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The analysis of water level fluctuations in a shallow, unconfined aquifer in Owens Valley, California

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The Analysis of Water Level Fluctuations in a Shallow, Unconfined Aquifer in Owens Valley, California

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science
in Hydrology/Hydrogeology

by

Diane M. Nork

March 1987

The thesis of Diane Nork is approved:

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ABSTRACT

TITLE: The Analysis of Water Level Fluctuations in a
Shallow, Unconfined Aquifer in Owens Valley,
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By: Diane M. Nork
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March 1987

Although water levels in both confined and unconfined aquifers fluctuate as a result of several natural forces, unconfined aquifer response has seldom been addressed in much detail. Periodic fluctuations observed in wells tapping a shallow, unconfined aquifer in Owens Valley, California are thought to be due to the aquifer's response to barometric pressure, evapotranspiration, and temperature. Actual and stochastically generated water level data are examined to determine whether the removal of these these forces results in a significant change in the aquifer's calculable hydrologic properties.

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1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

Wells penetrating confined and unconfined aquifers exhibit water levels that are seldom stationary in time. Water levels fluctuate as a result of several factors other than changes in recharge, discharge, and pumping stresses. For instance, atmospheric pressure, temperature, and evapotranspiration have long been recognized as some of the natural forces that perturb static water levels. Historically, the periodicities of these factors and their effects on water levels have been regarded as "noise" that contaminate water level records. The ordinarily small fluctuations that are caused by these factors, however, represent deviations of the water level from an equilibrium condition due to a measurable and/or estimatible driving force. Advancements in sensitive field instrumentation and data analysis throughout the past decade have greatly improved opportunities for the examination of the often subtle aquifer response to such driving forces. Whether the means of analysis is strictly physically based or statistical, the aquifer response has the potential to yield useful information about fundamental hydrologic characteristics that are commonly determined from pumping tests. Therefore, any refinement in the ability to interpret water level fluctuations may prove to be complementary to conventional aquifer testing and may have important implications with respect to estimating basin or aquifer yield. Confined aquifers characteristically exhibit a greater magnitude of response to natural factors than do unconfined aquifers. In fact, the most extensive examinations of water level fluctuations produced by these forces have been carried out in cases where wells tap confined water-bearing units. This may be due to the idea that a confined aquifer represents a less complicated system than an unconfined aquifer. Or, it may be attributable to the established relationships between imposing stresses and responding structural strain in confined systems. Also, it may be that the effects of these natural forces on the water level of unconfined aquifers have been thought to be insignificant with regards to the interpretation of data collected from pumping tests.

1.2 Objectives and Scope

The impetus for this study came from observing perturbations in the continuous water level records of a shallow, unconfined aquifer over an approximate 40-mile reach in Owens Valley, California. The perturbations are in the form of periodic diurnal fluctuations of the water surface. These fluctuations are thought to be due to the unconfined aquifer's response to natural forces, particularly barometric pressure, evapotranspiration, and temperature. The first objective of this work is to isolate and remove the effects of these natural forces on the water level of a well tapping a shallow, unconfined aquifer. The second objective is to determine whether the removal of the influences of the natural forces results in a significant change in the calculable hydrologic properties of the aquifer.

The scope of this work includes examination of: (1) the actual response of an unconfined aquifer to barometric pressure, evapotranspiration, and temperature in early March, 1985 and during a pumping test that occurred in December, 1983; and (2) the artificially generated response of an unconfined aquifer to a fictitious pumping test. In each of these cases, the influences of the three natural forces are removed from the water level record. When the period of record of the water level data does not coincide with that of the natural forces, the stochastic analysis technique of autoregressive integrated moving average (ARIMA) modeling is used to generate time series of the missing data. The aquifer's hydrologic properties are examined both before and after the removal of the three natural forces.

1.3 Previous Work and Literature Review

There exists a wide variety of man-induced phenomena and natural forces other than barometric pressure, temperature, and evapotranspiration that contribute to water level fluctuations. Withdrawal from and injection into aquifers produce substantial changes. With respect to natural phenomena, meteorological factors such as wind, frost, and precipitation have been documented as influencing water levels. Both ocean and earth tidal effects have also been observed to cause small yet nonetheless measurable fluctuations. In much the same way that fluid pressure and effective stress in a confined aquifer respond to changes in barometric pressure, external loading in the form of blasting, passing trains, and earthquakes has also led to short-lived perturbations in water levels. An (1985) provides a thorough review of these factors.

