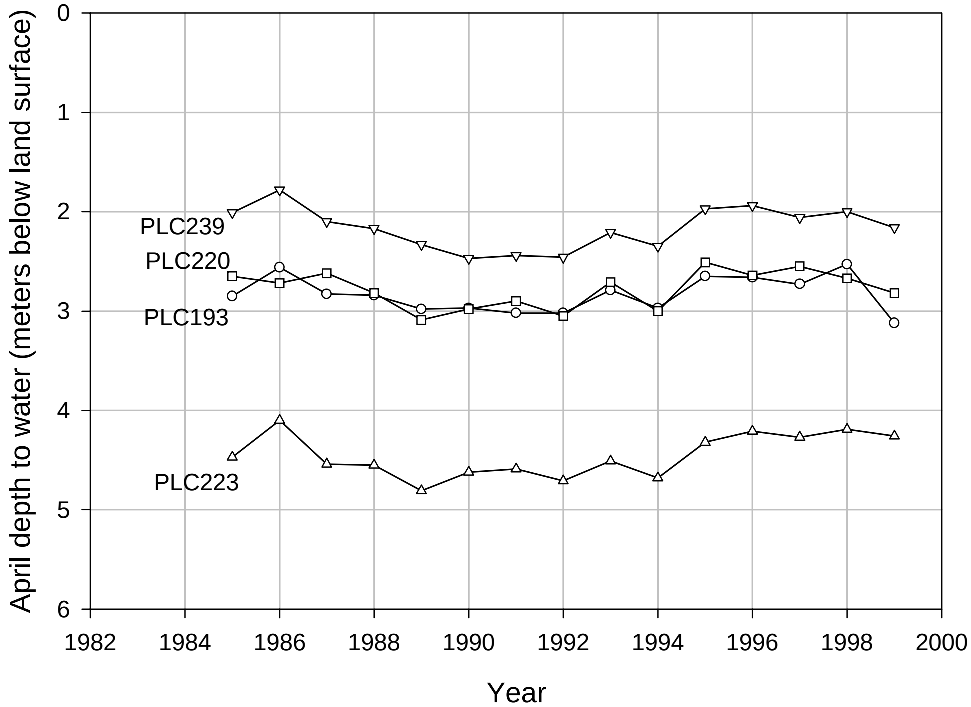

Figure 19. PLC220 and PLC223 are consistent with well 488T. PLC193 is consistent with 479T, including decline in 1999. PLC239 is consistent with 487T.

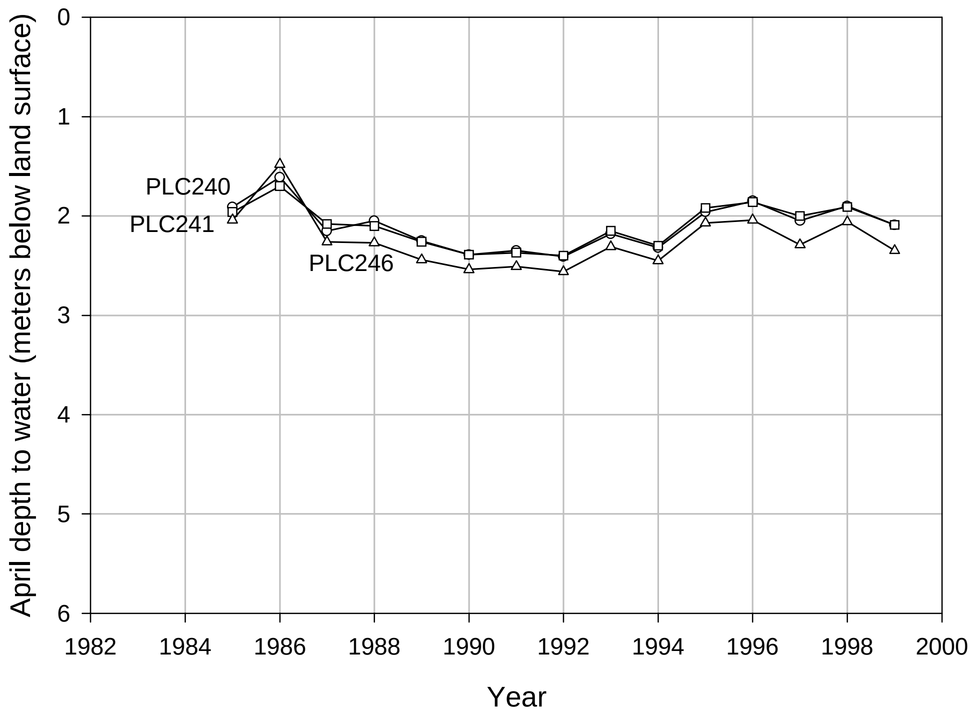

Figure 20. All three hydrographs are consistent with 487T, including peak in 1986.

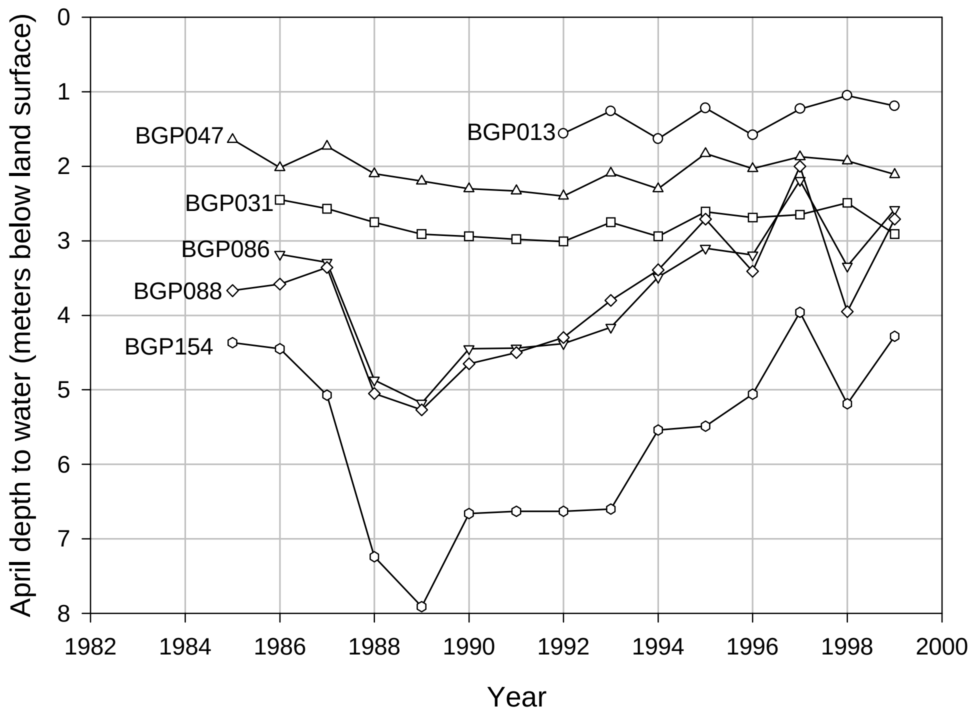

Figure 21. BGP013 is consistent with 476T and 478T; BGP031 and BGP047 are consistent with 474T and 479T; BGP086 and BGP088 consistent with 572T except for oscillations in 1995 through 1999. BGP154 is consistent with 572T.

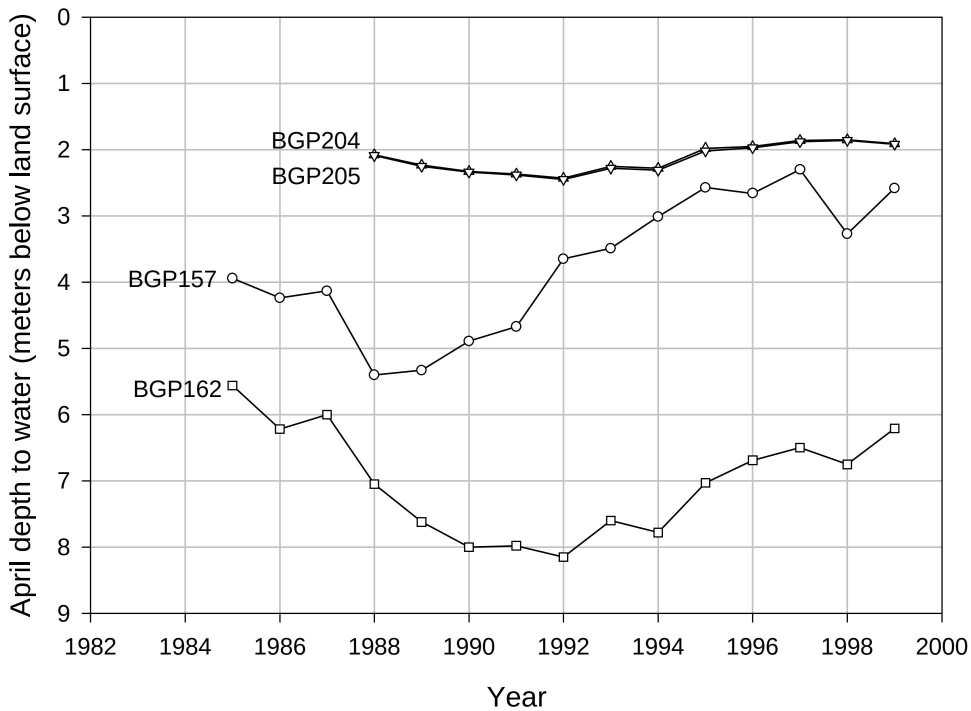

Figure 22. BGP204 and BGP205 hydrographs are of doubtful use, due to their distance and segregation by the river from any test wells. Note the large standard error for these parcels in Table 3. BGP157 is consistent with 428T, 429T, and 469T (including decline in 1998); BGP162 is consistent with 571T, 469T, 799T, and 569T.

