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ANALYSIS OF WATER LEVEL FLUCTUATIONS IN PAJARITO PLATEAU WELLS

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Abstract—Groundwater below Pajarito Plateau occurs in the shallow alluvium of some large canyons, discontinuous intermediate layers within lower portions of the Bandelier Tuff, Puye Fanglomerate, and Cerros del Rio basalt flows, and in the main aquifer within the Puye Conglomerate and Santa Fe Group sediments. These distinct water sources are separated by thick unsaturated volcanic deposits, erosional debris, and basalt flows. Hydraulic communication between sources is unclear. However, traditional time series analyses of water level fluctuations within each of these units can be used to quantify recharge. Although records are tantalizingly short, low-frequency, seasonal water-level oscillations in alluvial, intermediate, and main aquifer wells imply at least some intercommunication. Preliminary observations suggest that several factors are influencing aquifer water levels. These include cyclical drawdown in response to municipal water production, and seasonal recharge from canyon-bottom infiltration. Atmospheric pressure and solar-lunar earth tide effects are also identified in main aquifer wells. Collectively, these results suggest that portions of the main aquifer below Pajarito Plateau are partially confined, and that significant Plateau recharge areas within Los Alamos County are probably limited to large canyon bottoms containing perennial alluvial waters.

INTRODUCTION

The physiographic, geologic, and hydrologic setting on Pajarito Plateau is described in detail by others in this Guidebook. Los Alamos County is centrally located on the Plateau at 7000 ft, with Sierra de los Valles on the west above 10,000 ft and the Rio Grande on the east at 5400 ft. Thirteen watersheds drain the roughly 17 mile distance across the Plateau from the western headwaters, east-southeast toward the Rio Grande (McLin, 1992). The two-dimensional piezometric surface for the main aquifer appears as a subdued reflection of this drainage topography (Frenzel, 1995, fig. 16; Rogers et al., 1996, figs. 2-4).

Groundwater occurs in three distinct modes below Pajarito Plateau: (1) water in shallow alluvium in some of the larger canyons; (2) perched water in discontinuous intermediate layers within lower portions of the Bandelier Tuff on the western boundary, and the Puye Fanglomerate or Cerros del Rio basalt flows on the eastern boundary; and (3) the main aquifer in and below the Puye Conglomerate (Purtymun, 1995). All the municipal water supply wells on the Plateau produce water from Santa Fe Group sediments, which lie below the Puye (Purtymun et al., 1995a). The main aquifer is under artesian conditions along the eastern margin of the Plateau near the Rio Grande, and phreatic conditions farther to the west. In addition, the presence of numerous springs located within White Rock Canyon suggests that the Rio Grande is receiving a base-flow component from the main aquifer.

This paper examines historical (annual) and recent (hourly) water level trends in these aquifers using traditional time series techniques (Chatfield, 1984). Time domain plots reveal temporal pumping influences, seasonal effects, or water level trends. Frequency domain techniques identify the cyclical characteristics of these water level fluctuations, in addition to providing aquifer parameters (Hsieh et al., 1987; Ritzi et al., 1991). The ultimate objective of this exercise is to quantify the relative significance of spatial and temporal aquifer recharge mechanisms (Gelhar et al., 1979). For example, seasonal variations in alluvial, intermediate, and main aquifer water level series may suggest potential canyon-bottom recharge to the main aquifer. One might expect to see amplitude reductions and phase shifts in cyclical water level patterns between multilevel aquifers as water migrates through thick vadose layers separating these zones of saturation. The absence of any patterns may imply little or no hydraulic communication between isolated aquifer systems. An intermediate goal of these efforts is the development of physically-based, characteristic water level filters (e.g., Duffy and Harrison, 1987) that separate high-frequency background noise from low-frequency recharge. Sources of this noise include cyclical pumpage, atmospheric pressure variations, and solid earth tidal effects.

HISTORICAL WATER LEVEL TRENDS

Water levels have been measured annually in wells tapping the main aquifer since the late 1940s when the first exploratory wells were drilled by the U.S. Geological Survey (Purtymun et al., 1995b). These data represent non-pumping water level series from Los Alamos, Guaje, Pajarito, and Otowi municipal well fields (Fig. 1). In addition, annual water levels dating from the early 1950s and 1960s are also available from numerous main aquifer test wells. Collectively, these data confirm a plateau-wide declining trend in main aquifer water levels in response to municipal water production. The largest declines, represented by more than 100 ft of non-pumping drawdown, occur in the vicinity of the Guaje and western parts of the Los Alamos well fields (Rogers et al., this volume). Intermediate changes, represented by about 50 ft of non-pumping drawdown, occur in the central portion of the Plateau that is influenced by the Pajarito and Otowi well fields. The smallest changes, represented by about 10 ft of non-pumping drawdown, occur in the western and southern portions of the Plateau where no production wells are located. Finally, in those areas adjacent to the Rio Grande at Otowi Bridge, near-original artesian conditions have been reestablished in response to the 1991 abandonment of the Los Alamos well field.