It would be extremely difficult and quite expensive to attempt to measure and analyze the effects of all these factors. However earth tidal effects were initially considered to be included in this analysis of water level fluctuations. They were not included because although their semi-diurnal pattern can be adequately estimated from the water levels of confined aquifers, they are generally not considered to be significant in unconfined aquifers unless the porosity is small or the saturated thickness is large (Bouwer, 1978). The unconsolidated and varied nature of alluvial material that comprises Owens Valley yields a range of porosities (20 to 75 percent). For this reason, it is often difficult to determine the spatial continuity and thickness of unconfined or confined zones, or to assume a spatially constant porosity. Furthermore, the quantification of earth tidal strains requires the use of sensitive, single-purpose instrumentation that was not included in this study.

On the other hand, the investigation of the response of unconfined aquifers to the combination of barometric pressure, evapotranspiration, and temperature reveals a complicated inter-relatedness. The following literature review shows that some researchers address a single factor, while others try to differentiate between the influences of barometric ressure and temperature or between temperature and evapotranspiration. It is because of this interdependency that this thesis deals solely with these three natural forces.

1.3.1 Barometric Pressure Effects

Effects of the changing atmosphere on water levels in confined aquifers were reported as early as 1899 by F. N. King. As pressure increased, he attributed a decline on the water level to expansion of air below the water table. Jacob (1940) explained this inverse relationship with the principles of: (1) effective stress acting on the solid aquifer; and (2) the fluid pressure within the aquifer. An increase in atmospheric pressure produces a corresponding increase in the effective stress and fluid pressure, and consequently, a decrease in the pressure head that is measured in the piezometer tapping the confined aquifer. Additionally, Jacob devised a method for calculating the storage coefficient of the aquifer by using the barometric efficiency of the well. Tuinzaad (1954) also took into account the elastic properties of the aquifer and the water confined therein to explain fluctuations in water levels.

With respect to confined aquifers, Von Eimern (1950) attributed barometrically induced water level fluctuations to the fact that the nature of the unsaturated zone materials prevented the barometric pressure from being entirely transmitted to the water table, whereas the pressure was transmitted instantaneously down the well bore. Stallman (1967) suggested that such a lag could be quantified and used to determine the hydraulic properties of materials in the unsaturated zone. Weeks (1979) developed a means of examining the effects of barometrically induced fluctuations on wells tapping deep unconfined aquifers. He stated that air movement through the unsaturated zone is slowed as a result of the finite permeability of the materials and by their capacity to store or release soil gas as atmospheric pressure changes. Therefore, a pressure imbalance develops between the water in the well and water in the adjacent aquifer, resulting in water level fluctuations in the well.

Other workers have attributed barometrically induced fluctuations in shallow unconfined aquifers to the presence of entrapped air below the water table. Peck (1960a) performed a series of laboratory experiments in columns of sandy soil. Neglecting the effects of hysteresis and changes in the solubility of trapped air, Peck concluded that water tables will fall when external air pressure increases provided that gas is entrapped in the soil water. For other laboratory experiments on wetting and drainage characteristics, Debacker (1967) showed that gas entrapment occurs mainly during the wetting phase. Norum and Luthin (1968) took Peck's work a step further by introducing a transient situation into their laboratory experiments. By assuming a constant state of equilibrium, they believed that Peck underestimated the magnitude of the water level fluctuations. Norum and Luthin concluded that changes in water levels due to barometric pressure changes may obscure the effects of other natural factors such as evapotranspiration. In fact, Stevenson and Van Schaik (1967) had some difficulty in monitoring the water use by plants in lysimeters because as the atmospheric pressure increased, water levels dropped, thus causing the addition of water to the tank by means of a mariot syphon.

1.3.2 Temperature Effects

Much of the earliest research concerning moisture migration due to temperature gradients was conducted by soil scientists. Therefore, the majority of work has dealt with water movement in the unsaturated zone. Hydrologists have also been concerned with temperature-induced water movements that are manifested in water level changes in unconfined aquifers.