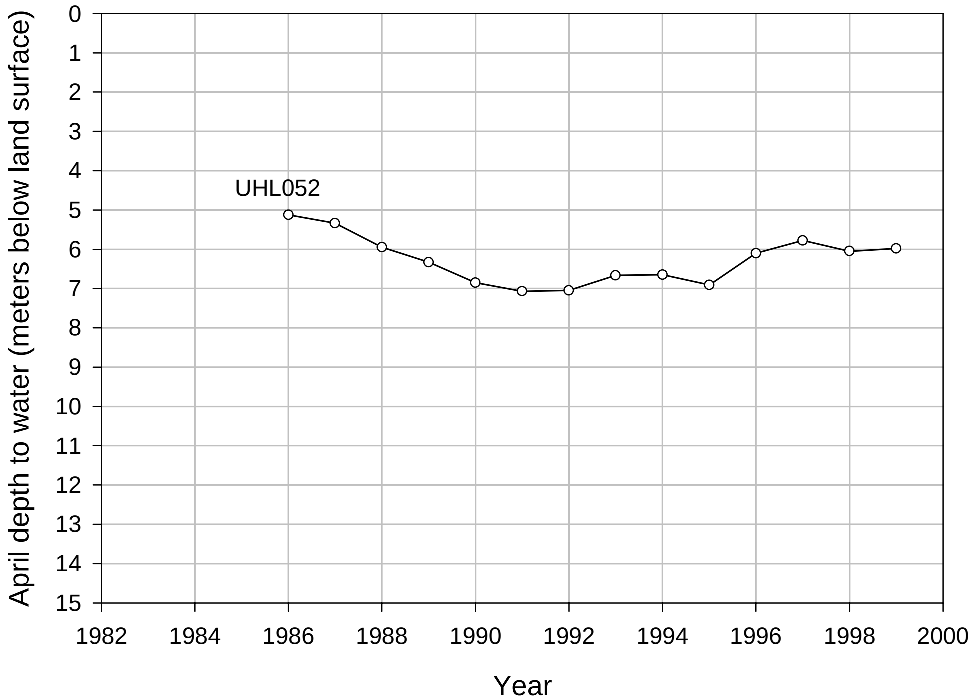

Figure 23. An anomaly in 1985 due to the absence of V0016B was removed; the parcel hydrograph is consistent with that well thereafter.

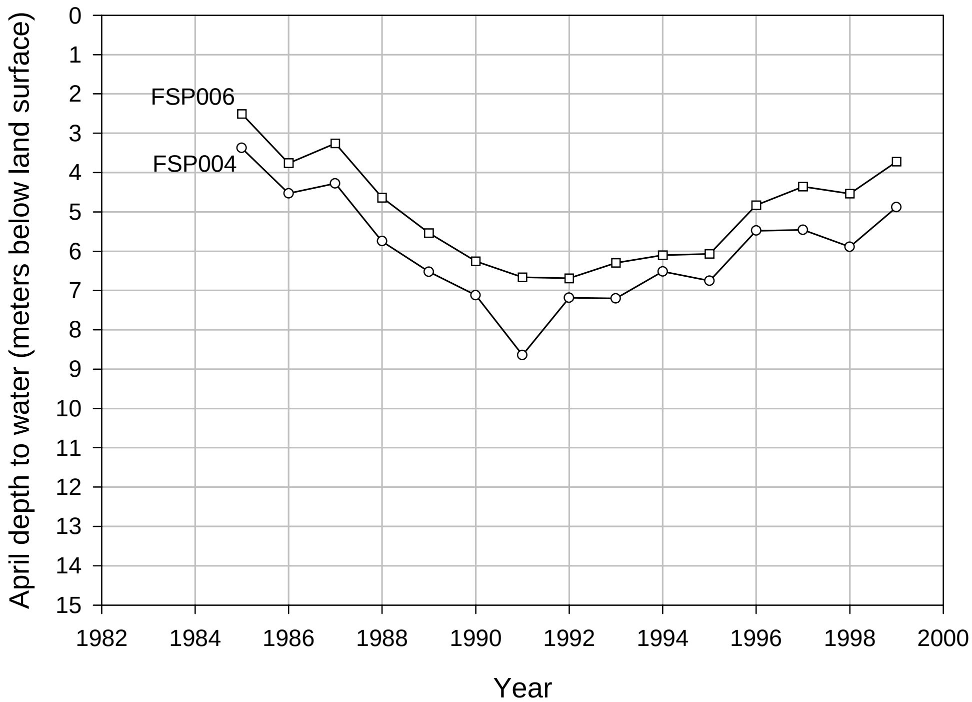

Figure 24. Both FSP004 and FSP006 are consistent with wells 567T, 568T, and 425T.

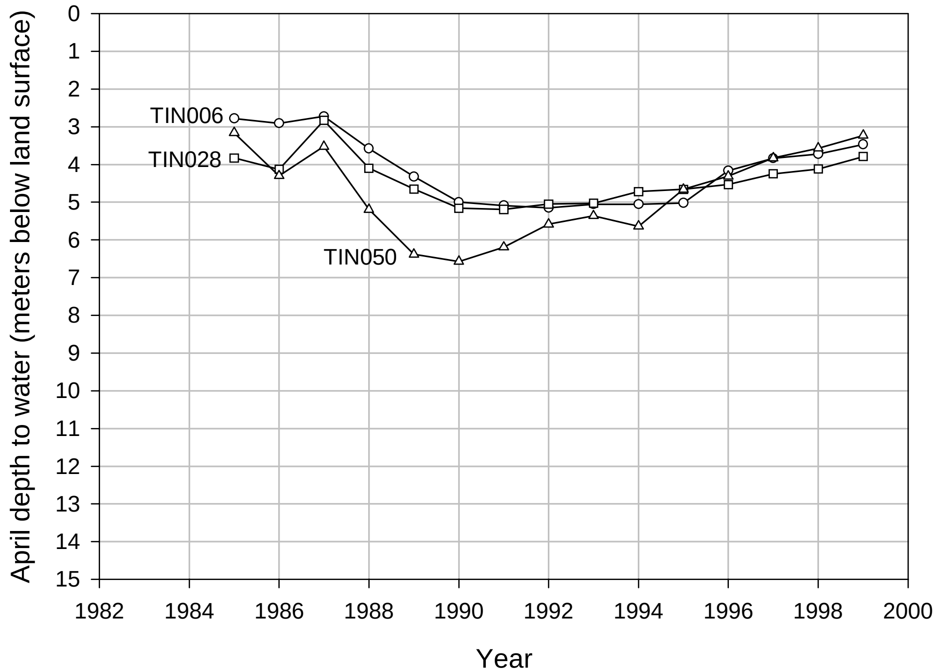

Figure 25. TIN006 is consistent with well 426T, which is within the parcel. The decline and rise during 1986 and 1987 in TIN028 is consistent with wells 556T and 425T. TIN050 is consistent with 502T. Because 502T occupies a position on the fan above the parcel, the actual DTW for the parcel is probably less than estimated because of the influence of 502T.

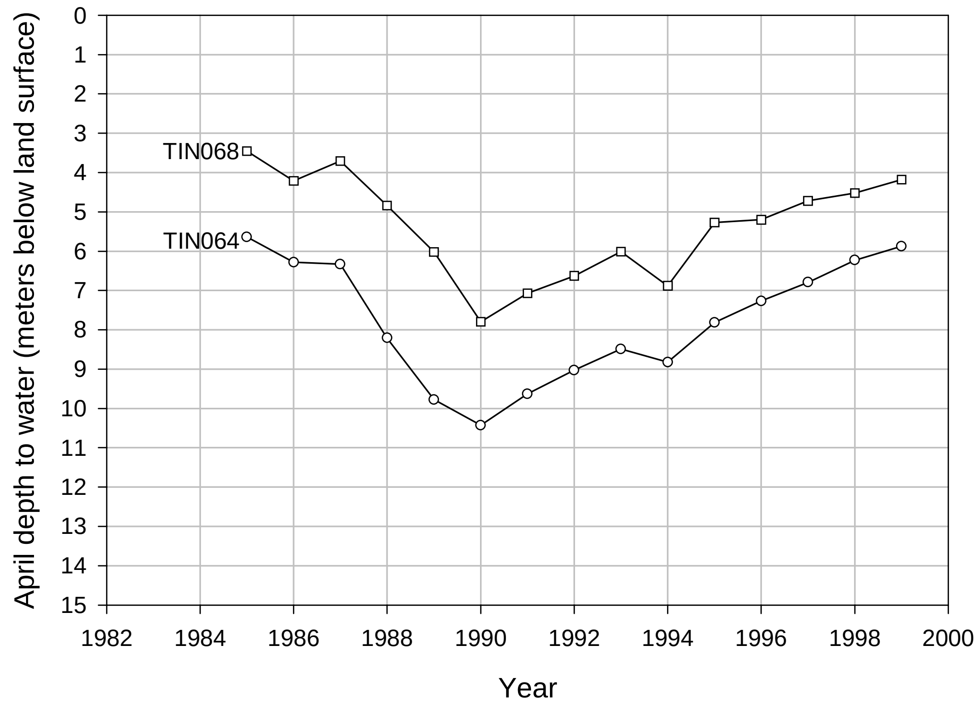

Figure 26. TIN064 and TIN068 are consistent with wells 420T and 421T.

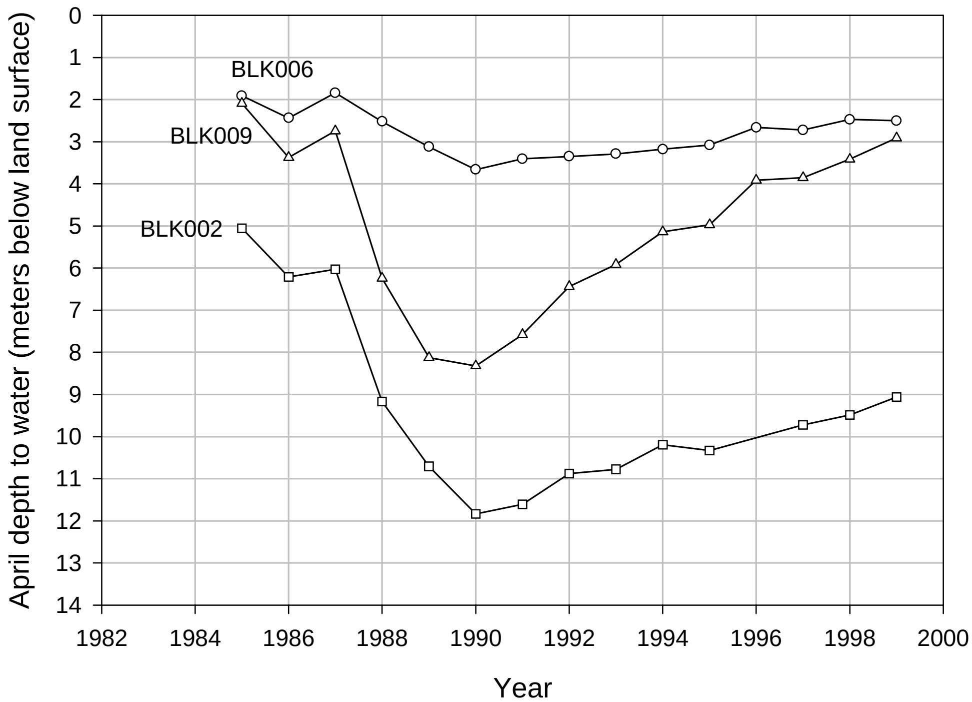

Figure 27. BLK002 is problematic: its hydrograph is inconsistent with wells 420T and 421T. The well hydrographs show more recovery to baseline than the parcel hydrograph. This is because wells 671T, 672T, and 675T did not contribute to the baseline estimates, but after 1989, these wells' relatively deep water tables result in increased parcel-averaged DTW estimates relative to baseline. An anomaly in 1996 resulted from the absence of 671T and 672T, for similar reasons as the discrepancy in recovery to baseline.