Test wells penetrating to the main aquifer show water level declines ranging from less than 10 to about 35 ft over the 46-year period of record. These gradual trends are in response to increasing annual pumping rates from municipal supply wells. They fall into four geographic groups. The westernmost well, TW-4, shows less than 10 ft of change. The southernmost group of wells, DT-5A, DT-9, and DT-10, show declines ranging from 10 to 15 ft since 1960. TW-8, located in the central portion of the Plateau, shows a decline of about 25 ft, and is within the range of declines seen in the Pajarito supply wells. The north-central wells, TW-2 and TW-3, both show about 35 ft of decline over the period of record. All of the main aquifer wells penetrate to varying depths and hydrogeological units, as summarized in Table 1.

The importance of long-term water level declines in the main aquifer below Pajarito Plateau is unclear at present. A simple hydraulic comparison of these drawdown levels with the known saturated thickness of the main aquifer suggests that impacts are not significant (i.e., the Boussinesq approximation). However, water quality variations at depth within the main aquifer are not fully understood. Hence excessive drawdown associated with concentrated and prolonged pumpage may induce vertically upward flow of naturally contaminated geothermal fluids, as was apparently the situation at well LA-6 (Purtymun, 1977). This well began to yield excessive arsenic concentration levels in 1976, and the well was subsequently abandoned. It was suspected that this arsenic originated from naturally contaminated groundwater migrating vertically upward from formations located below the bottom of the well screen, much like the saltwater upconing phenomenon in coastal wells. This interpretation suggests that long-term declines in water levels, or excessive drawdown near individual production wells, may represent a significant potential impact to water quality that might affect water supplies. Hence, a major goal of future investigations should be the delineation of vertical changes in piezometric head and water quality so that this potential effect can be clarified.

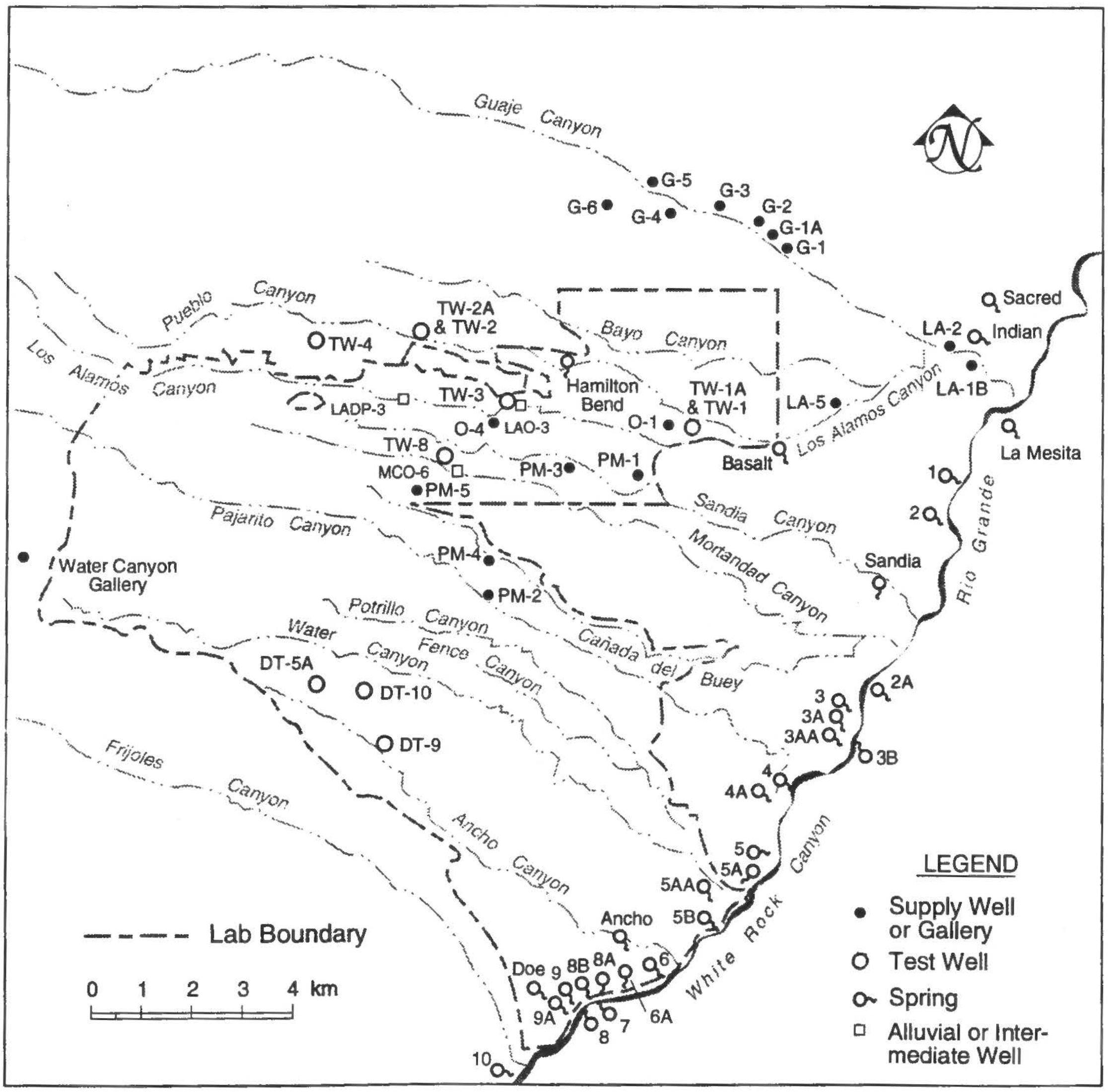

Figure 1. Locations of selected wells and springs on Pajarito Plateau.