Peck (1960b) was one of several researchers who recognized that changes in the surface tension of unsaturated zone materials due to thermal effects are related to water level fluctuations. Using results obtained from laboratory experiments, he developed equations relating changes in moisture tension with changes in temperature and atmospheric pressure. Turk (1975) also determined a relationship between temperature and surface moisture tension. Upon examining data from aquifer tests conducted in the Bonneville Salt Flats, Turk noticed that natural water table fluctuations were of the same magnitude as the drawdowns measured in observation wells. Ruling out the effects of evaporation and evapotranspiration, he explained the fluctuations as resulting from temperature changes: as the temperature increased, water drained from the soil's porous matrix and traveled downward, thereby raising the water table.

Earlier work performed by Meyer (1960) supported Turk's hypothesis. Meyer showed that in cold weather, water levels decline because cold soils hold more moisture by capillarity than do warm soils. Turk suggested that water level fluctuations resulted from the combined effect of temperature-induced surface tension changes and temperature-induced atmospheric pressure changes. Turk noted a reinforcing effect between these natural phenomena, as did Raffo (1954). However, Turk also noticed that barometric pressure effects on water levels were instantaneous, whereas temperature effects were somewhat lagged depending on depth to the water table.

In one of the few field experiments that attempted to differentiate the effects of atmospheric pressure and temperature, Gatewood et al (1950) found that water level changes identifiable with barometric pressure changes generally occurred during winter months in vegetated lysimeters, and throughout the year in unvegetated lysimeters. In support of these findings, the authors noted that when hot rocks were applied to the surface of vegetated lysimeters, water levels rose rapidly although there was not significant corresponding change in barometric pressure. Furthermore, Gatewood et al noted that while the water table responded quickly to the temperature increase, the temperature of the soil in the capillary fringe did not begin to increase until about one hour after the hot rocks had been applied. This study indicated that, in general, diurnal fluctuations in soil temperature were apparent to a depth of one foot, but were not at a four-foot depth. In a similar discovery, Hunt et al (1966) noted that in Death Valley, where the land surface is subjected to an extreme range of temperatures, there is actually little daily variation in the temperature only a few centimeters below the surface. Consequently, the time lag between changes in air temperature and changes in soil temperature can be significant.

1.3.3 Evapotranspiration Effects

In addition to the previously mentioned natural factors, water level fluctuations in shallow unconfined aquifers may also occur as the result of plant water use. Van Hylckama (1968) attempted to discern the most reasonable explanation for water level fluctuations observed in plastic-lined evapotranspirometers. He found that for bare soil and non-transpiring vegetation, the rise in water levels during the day and the decline at night correlated with microbarograph records. Barometric pressure fluctuations and water level fluctuations were out of phase, however, in the case of transpiring, vegetated tanks, Van Hylckama reasoned that this occurred because plants first use readily available soil moisture before extracting groundwater to sustain transpiration. However, even most deep-rooted phreatophytes exhibit a significant decrease in uptake of groundwater when the water table drops below about six feet from the surface, although shallow rootlets may continue to absorb moisture from the unsaturated zone (Bouwer, 1978).

White (1932) used this concept of selective plant water use to develop a means of computing the quantity of water lost from the soil via evapotranspiration. Expanding on White's conclusions, Troxell (1936) observed that water levels influenced by evapotranspiration were highest in mid-morning and lowest in the early evening. Not surprisingly, the highest water levels coincide with the time of minimum evapotranspiration demand, which naturally occurs at or near the time of minimum daily temperature. The converse is likewise true.

Unlike previous work, this study deals with an unconfined aquifer's water level response to the combined influences of barometric pressure, evapotranspiration, and temperature. Although the resulting effects of these natural forces may be somewhat small, they may impose a complicating factor on the interpretation of water levels during an aquifer test, and consequently obscure the determination of unconfined hydrologic characteristics.

2.0 DESCRIPTION OF THE STUDY AREA

2.1 Setting and Climate

Owens Valley is located in east-central California at the western edge of the Great Basin region (see Figure 1). The Sierra Nevada Mountains form the western boundary to the valley, and the White and Inyo Mountains lie on the east. In addition to the valley itself, the Owens Valley area includes Round Valley, which is a branch of Owens Valley northwest of Bishop, Long Valley, and the extension of the Owens Valley basin north along the front of the White Mountains.