BLK006 is consistent with well 421T. The subdued drought effect in this parcel is probably due to buffering by the proximity of the Owens River. BLK009 is consistent with wells 504T and 586T. The anomaly in 1986 present in all three of these parcel hydrographs is probably real; it is consistent with wells 421T, 502T, and 504T.

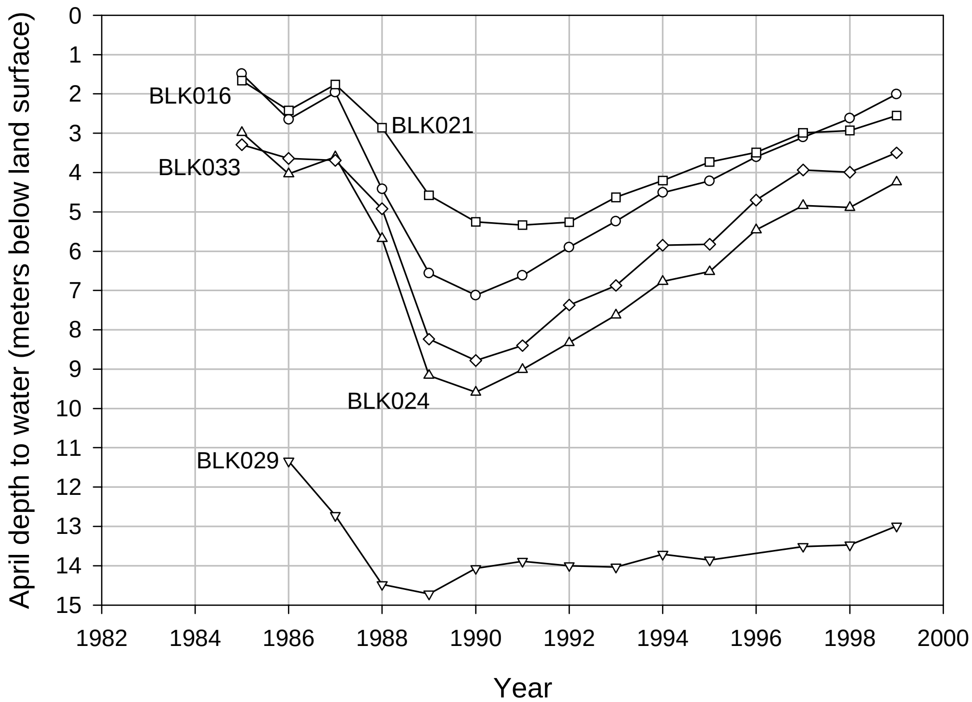

Figure 28. BLK016, BLK021, BLK024, and BLK033 are consistent with the nearby monitoring wells 418T, 419T, 504T, 505T, and 455T. An anomaly in 1996 due to the absence of 665T and 666T was removed from the hydrograph for BLK029. BLK029 probably suffers from the same flaw as BLK002: because wells were installed after the baseline period that have deeper water tables than the wells from which baseline was derived, the parcel hydrograph is not recovering to baseline.

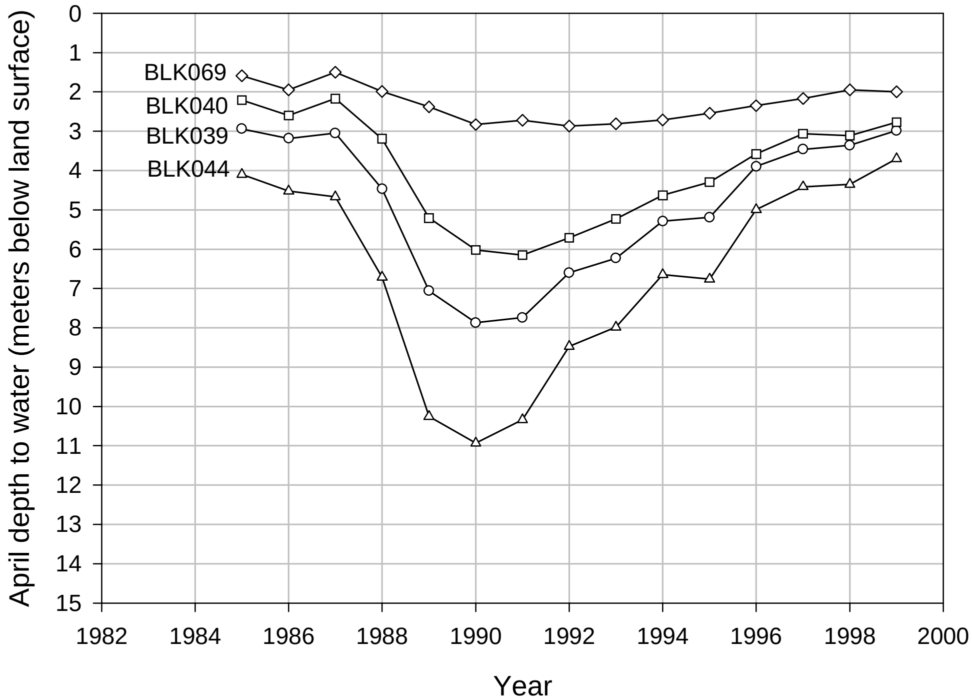

Figure 29. BLK039 shows more recovery than wells 417T and 455T, probably due to the installation of well 803T after the baseline period. BLK040 is consistent with wells 455T and 505T. BLK044 shows more recovery than 417T, also probably due to the addition of well 803T after the baseline period. The subdued drawdown beneath BLK069 is probably due to buffering by nearby surface water bodies; its hydrograph is consistent with 507T and 584T.

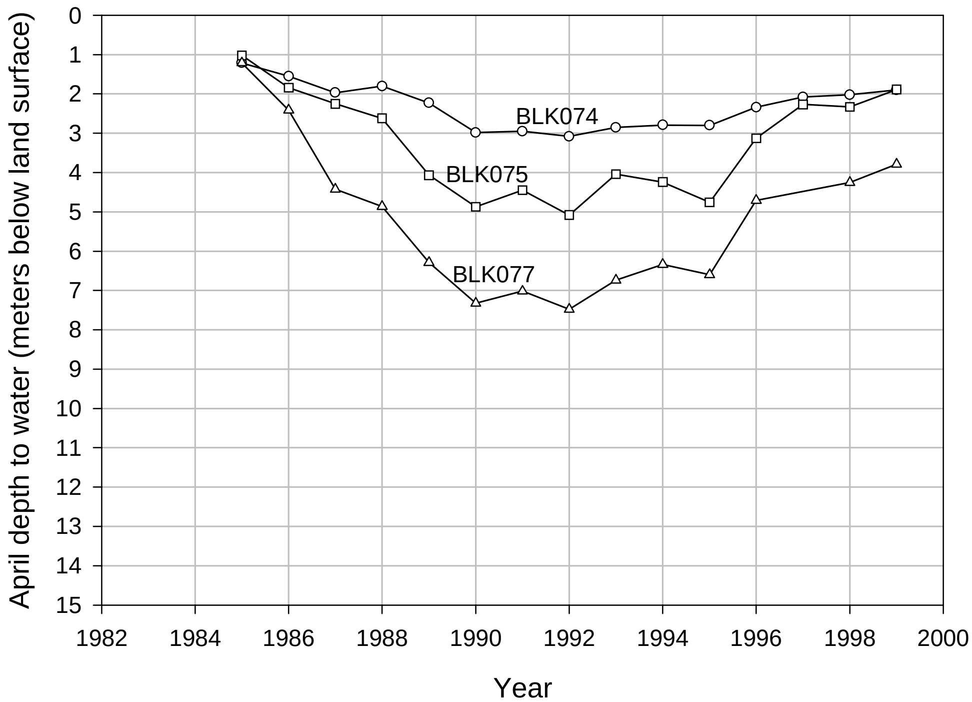

Figure 30. BLK074 and BLK075 are consistent with wells 416T, 417T, and 584T. BLK077 had an anomaly in 1996 due to the absence of data from 415T. Otherwise, the BLK077 parcel hydrograph is consistent with nearby wells.