TABLE 1. Pajarito Plateau well completion summary; unless noted, all units are in ft above mean sea level.

Well Number	Surface Elevation	Diameter (in)	Total Depth (ft)	Water Level	Screen Interval	Geologic Formation
		A. Main Aquifer Test Wells				
TW-1	6369	6	642	5819	5737-5727	Lower Puye
TW-2	6648	6	834	5851	5880-5824	Lower Puye
TW-3	6595	10	815	5817	5790-5780	Lower Puye
TW-4	7245	6	1205	6069	6050-6040	Tschicoma
TW-8	6878	8	1065	5885	5925-5813	Upper Puye
DT-5A	7144	8	1821	5961	5972-5323	Puye/Santa Fe
DT-9	6935	12	1501	5920	5895-5434	Puye/Santa Fe
DT-10	7020	12	1409	5923	5940-5611	Puye/Santa Fe
		B. Municipal Water Supply Wells				
Otowi-1	6396	16	2609	5722	5379-3919	Santa Fe
PM-1	6520	12	2501	5766	5575-4041	Santa Fe
PM-3	6640	12	2552	5872	5684-4108	Santa Fe
LA-1B	5622	12	1655	5635	5296-3967	Santa Fe
		C. Intermediate Wells				
TW-1A	6369	6	225	6177	6154-6144	Upper Puye
TW-2A	6650	6	133	6540	6522-6517	Upper Puye
LADP-3	6435	2	325	6116	6115-6110	L. Bandelier
		D. Alluvial Wells				
LAO-3	6578	2	32	6571	6561-6546	Alluvium
MCO-6	6849	2	47	6820	6822-6802	Alluvium

RECENT WATER LEVEL TRENDS

In October 1992, the Los Alamos National Laboratory began making continuous water level measurements in main aquifer test wells. These data are automatically recorded at hourly intervals using computer-controlled pressure transducers. Daily water level fluctuations typically range from 0.25 to 0.50 ft or more, with a total measurement accuracy of less than 0.04 ft for any given water level value. Daily water levels in main aquifer test wells TW-4, TW-2, TW-1, and Otowi-1 in Pueblo Canyon (Fig. 1) clearly show cyclical downward trends from mid-1993 to early 1996 (Fig. 2). Overall, these trends are consistent with historical records that reflect municipal water production from Guaje, Pajarito, and Otowi-4 production wells (recall that the Los Alamos well field was abandoned in 1991).

A close inspection of Figure 2 reveals some interesting departures from anticipated drawdown trends. For example, municipal water production is largest during the summer months (8 mgpd), and lowest during the winter (2 mgpd). Corresponding drawdown records in test wells should imitate this cyclical pattern. Except for Otowi-1, this pattern is not obvious in any of the records shown in Figure 2. Furthermore, total water level declines in TW-1, TW-2, and TW-4 are almost identical at about 5 ft. Water level declines should be greater in test wells located closer to municipal water supply wells (e.g., TW-1 and TW-2), or in observation wells completed into the same stratigraphic interval as pumping wells (e.g., Otowi-1). Likewise, smaller drawdown should be seen in those test

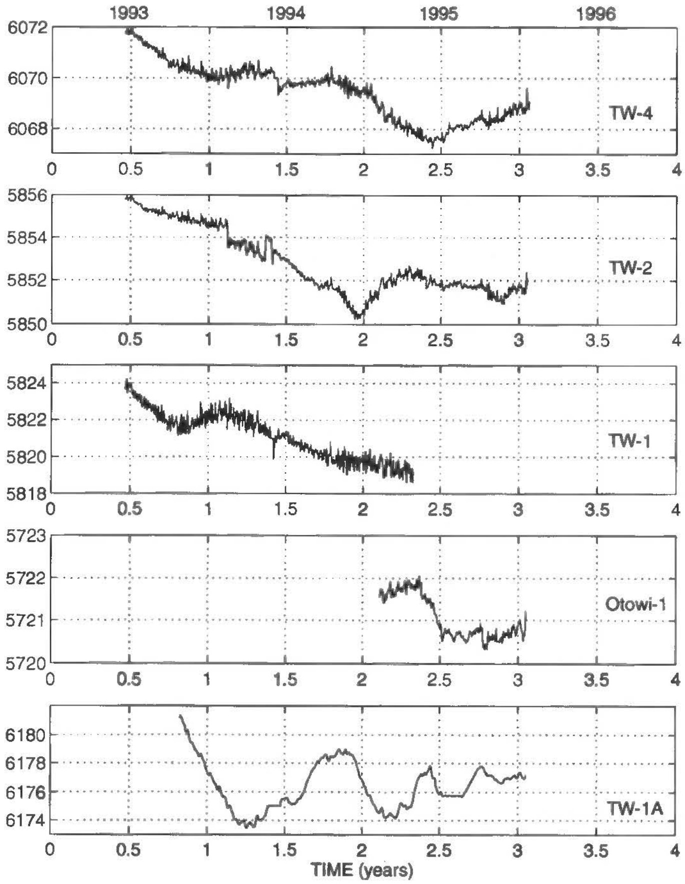

FIGURE 2. Water level fluctuations in the main aquifer along the west-east transect following Pueblo Canyon, from test wells TW-4, TW-2, TW-1, and Otowi-1; intermediate aquifer water levels in TW-1A are shown for comparison.