The valley proper lies approximately 250 miles north of Los Angeles. Its length from the Mono Divide to the south end of Owens (Dry) Lake is 120 miles. The valley floor ranges in width from two to eight miles and has an average elevation of 4000 feet.

The Owens Valley climate is strongly influenced by the surrounding mountain ranges. The majority of storms that affect the area originate in the Gulf of Alaska and move south and east into Central California. As moist air moves eastward over the Sierra Nevada range, most of the precipitation is deposited on the western Sierra slopes. Precipitation rapidly diminishes as the storms move over the summit and encounter decreasing elevations on the steep eastern slopes. Along the Sierra Nevada crest, precipitation ranges from 20 to more than 70 inches per year. The valley floor is semi-arid to arid. Annual precipitation ranges from approximately four inches at the southern end

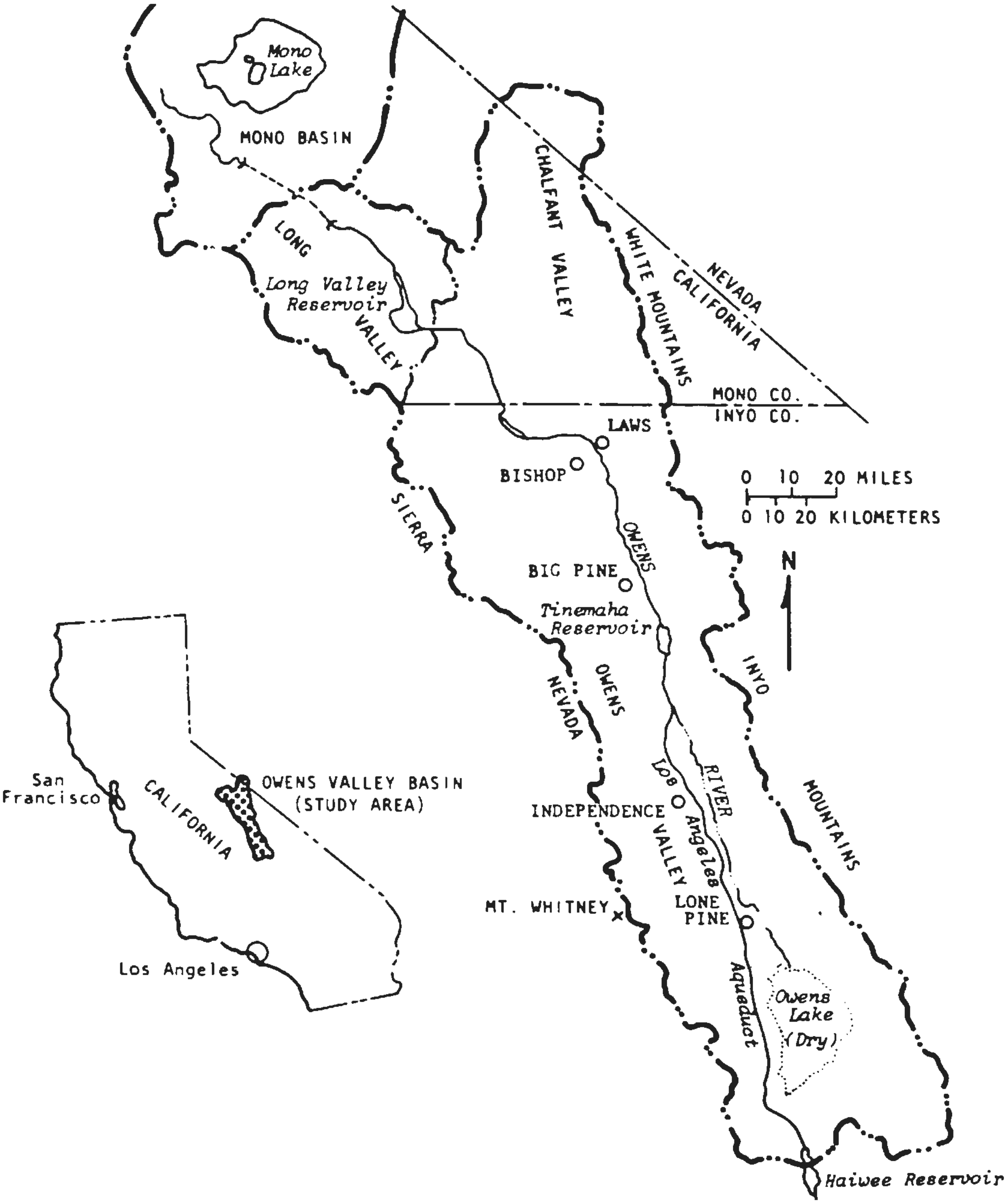

Figure 1. Location of study area.

of Owens Valley to greater than six inches in the Bishop area. Precipitation increases again as air masses continue to move eastward over the White and Inyo Mountains, where average precipitation ranges from 7 to 16 inches per year.

The amount and timing of precipitation in Owens Valley varies widely. Generally, however, the seasonal distribution is typical of the majority of California's weather pattern. Over 80 percent of the annual precipitation occurs during the period of October through February. Due to runoff from the flanking mountain ranges, approximately 75 percent of stream flow generally occurs from April to September.

Wind and temperatures in Owens Valley vary through wide ranges seasonally and daily due to the mountains that surround the valley and the desert regions to the south. Heating and cooling of the Mojave Desert produces a diurnal pattern of air movement in the valley during the summer and fall. During early morning and late evening, winds are predominently out of the north; mid-day air movement is characterized by southerly winds. It is not uncommon for summer temperatures on the valley floor to range from over 38 degrees Celsius (^{o}C) at mid-day to 10^{o}C degrees at night. Winter and spring are generally mild with temperatures ranging from 10^{o}C to -7^{o}C. The strongest winds occur in late winter through early spring. During these months, dust storms can be severe enough to restrict traffic, particularly in southern Owens Valley.

2.2 Geology