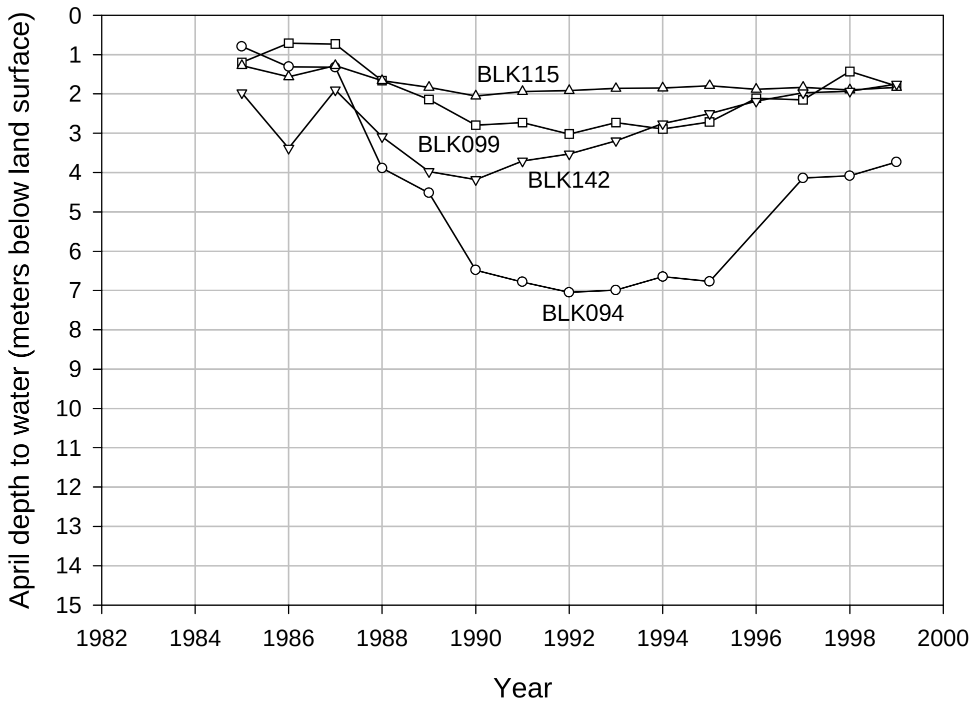

Figure 31. BLK094 had an anomaly in 1996 due to the absence of data from wells 660T and 807T, and displays less recovery than well 582T, possibly due to the addition of 806T and 807T since the baseline period. BLK099 is consistent with well 581T. BLK115 is consistent with 458T; the subdued drawdown and shallow water table of both the parcel hydrograph and well hydrograph are due to buffering by nearby surface water. Anomaly in 1986 in BLK142 is probably real; it is consistent with 504T. Recovery of BLK142 is consistent with 420T and 586T, and greater than 504T.

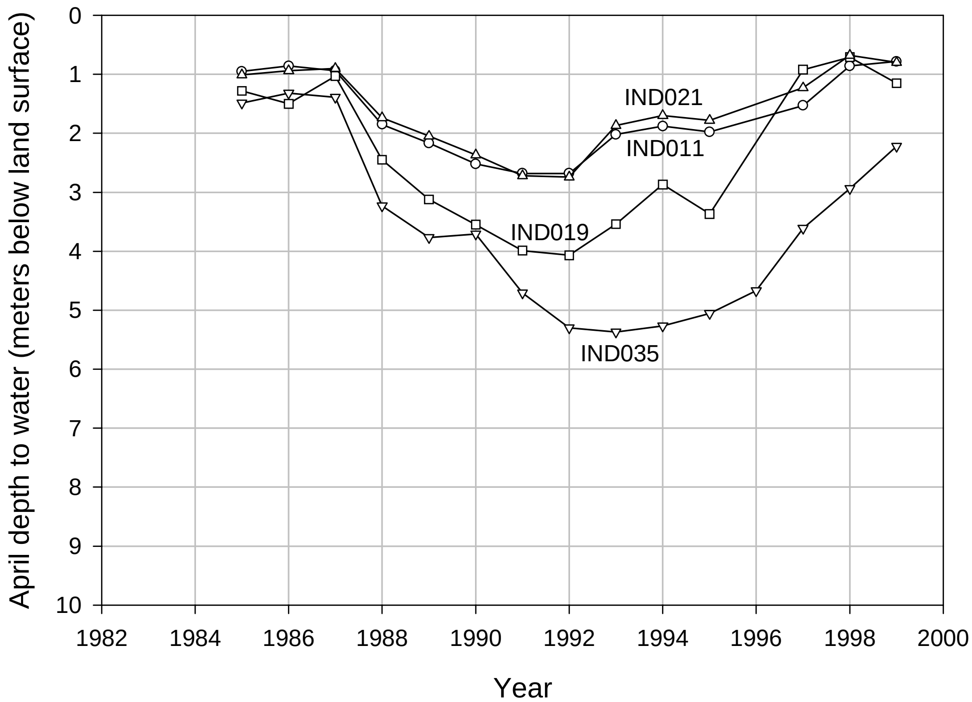

Figure 32. IND011, IND019, and IND021 are consistent with nearby wells 411T, 452T, and 453T. These three parcels each had an anomaly in 1996 due to the absence of data from wells 411T, 412T, and 453T. The baseline DTW for IND035 was derived without data from well 808T; therefore, though no glaring anomalies are apparent, the comparison between baseline and the recovery period is doubtful. The earliest record from well 808T is in 1990, which may account for the cusp in the hydrograph at that point.

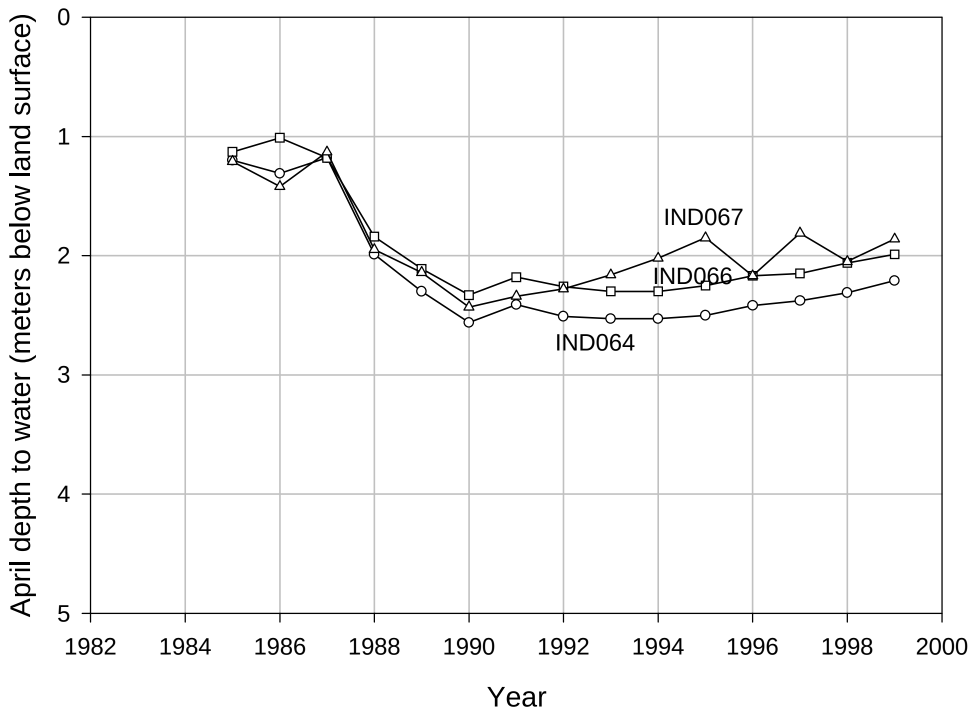

Figure 33. IND064, IND066 and IND067 are consistent with wells 374T, 382T, 450T, and 451T. The lack of recovery of these hydrgraphs to baseline is largely a reflection of water spreading activities in this area in 1983 and 1986.

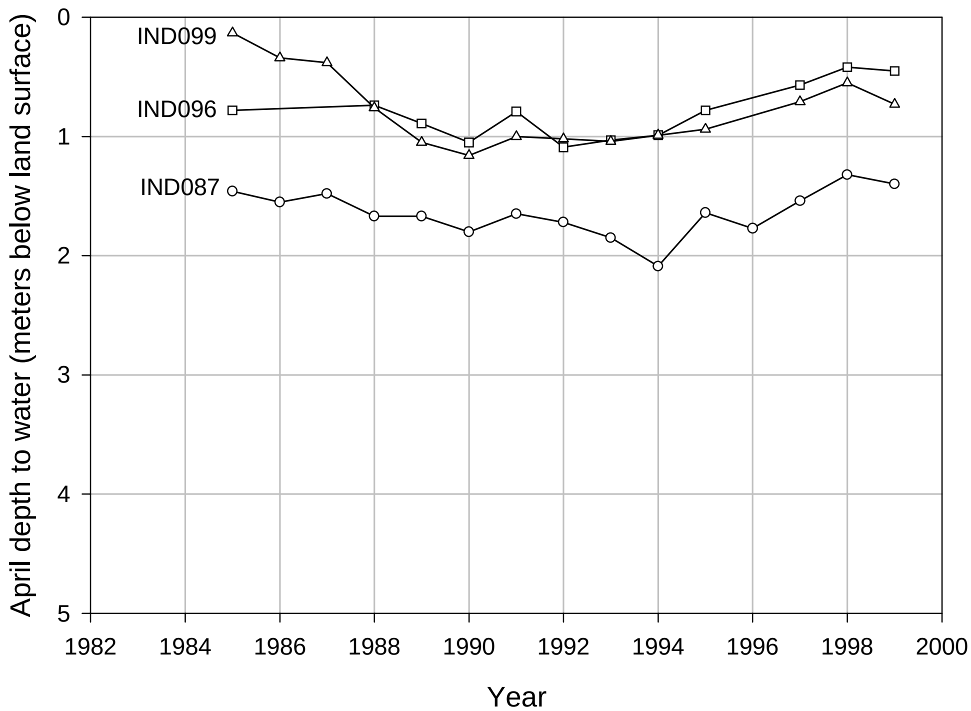

Figure 34. IND087 is consistent with well 451T. IND096 and IND099 had an anomaly during 1986 and 1987 due to drawdown due to the USGS fast drawdown site, and an anomaly in 1996 due to an absence of data from USGS site H. Otherwise, these hydrographs are consistent with wells 405T and 509T.