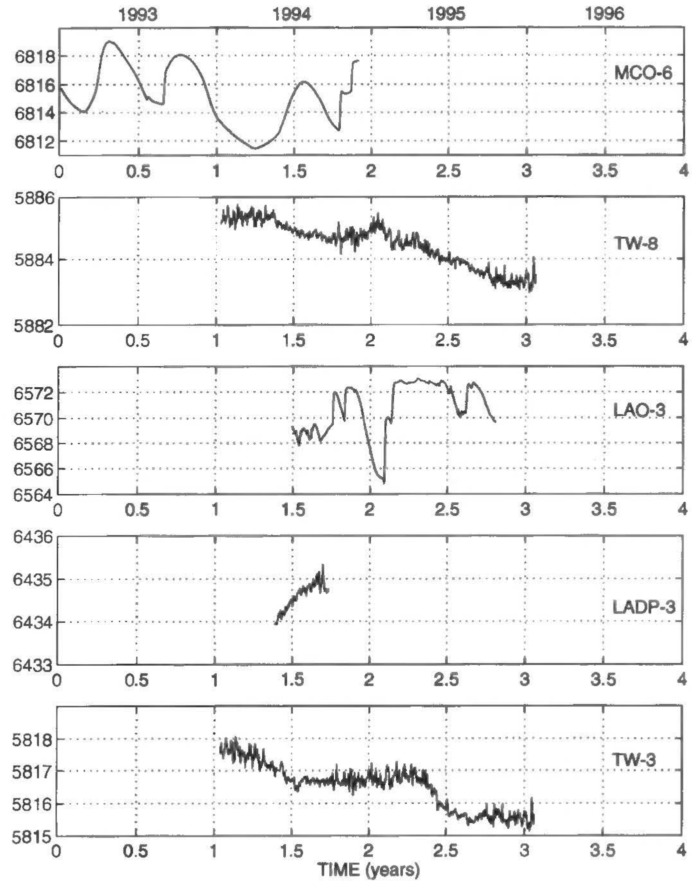

FIGURE 3. Water level fluctuations in Mortandad Canyon alluvial aquifer well MCO-6 and main aquifer well TW-8; and in Los Alamos Canyon alluvial aquifer well LAO-3, intermediate aquifer well LADP-3, and main aquifer well TW-3.

wells located farther away (e.g., TW-4). Instead, the smallest declines are seen in Otowi-1, located about 1000 ft west of TW-1. In all likelihood, the 1 ft decline observed in Otowi-1 is in response to pumping at supply well PM-1, located in Sandia Canyon about 0.85 mi away. Both the water level declines in Otowi-1, and heavy pumping rates in PM-1, begin in May 1995, and continue through September. Finally, TW-1A, an intermediate aquifer test well located adjacent to TW-1, shows a cyclical trend that is related to seasonal surface water flows in Pueblo Canyon. These observations suggest that several factors are simultaneously influencing water levels in test wells shown in Figure 2. These factors include cyclical drawdown in response to municipal water production, seasonal recharge from canyon-bottom infiltration, and atmospheric pressure and solid earth tide effects (discussed later).

Test well TW-1 is the only main aquifer well to show an increasing trend in post-1990 water levels after many years of decline. This anomalous behavior is most likely related to lost fluid circulation at about 700 ft below ground surface (in the Fanglomerate Member of the Puye Conglomerate) during drilling operations at supply well Otowi-1 in late 1990. At that time a water level increase of about 80 ft was observed in TW-1. A smaller corresponding increase of between 2 and 10 ft was seen in TW-1A. The level in TW-1 began declining by mid-1992, and has since dropped more than 50 ft. A clear downward water level trend has resumed, as seen in Figure 2. Although not as long, the corresponding water level trend in Otowi-1 has stabilized to a cyclical 1 ft annual variation. Water levels in TW-1A also began declining in mid-1992; however, these levels are more cyclical than TW-1 and Otowi-1 because they are influenced by seasonal infiltration from Pueblo Canyon surface waters. Other indications of hydraulic communication between TW-1, TW-1A, and the surface are reflected by trace-level tritium measurements (Rogers et al., this volume), and similarities in major ion water quality (Environmental Protection Group, 1993, 1995). Initially all of these observations were attributed to a leaky wellbore at TW-1; however, continuous water level records since 1992 suggest this communication is through the undisturbed porous media. During 1995, persistent vertically downward hydraulic gradients exceeding 0.88 were measured between wells TW-1A and TW-1, and 0.29 between TW-1 and Otowi-1. Trace-level tritium measurements have not been made in Otowi-1 well waters.