The Owens Valley area is a classic example of the geologic activity common to the Basin and Range province. It is typified by an anomalous upper mantle, a thin crust, high heat flow, and regional uplift. The block-faulted structure is characterized by elongate mountain ranges alternating with alluvia-filled valleys (Stewart, 1977). Owens Valley proper is a long, narrow, V-shaped graben formed mainly by deformation of pre-Tertiary rocks and is filled primarily with unconsolidated Tertiary and Quaternary sediments originating as mountain detritus and river and lake deposits (Lee, 1906).

At the valley's eastern border, the White-Inyo range is an elongated north-northwest trending horst that has been tilted to the east. In Owens Valley, high-angle Cenozoic normal and right-oblique slip faults bound the mountains. Forming the western boundary to the valley, the Sierra Nevada range was perhaps no more than 300 feet above sea level after the emplacement of the Sierra Nevada batholith in the late Cretaceous (Bateman, 1965). Then, a series of uplift and tilting began in late Cretaceous to Eocene time, culminating in orogeny in mid-Pleistocene time. Following the tilting, the V-shaped block of the Owens Valley area subsided and alluvial debris eroded from the flanking ranges, accumulating at the base of the mountains as well as on the valley floor. Cinder cones and associated basaltic flows broke out along the valley's bordering faults, and the rhyolitic Bishop tuff poured into

Owens and Round Valleys from a source to the north. Subsequently, Pleistocene glaciers scoured the slopes of the Sierra Nevada range and deposited moraines in the Owens Valley area. Finally, recent stream action modified Owens valley to form the present landscape.

2.3 Hydrology

Owens Valley is considered to be a virtually closed hydrologic system. Therefore, because the floor and walls of the Owens Valley area are relatively impermeable and since there is virtually no natural surface or subsurface outflow, all the water entering the valley must be consumed within its boundaries, except for what is exported to Los Angeles. The following water balance was computed by the Los Angeles Department of Water and Power (LADWP), and is based on data from 1935 to 1966 (LADWP, 1979). While the balance paints an adequate picture of inflows and outflows, it should be noted that because Owens Valley is not hydrologically static, the absolute numbers should be regarded as qualitative indicators of the valley's current hydrologic environment (Griepentrog and Groeneveld, 1981).