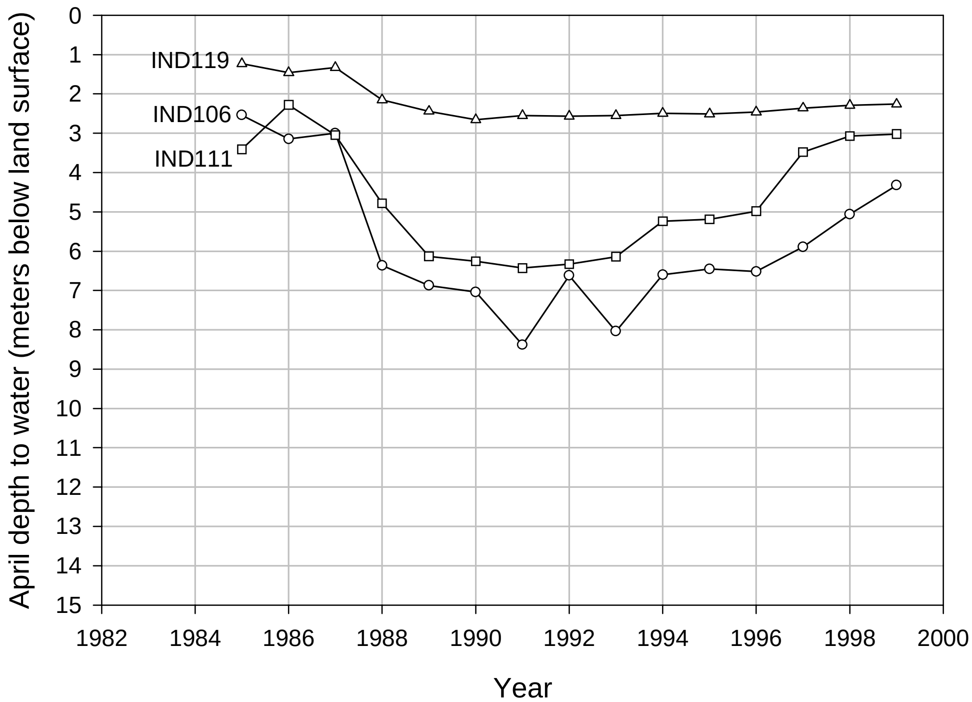

Figure 35. IND106 is consistent with wells 548T, 555T, and 556T. These wells were dry during the drought of the early nineties, so it is likely that the DTW was actually deeper than the hydrograph shows. IND111 is consistent with wells 552T, 809T, and 554T. IND119 is influenced by water spreading during 1983 and 1986, similar to IND064, IND066, and IND067.

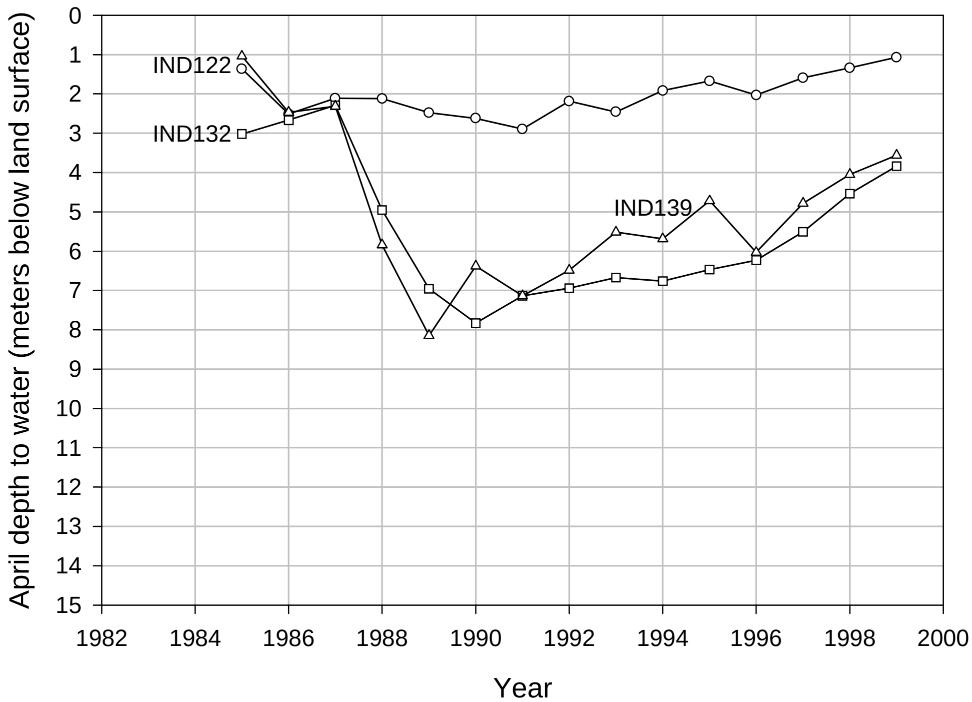

Figure 36. IND122 is consistent with 550T, but has recovered more than wells 407T and 548T. 1985 may be anomalous due to the absence of data from 548T and 555T. IND132 is consistent with 547T. IND139 is consistent with wells 403T and 404T.

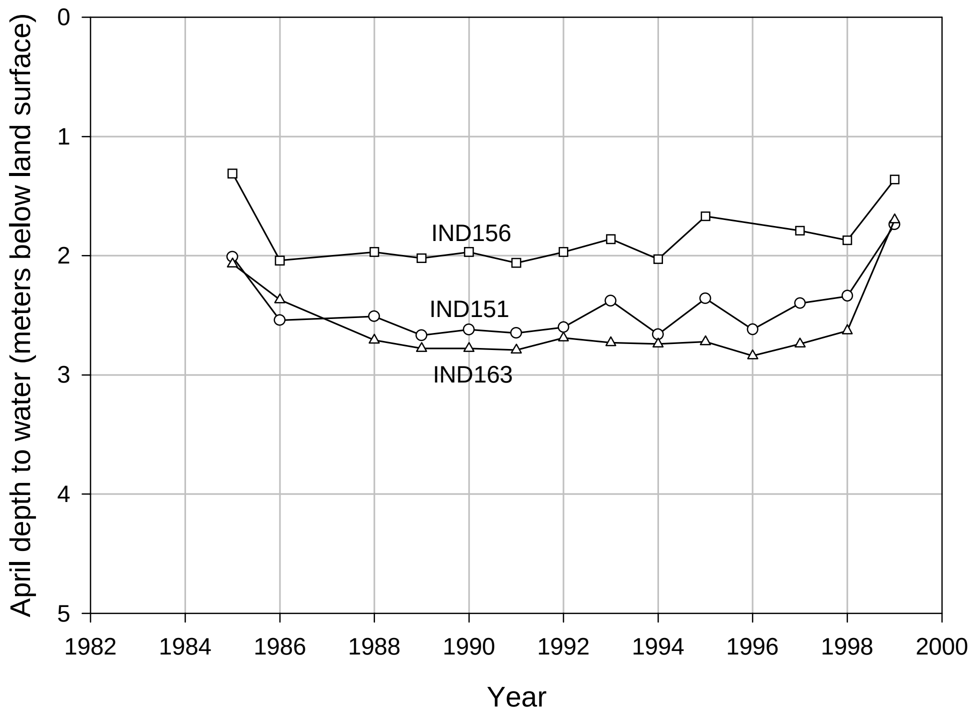

Figure 37. IND151, IND163, and IND156 are consistent with wells 440T, 442T, and 443T, except for the increase in 1999. This increase is due to the absence of 449T in the 1999 data. These wells were apparently affected by spreading during the mid-eighties, similar to the IND064 area.

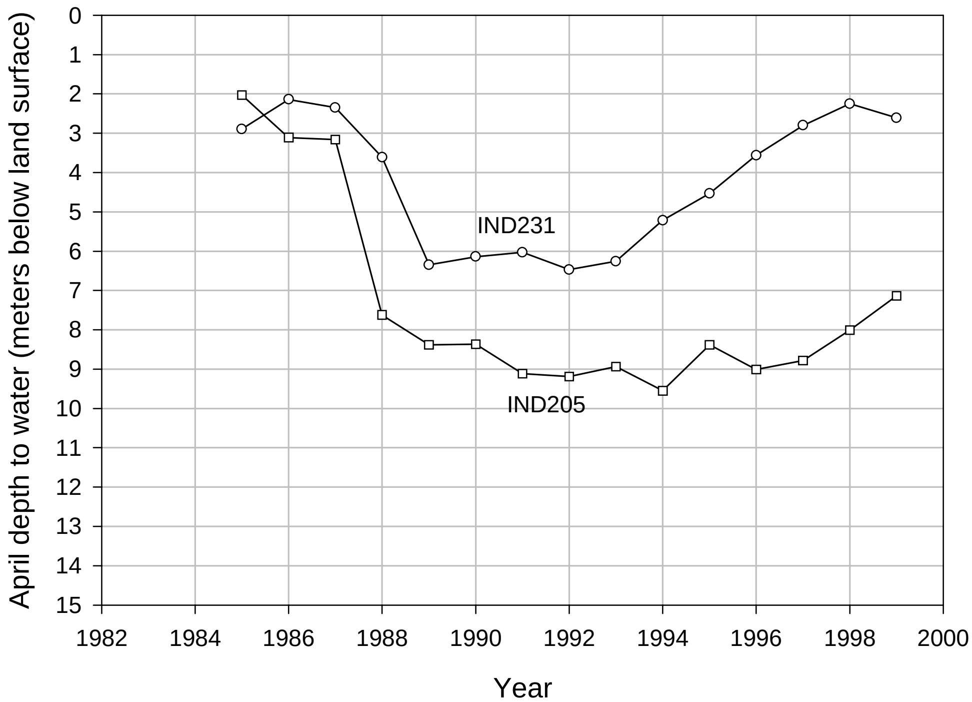

Figure 38. IND231 shows more recovery than 511T; there is a pronounced DTW gradient across this parcel, with greater DTW on west side. IND205 shows less recovery than 546T or 552T.