Water level data from alluvial and intermediate aquifer wells are much more limited than for the main aquifer. In alluvial well MCO-6, located in Mortandad Canyon (Fig. 3), a 7-ft water table fluctuation is obvious, and reflects snowmelt runoff (March-April), summer storm-water runoff (July-August), and random discharges into Mortandad Canyon from the TA-50 industrial waste-water treatment plant. A nearly 3-ft, downward oscillation is apparent in TW-8, and suggests the possibility of both pumping-induced drawdown and seasonal infiltration from above. Canyon-bottom recharge to the main aquifer is also suggested by the occurrence of trace levels of tritium detected in TW-8 well waters (Rogers et al., this volume). Unfortunately, the water level records shown in Figures 2 and 3 are too short for exact peak-to-peak correlation. Hence this comparison highlights one shortcoming of time series analysis: low-frequency seasonal oscillations require long-term records for validation.

Figure 3 also illustrates a similar comparison in water levels for Los Alamos Canyon wells LAO-3, LADP-3, and TW-3. The 8-ft seasonal oscillation in alluvial well LAO-3, located about 300 ft downstream of TW-3, is similar to that in MCO-6. This pattern, along with stream gaging data, verifies surface infiltration to the alluvium. Short-term water levels for LADP-3, an intermediate aquifer well located about 1.64 miles upstream of LAO-3, suggest canyon-bottom recharge to this intermediate depth. LAO-3 and LADP-3 waters also show minor levels of tritium (Broxton et al., 1995, Table 1), confirming this intercommunication. Water levels in main aquifer test well TW-3 are strikingly similar to those in TW-8, but do not resemble LAO-3 or LADP-3 water levels. This absence of correlation may be due to the large separation distances between these wells, rather than a lack of canyon-bottom infiltration to the main aquifer. Hence these records, along with the ephemeral nature of flows in the stream channel, imply that canyon-bottom infiltration to the deep subsurface diminishes in the downstream direction.

Several mesa-top test wells (DT-5A, DT-9, DT-10) are located in the southern Plateau area, and are removed from any municipal supply wells. These test wells still show a small, but persistent, downward trend in water levels in response to municipal pumping (Fig. 4). Such observations imply that Santa Fe Group aquifer transmissivity and specific yield values in the central Plateau area are relatively high. Large values for these aquifer parameters yield areally extensive cones of depression in response to pumping, and have small drawdown values at any given location. Broxton et al. (this volume) relate this same area to the Pleistocene landscape prior to the eruption of the Bandelier Tuff. More importantly, these central-plateau test wells do not appear to be receiving significant mesa-top or canyon-bottom recharge. Former production well LA-1B, located in Los Alamos Canyon near the Otowi Bridge, is also shown in Figure 4. These water levels show a return to near-original artesian conditions after the 1991 abandonment of this well.

ATMOSPHERIC PRESSURE AND SOLID-EARTH TIDE EFFECTS

Hourly water level records from wells are not depicted in Figures 2-4 because they reflect significant high-frequency noise. Instead, daily water levels are shown for clarity. We may still analyze these hourly data in the frequency domain using spectral analysis techniques. Here the familiar horizontal time axis is replaced by a linear transformation to frequency, while the vertical axis represents the Fourier transform of the autocovariance function computed from uniformly spaced (in time) water level measurements (Gelhar, 1993). The resulting spectrum for each series represents the distribution of water level departures from the mean as a function of frequency. In this study all spectra were computed with normalized water levels. These were obtained by removing the series mean from each water level measurement, and then dividing by the series standard deviation.

Figure 5 shows the computed spectrum for recorded atmospheric pressure on Pajarito Plateau. Corresponding water level spectra for selected intermediate and main aquifer wells are shown in Figures 5 and 6 for comparison. All of these spectra have strong peaks at 1 and 2 cycles per day (cpd) for all wells, in addition to numerous other strong peaks below 0.5 cpd, as seen in Figure 7. These peaks mimic those in the atmospheric pressure spectrum, and are related to atmospheric solar heating and synoptic-scale weather patterns, respectively. I conclude that all sampled intermediate and main aquifer test wells on Pajarito Plateau show influences of atmospheric pressure variations.

Figure 8 shows the computed spectrum from the theoretical tide potential (Harrison, 1971) on Pajarito Plateau. Water level spectra from DT-5A, Otowi-1, and LA-1B are also shown for comparison. These wells clearly show four strong peaks at 0.93 cpd (corresponding to the O1 principal lunar diurnal frequency), at 1.00 cpd (the K1 principal solar diurnal frequency), at 1.93 cpd (the M2 principal lunar semi-diurnal frequency), and at 2.00 cpd (the S2 principal solar semi-diurnal frequency). While there are other lines in the tidal spectrum, only these four have enough power to cause measurable water level fluctuations in Pajarito Plateau wells. These influences from solar and lunar earth tides arise from distortions in the earth's crust in response to revolutional and rotational periodicities of the earth-moon-sun system. There are no significant tidal peaks in these spectra below 0.5 cpd as in the atmospheric pressure spectrum. These tidal phenomena are physically unrelated to the atmospheric effects shown in Figures 5-7, even though the K1 and S2 solar frequencies overlap with atmospheric frequencies. These observations are being used to estimate values for aquifer transmissivity employing techniques developed by Ritzi et al. (1991). Using synthetic data