Inflows to Owens Valley consist of: (1) precipitation in the form of snowmelt from the surrounding mountains (34 percent); (2) precipitation in the form of rainfall on the alluvial fans and valley floor (36 percent); (3) outflow of the Owens River at Pleasant Valley Reservoir (27 percent); and (4) groundwater underflow from valleys to the north (3 percent). Sources of outflow from Owens Valley include: (1)

water export to Los Angeles (34 percent); (2) evaporation from the bare soil, vegetated areas, and water surfaces (65 percent); and (3) groundwater underflow from the basin in the southern portion of the valley (1 percent).

The extent of the Owens Valley groundwater basin evaluated for the LADWP water balance ranges from the volcanic tableland north of Bishop to Haiwee Reservoir at the southern end of the valley. Inflows to the groundwater basin consist of: (1) recharge from streams, irrigation ditches, and canals (62 percent); (2) recharge from precipitation infiltrating past the root zone (33 percent); and (3) groundwater flow from aquifers in adjacent northern valleys (5 percent). Outflows from the groundwater reservoir are made up of: (1) consumption by phreatophytes and evaporation in areas with shallow water tables (78 percent); (2) springs and artesian wells (14 percent); (3) pumping (4 percent); and (4) groundwater underflow from the basin in the vicinity of Haiwee Reservoir (4 percent).

Because the extensive depth of the valley fill is composed of unconsolidated sediments, water-bearing units in Owens Valley are not easily classified into distinct unconfined and confined aquifers. Since the valley is not one large bathtub, water entering the subsurface in the northern portion of Owens Valley cannot necessarily be extracted in the southern portion. For the sake of classification of water-bearing units, however, the following generalities are true: (1) unconfined aquifers are typically encountered in volcanic and upper alluvial fan deposits; and (2) alluvial fans and lakebed deposits frequently exhibit at least partially confined or artesian characteristics.

Most of the subsurface of the valley floor exhibits some degree of confinement although horizontal and vertical extent of confining layers varies. In general, there is a marked increase in the occurrence of confining layers from west to east, and to a lesser extent, from north to south.

The majority of pumping wells in the southern portion of Owens Valley are located just to the west of the confined zones, and thereby influence surrounding water levels differently than would groundwater withdrawal from a purely unconfined or purely confined aquifer. In areas where pumping occurs at the lateral boundary between unconfined and confined aquifers, the water level declines rapidly as the cone of depression intersects the unconfined zone. For instance, a well tapping an unconfined aquifer induces a rapid lowering of the water table; a cone of depression produced by pumping from a confined aquifer disturbs the natural hydraulic continuity between the shallow water table and the lower confined aquifer. In the latter case, discontinuous confining lenses may act to perch the shallow water table and restrict downward movement of the water. The rate of decrease of the water level in the upper shallow aquifer depends on the duration of pumping and permeability of the confining lenses. In areas where the cone of depression intersects confining layers, there is generally no perching of groundwater or any restriction to downward flow. In short, the response of the shallow water table to pumping of a lateral unconfined/confined boundary system is approximately similar to that of water withdrawal from a shallow, purely unconfined aquifer.

3.0 DATA TYPES AND ACQUISITION

In 1983, the U.S. Geological Survey, in cooperation with Inyo County and LADWP began work on extensive groundwater modeling and plant survivability investigations. The investigations were initiated to evaluate alternative strategies for mitigating impacts of groundwater withdrawal on native vegetation of Owens Valley. To accomplish this, data collection sites were established throughout the valley, ranging from the Laws area north of Bishop to Haiwee Reservoir south of Independence (see Figure 2). All data pertaining to this thesis were collected in the vicinity of Bishop, particularly those areas known as Site 2 and Site 12.

Water level data were measured in wells equipped with U. S. Geological Survey Fischer-Porter water level recorders. Data were recorded every 15 minutes on a punched tape, from which hourly averages were calculated. The precision of the recorders is ±0.01 feet. Water level recorders were in use at various sites throughout Owens Valley. Most of the data examined in this investigation, however, were collected from Site 2, located approximately 4.1 miles south of Bishop.