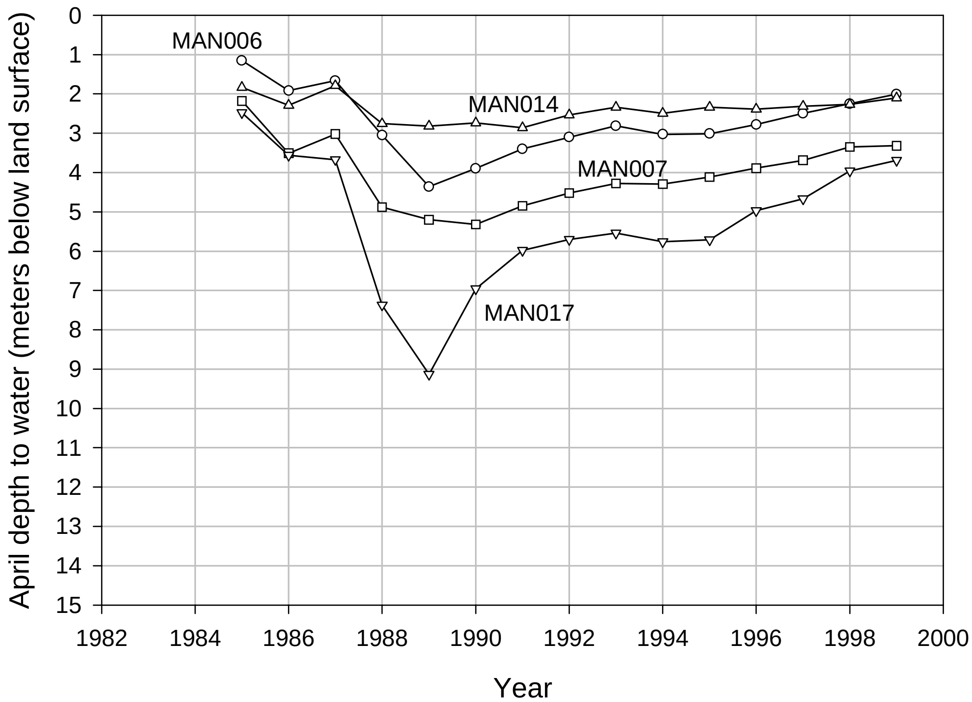

Figure 39. MAN006 is consistent with 403T, 404T, and 562T. MAN007 is consistent with the many wells within this parcel. MAN014 is consistent with 443T. MAN017 is consistent with 364T and 562T; but baseline DTW coverage is poor in this area.

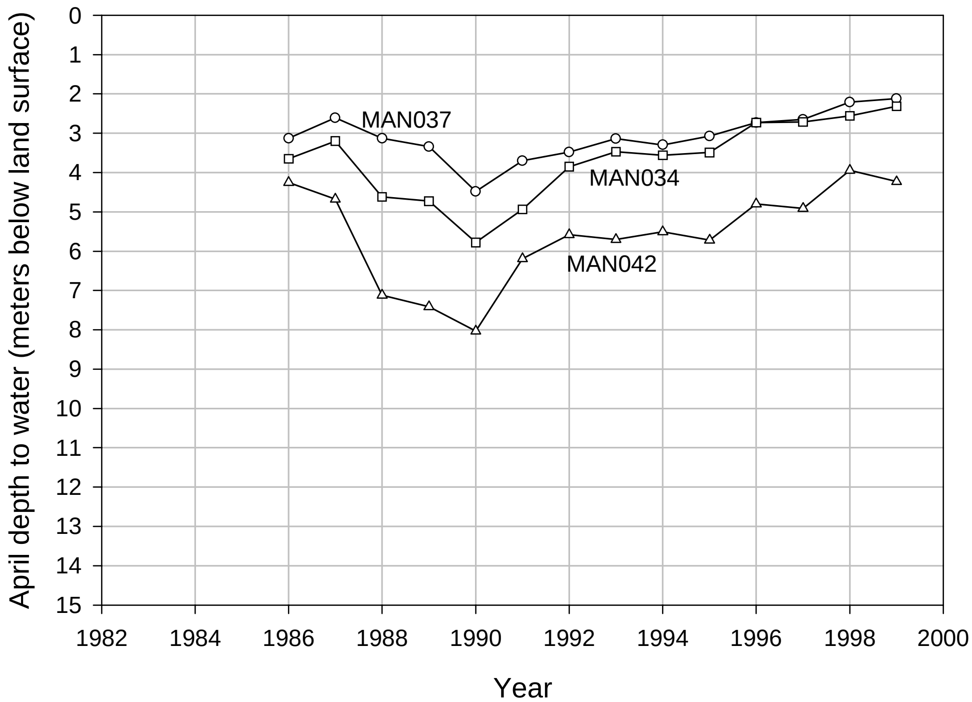

Figure 40. The estimate for 1985 for all three of these parcels is suspect due to poor well coverage. MAN037 and MAN034 show more recovery than nearby wells 598T and 599T. DTW estimates for MAN042 are suspect due to sparse data.

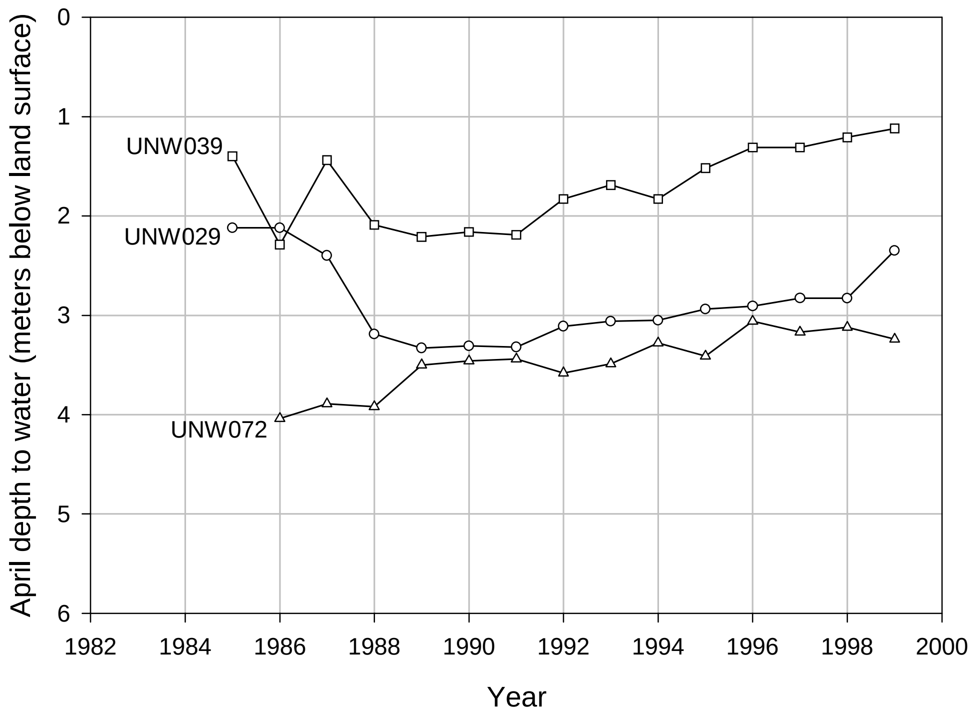

Figure 41. UNW029 has no nearby wells, but is consistent with 442T, 1.6 km to the north. UNW039 is consistent with 444T (the anomaly in 1986 is apparently real). UNW072 has no nearby wells and is near geologic features that complicate the hydrology (the bedrock of the Alabama Hills, the Owens Valley Fault); therefore, this hydrograph is suspect.

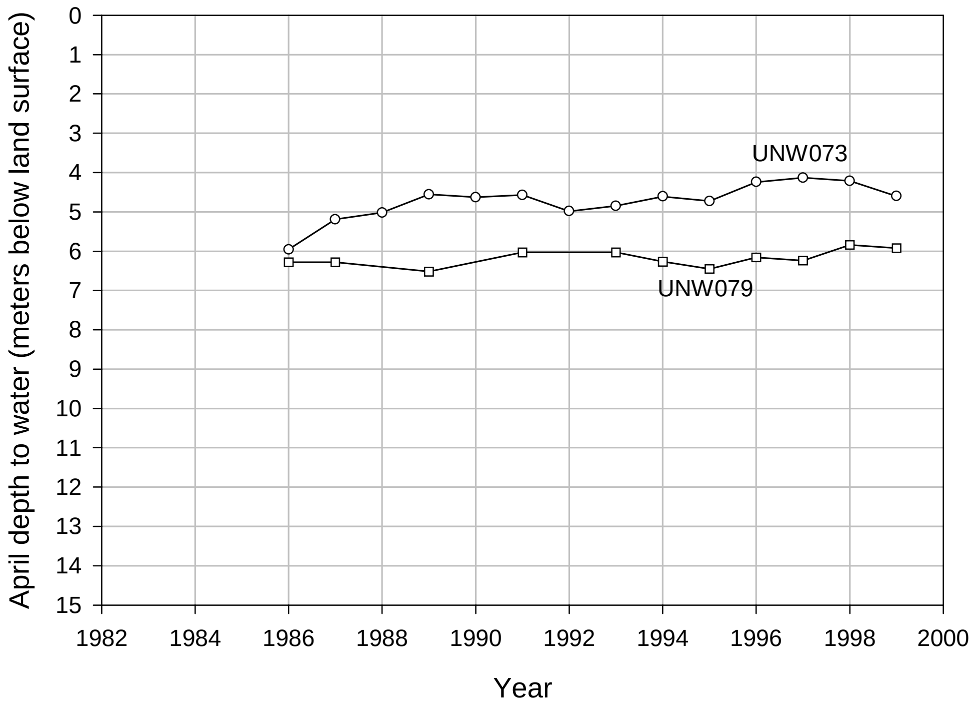

Figure 42. UNW073 is suspect for the same reasons as UNW072. UNW079 had oscillations due to an intermittent record for well 445T; these were removed. The hydrograph for UNW079 is probably inaccurate because the nearest wells (393T, 394T, 395T, and 396T) all lie upslope from the parcel.

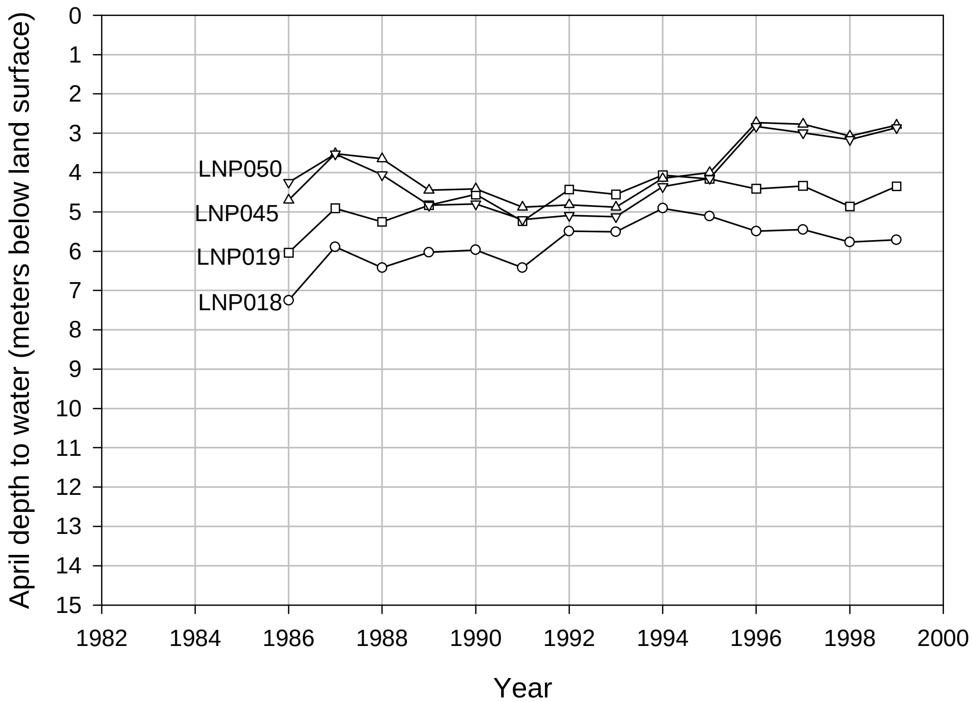

Figure 43. The general trends of LNP018, LNP019, LNP045, and LNP050 are consistent with Lone Pine area monitoring wells.