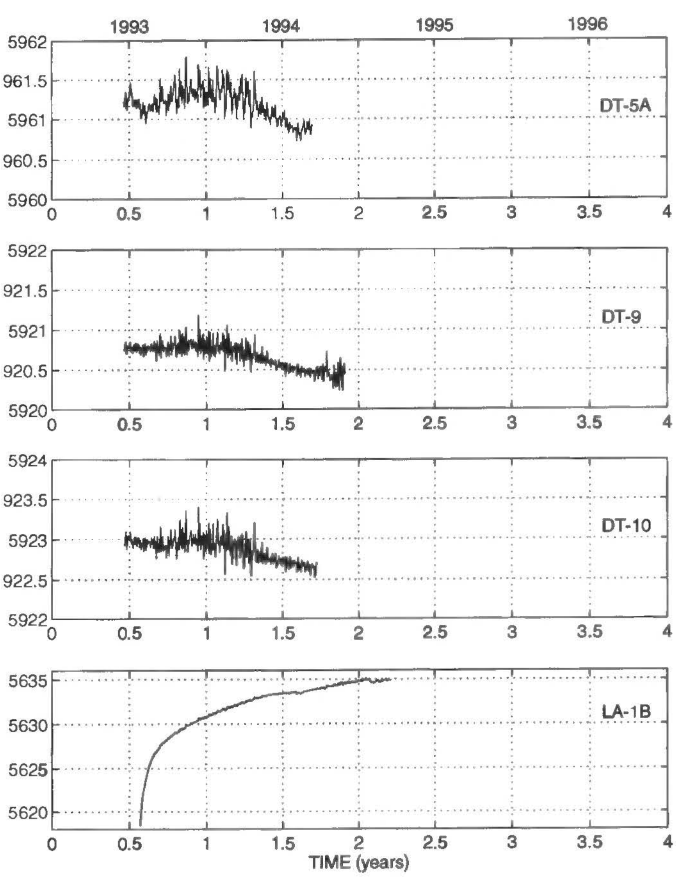

FIGURE 4. Water level fluctuations on Pajarito Plateau from main aquifer test wells DT-5A, DT-9, and DT-10; and in former production well LA-1B.

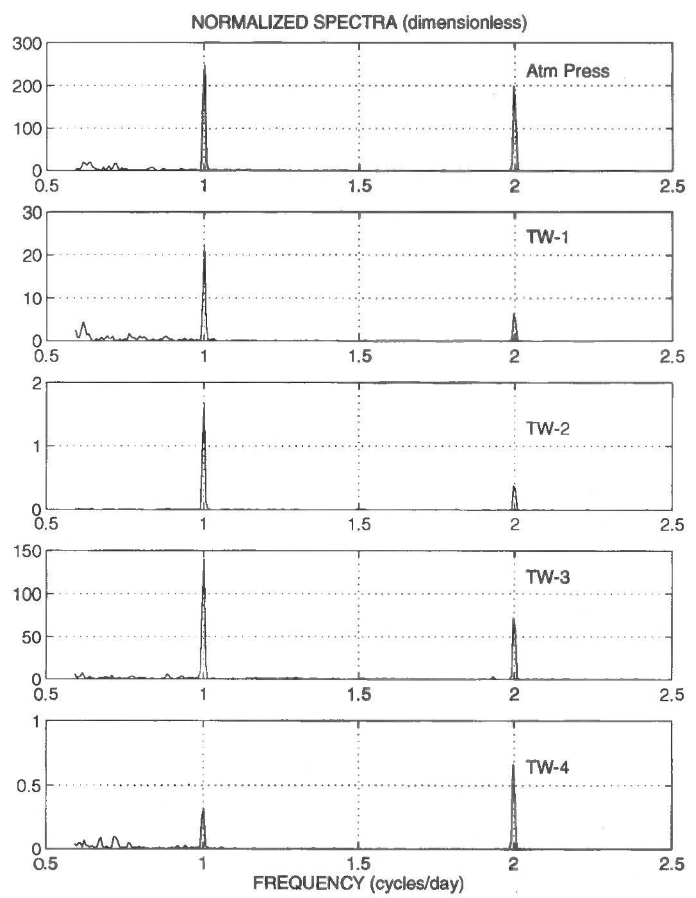

FIGURE 5. Spectrum of observed atmospheric pressure variations on Pajarito Plateau, and corresponding water level spectra from main aquifer test wells TW-1, TW-2, TW-3, and TW-4. Note the peaks at 1 and 2 cpd.