RECOMMENDATIONS

Variograms. Variogram models should be developed and used in future DTW mapping efforts. The experimental variograms produced for this report had well-defined ranges and sills, and no extraordinary problems were encountered with these relatively well-behaved data. Cross validation suggested that anisotropic variograms provided a consistent (however modest) improvement over isotropic variograms. It is recommended that future gridded DTW products be developed using spherical anisotropic variograms. The feasibility of using a single variogram for all years should be investigated.

Dry wells. The procedure described earlier, where dry wells are treated on a case by case basis and only included in the kriging data set when they produce a definite improvement in estimation, should be adopted for the future development of gridded DTW maps. The method is systematic and dry wells are only added to the data set where the kriged water table would be above the bottom of the dry well. The large number of dry wells that were added to the wet well data provides a significant improvement in DTW estimates in some regions.

Surface water points. The cross validation results described above clearly show that including the surface water points in the kriging data set biases the water table upward in areas near surface water bodies and produces unrepresentative kriging variances. Removing the surface water points removed most of the bias and resulted in more representative kriging variances. While the addition of supplemental surface water points was a plausible and worthy idea, it appears to degrade DTW estimates. It is recommended that future gridded DTW maps be produced without the surface water points. As noted below, this conclusion may not hold for other variables such as WTE or change in DTW.

Assessment of uncertainty. For this application, the smoothly varying and homoscadastic nature of the DTW field and the cross validation results justify use of the kriging variance to quantify confidence intervals about the mean DTW estimate for a parcel. The cross validation results given in Table 3 indicate that anisotropic spherical variograms applied to data sets without surface water points provide relatively unbiased and representative estimates of the uncertainty associated with DTW estimates.

Further work. The level of uncertainty in kriged DTW estimates can be rather high (Table 3), which suggests that further refinement of DTW mapping strategies may be warranted. Annual April DTW was the only variable explored in this effort, but other variables, such as WTE or change in DTW, may provide better estimates of the position of the water table. The conversion of DTW to WTE is straightforward if the land surface elevation is known; however, in terms of interpolation and extrapolation, WTE and DTW are fundamentally different variables. When DTW is extrapolated away from a data point, the extrapolated estimate tracks changes in topography, because the land surface is the reference point for the DTW measurement. In contrast, because WTE is referenced to a fixed elevation, when it is extrapolated away from a data point it maintains a constant elevation. The relation between the estimated DTW, estimated WTE, and the true position of the water table will depend on the configuration of the observation points, topography, and water table. This relationship is illustrated in Figure 44. In general, it is not clear whether DTW or WTE will provide a better representation of the true position of the water table. Local topographic variability is a source of noise in DTW measurements, and using WTE as the interpolated variable may remove some of this noise. These considerations suggest that water table maps developed from WTE are likely to differ from maps developed from DTW. DTW is the relevant variable for relating hydrologic fluctuations to vegetation conditions; therefore, WTE maps would need to be converted to DTW by subtracting WTE from a digital elevation model (DEM). This would require scrutiny of errors in the DEM and the consistency between the well RP elevations and the DEM elevations. WTE has a regional trend reflecting the regional down-valley topographic gradient and groundwater flow, which should be accounted for in the kriging procedure. Though not intractable, these difficulties motivated conducting the current effort using DTW rather than WTE. Considering the large errors that are probable in DTW interpolations, it may be worthwhile to explore the use of WTE or other variables in the future.

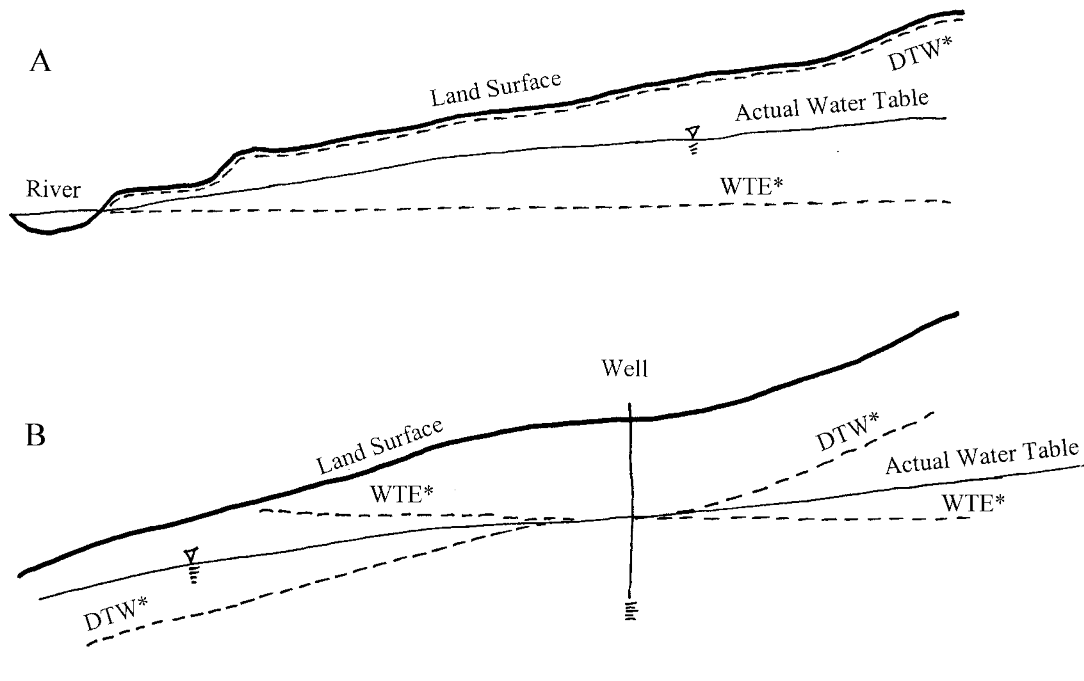

Figure 44. This figure illustrates the difference between DTW and WTE with respect to interpolation or extrapolation. Asterisks denote variables estimated by spatial interpolation/extrapolation. 44A shows how assigning a value of DTW = 0 to surface water bodies results in an underestimate of DTW as the water table is extrapolated up the topographic slope from the surface water body. Conversely, using water table elevation as the interpolated variable results in an overestimate of the depth to water. 44B shows the relation between a sloping topographic surface, a well used for estimation, the actual water table, and estimates of the water table position based on DTW and WTE. Similar to the situation in 44A, DTW and WTE produce intrinsically different interpolations, because DTW is measured relative to the land surface, and WTE is measured relative to a fixed elevation datum.

Another variable worth exploring is annual change in depth to water, as done in previous efforts (Jackson, 1996). Change in DTW maps could be made in two ways: one could either take the observed change in wells and interpolate those data to produce a grid of change in DTW, or one could produce interpolated grids of DTW and subtract the grids. A determination of which method of estimating change in DTW is preferrable should be made using a cross validation strategy similar to the one used in this report to assess the use of surface water points.

Another promising opportunity for improving DTW is by exploiting the correlation of DTW with other variables through the use of cokriging (Deutsch and Journel, 1998; Isaaks and Srivastava, 1989). Cokriging utilizes one or more secondary variables that are correlated to the primary variable improve the estimation of the primary variable. Thus, the weighted average given in Equation 1 is extended to incorporate a second variable,

$$z^* = \sum_{i=1}^{n} w_i z_i + v_i y_i \qquad 9$$

where y is a spatially distributed variable that is correlated to z, and the weights v are analogous to w. Cokriging has the potential to incorporate information from other variables into the DTW estimate, a capability that is not available with simpler interpolators or surface fitting routines. Topographic elevation (Hoeksma et al, 1989), vegetation type, or the output of a groundwater flow model are possible secondary variables that might be used to improve DTW estimates.

Finally, the accuracy of the kriged estimates is directly influenced by proximity of data to the point where the estimate is being made. This suggests that (1) more monitoring wells would benefit future DTW estimation efforts, and (2) the work presented here may be useful in siting future monitoring well sites.

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APPENDIX I.

Depth to water (DTW) data. Coordinates are UTM zone 11 NAD 27 (McGhie, 1997). Data are depth to water in feet below land surface, taken from LADWP monthly well reports. Blank fields indicate no reading was taken. "—" indicates the well was wet at the depth given; "D" indicates well was dry; bold faced "**D**" indicates that the dry well was included in the kriging data set.

APPENDIX II.

DTW variograms. Lines with open circles are experimental varigrams computed using equation 2; solid lines are model variograms fit to the experimental variograms using equations 3a and 3b.

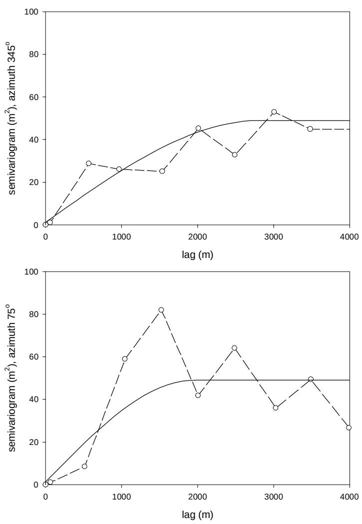


Figure A2.1. 1985

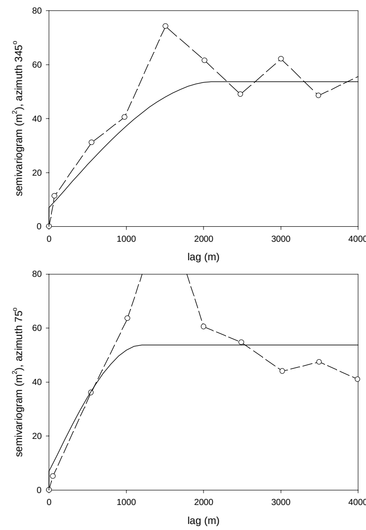


Figure A2.2 1986

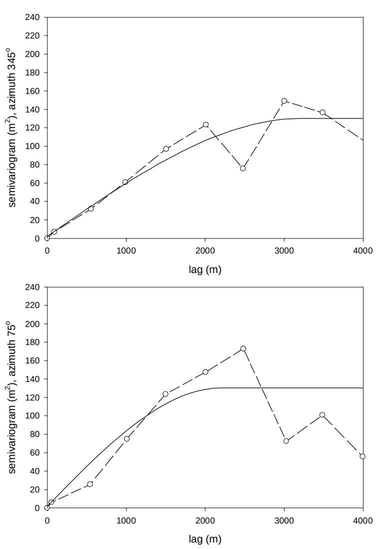


Figure A2.3 1987

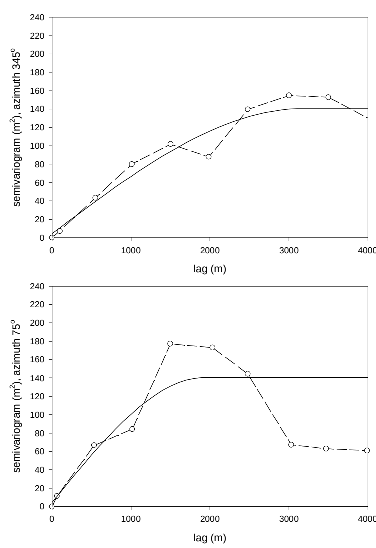


Figure A2.4. 1988

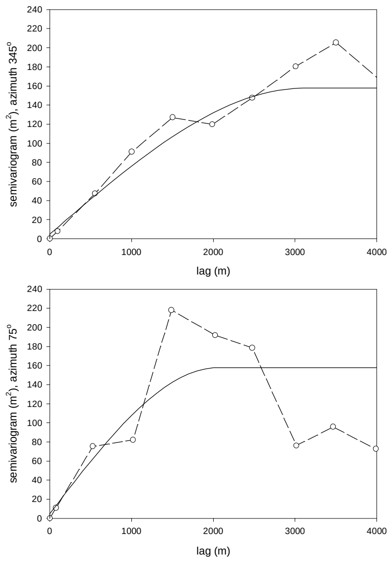


Figure A2.5 1989.

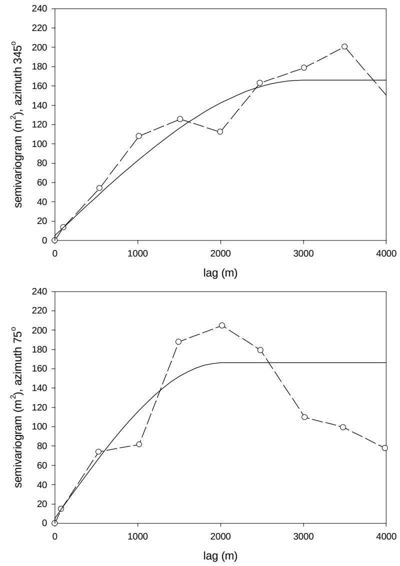


Figure A2.6. 1990.

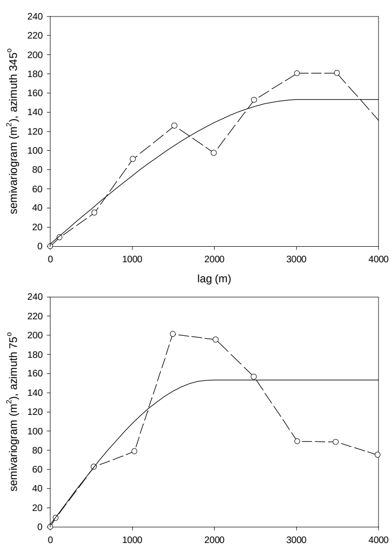


Figure A2.7. 1991.

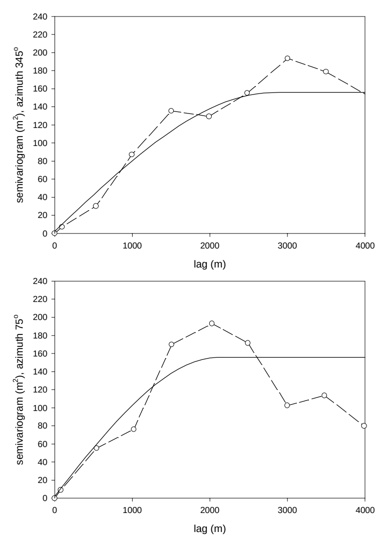


Figure A2.8. 1992

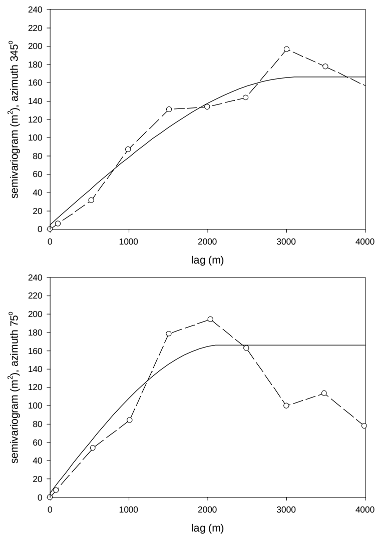


Figure A2.9. 1993

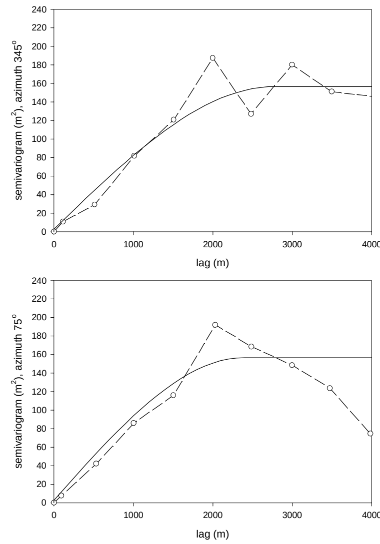


Figure A2.10. 1994.

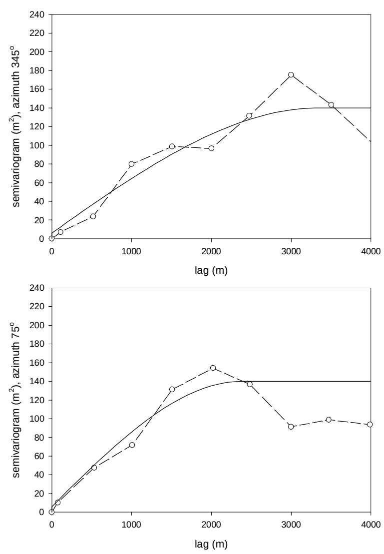


Figure A2.11. 1995.

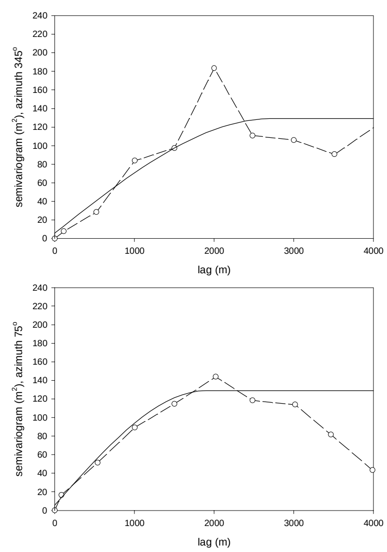
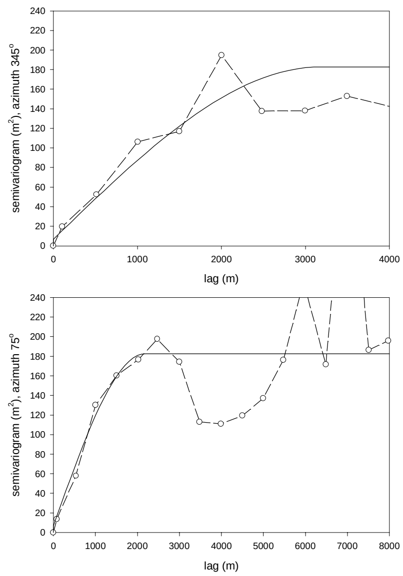


Figure A2.12. 1996



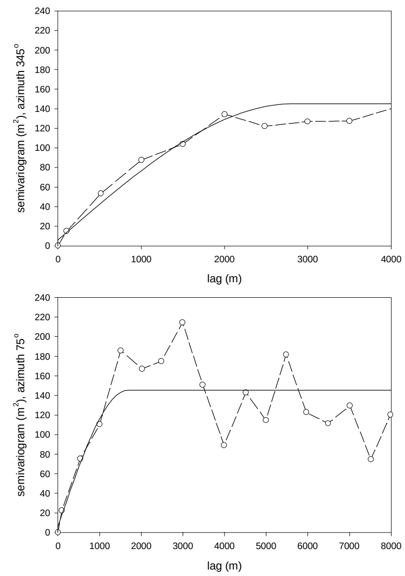


Figure A2.12. 1997.

Figure A2.13. 1998.

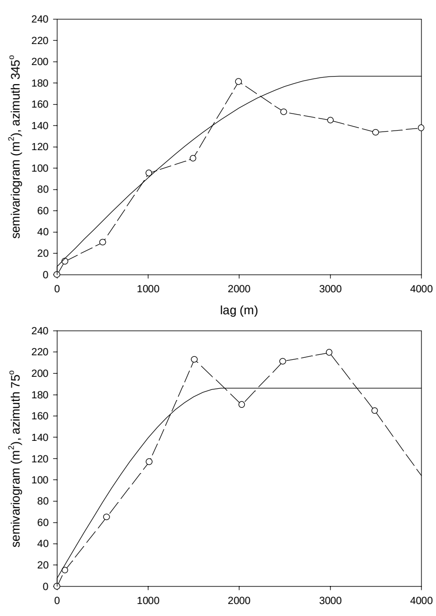


Figure A2.14. 1999.