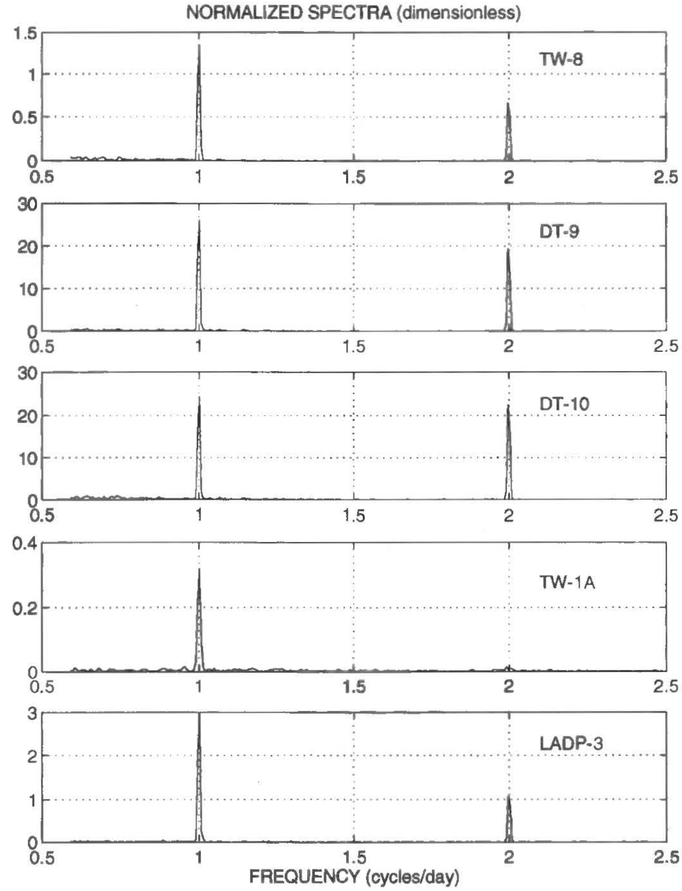

FIGURE 6. Water level spectra from main aquifer test wells TW-8, DT-9, and DT-10; and intermediate aquifer wells TW-1A and LADP-3. Note the peaks at 1 and 2 cpd.

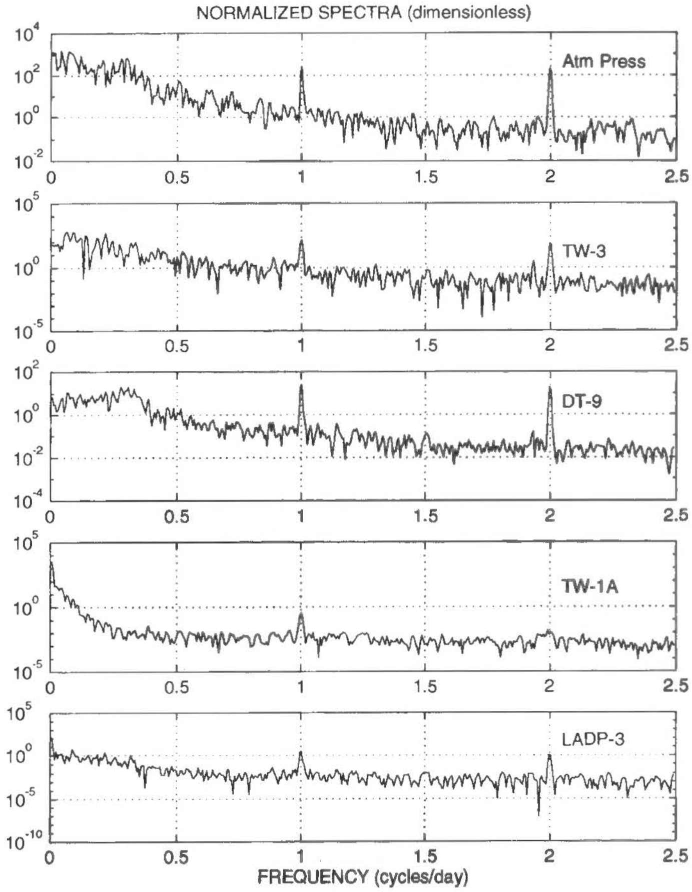

FIGURE 7. Spectrum of observed atmospheric pressure variations on Pajarito Plateau, with selected water level spectra shown for comparison. Peaks below 0.5 cpd result from synoptic-scale weather systems on a time scale of weeks to months, and result in significant water level variations.

from a hypothetical well opened to the atmosphere, these authors concluded that at least 43 days of hourly water level measurements are required to estimate transmissivity to within one order of magnitude.

Atmospheric pressure and earth-tide effects also reveal important information about aquifer isolation characteristics. Recall that the portion of the Rio Grande shown in Figure 1 is a regional groundwater discharge zone (Griggs, 1964). Supporting evidence for this observation comes from pumping tests in the Los Alamos well field (Theis and Conover, 1962; Cushman, 1965), observed vertically upward hydraulic gradients in western portions of the Buckman well field (Hart, 1989) during non-pumping intervals in Santa Fe municipal water supply wells, and the occurrence of numerous springs in White Rock Canyon (Fig. 1). Near former production well LA-1B, the main aquifer responds like a Theis-type confined aquifer to pumping stresses (Purtymun et al., 1995a). However, this well also reflects small atmospheric pressure and tidal perturbations during hydrostatic conditions. Hence the spectral pattern for LA-1B shown in Figure 8 suggests the presence of strong, vertically upward hydraulic gradients. These gradients isolate the subsurface from the atmosphere by preventing downward water percolation.

Farther west of the river, the main aquifer behaves like a phreatic aquifer during pump testing at some locations (Otowi-1), and a confined to leaky-confined aquifer (Otowi-4) in other areas (Purtymun et al., 1995a; 1995b). Hence there is a complex transition zone within the Santa Fe Group that reflects spatially variable, leaky-confined to phreatic aquifer behavior as one moves westward from the Rio Grande and across Pajarito Plateau. This transition zone roughly corresponds to thick portions of the overlying Puye Conglomerate (Purtymun and Stoker, 1988, fig. 13; Broxton, 1996), which extends from just west of the Otowi-1 production well (where atmospheric and tidal effects are also observed, as seen in Fig. 8), westward toward the Otowi-4 production well, and then southerly to test well DT-5A (where atmospheric and tidal effects are again

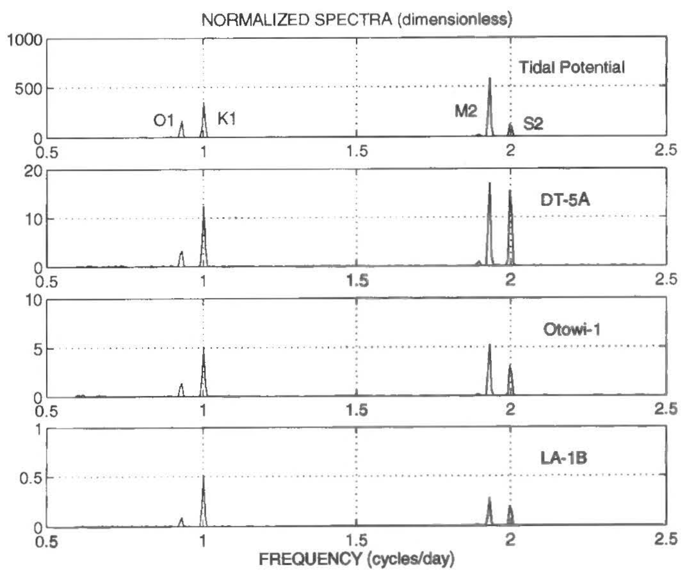

FIGURE 8. Spectrum of theoretical tidal potential (Harrison, 1971) on Pajarito Plateau, and corresponding water level spectra from main aquifer wells DT-5A, Otowi-1, and LA-1B. Significant earth tide effects on water levels suggest confined aquifer behavior.

observed, as seen in Fig. 8). None of the other test wells listed in Table 1 show these characteristic behavior patterns, and are either outside of this zone or are too shallow for hydraulic detection. Unfortunately none of the other production wells within this zone can be adequately tested because of cyclical pumping operations, and the lack of adjacent observation wells. All of the characteristic wells within this zone have one thing in common: long screened sections that penetrate deeply into Santa Fe Group sediments. Hence these observations may simply reflect the presence of relatively thin hydrogeologic zones within the Santa Fe Group sediments that show relatively high yields to pumping stresses, or tidal effects under hydrostatic conditions. Both of these characteristic behavior patterns are interpreted to reflect stratified aquifer conditions, which exhibit vertical hydraulic gradients. Delineation of these gradients is critical too our understanding of aquifer recharge.

CONCLUSIONS

In late 1992, the Laboratory began collecting hourly water levels from numerous observation wells on Pajarito Plateau. Several of these wells are completed into the saturated alluvium found in some canyons. Other wells penetrate to perched water zones at intermediate depths below these canyon bottoms. The deepest wells penetrate into the main aquifer, located within the Puye Conglomerate and Santa Fe Group sediments. Collectively, these water level series confirm the following: (1) main aquifer recharge below Pajarito Plateau mesa-tops does not appear to be significant; (2) seasonal channel infiltration replenishes shallow alluvial aquifers found in several large canyons; (3) alluvial recharge to perched water bodies at intermediate depths is observed in Pueblo and Los Alamos Canyons; (4) canyon-bottom recharge penetrates to the main aquifer below Pueblo and Mortandad Canyons; and (5) alluvial infiltration to the deep subsurface in Los Alamos Canyon diminishes in the downstream direction. Recharge in these areas has not been quantified. However, annual municipal water production rates from the main aquifer appear to exceed annual recharge rates because historical drawdown trends are persistent and widespread across the Plateau.

Small-amplitude, cyclical water level fluctuations in main aquifer observation wells show influences from atmospheric pressure variations. All of these wells have a relatively thick unsaturated zone overlying a water table aquifer. Some main aquifer wells also show fluctuations that correspond to solar-lunar earth tides. These central-plateau wells penetrate into Santa Fe Group sediments, revealing a complex transition from confined to phreatic aquifer behavior moving westward from the Rio Grande. This area roughly corresponds to thick portions of the overlying Puye Conglomerate. Shallow alluvial wells on Pajarito Plateau do not show either of these frequency domain behavior patterns, while intermediate wells show only atmospheric pressure influences. Hourly water levels are being used to estimate values for aquifer transmissivity.

Time series analyses of water level fluctuations can lend powerful assistance to our understanding of groundwater recharge below Pajarito Plateau. This approach requires long-term records, however, if we are to identify and separate multiple low-frequency recharge sources. As other studies have suggested, these potential sources of variation include recharge from the eastem flanks of the Jemez Mountains, infiltration from alluvial and intermediate aquifers, and lateral inflows from ancestral Rio Grande waters located within the Espanola Basin, or from the Sangre de Cristo Mountains. Isolation of individual recharge sources to the main aquifer will undoubtedly require multiple stratified water level and water quality measurements over time across the Plateau.

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