Barometric data were measured hourly by microbarographs housed in a facility at the Bishop Airport, and were provided by the National Weather Service. Barometric pressure is measured with an instrument precision of ±0.02 inches of mercury; for the sake of consistency with the water level data

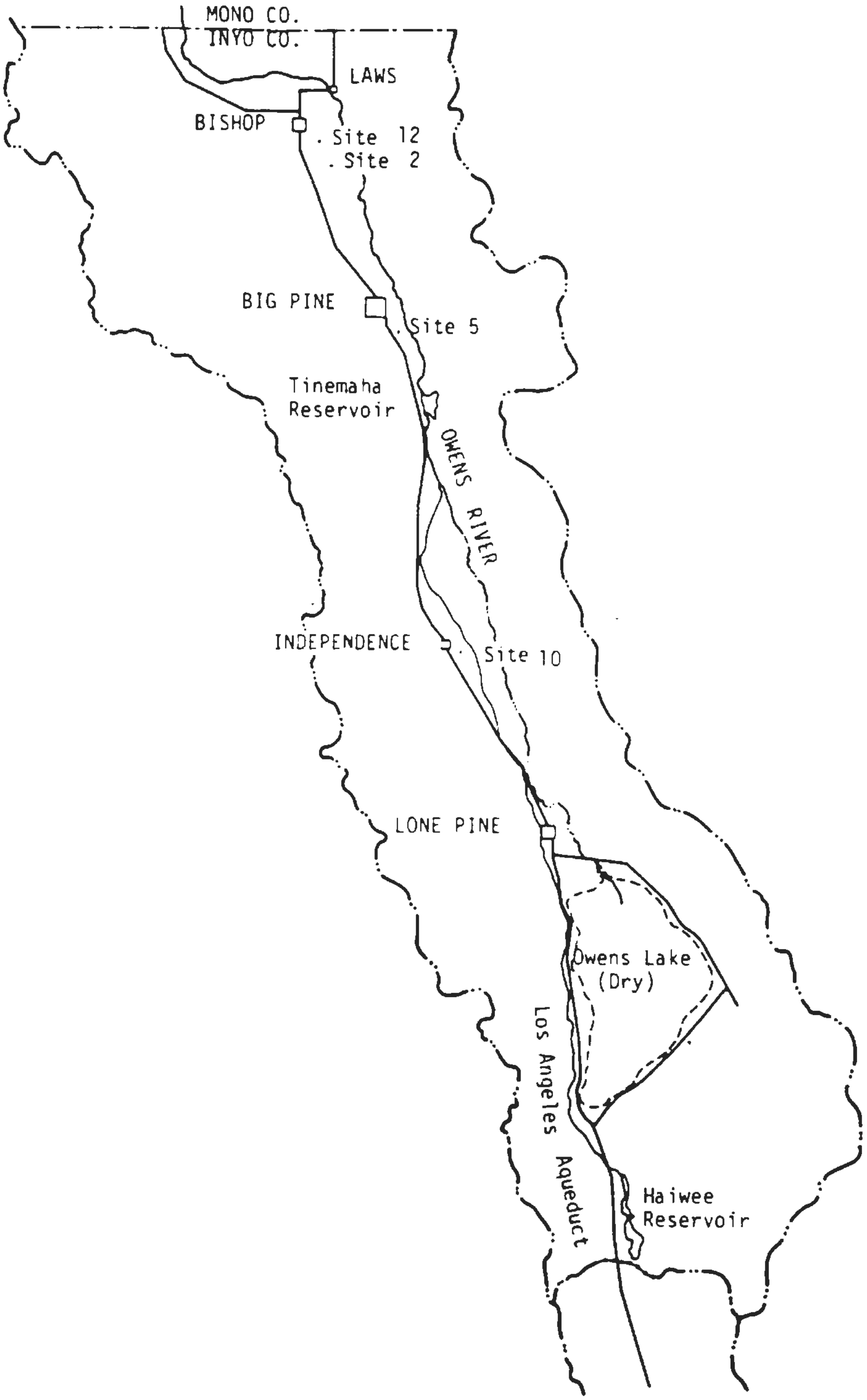

Figure 2. Site locations in Owens Valley.

these units were converted to equivalent feet of water. The airport is located about 4.6 miles north of Site 2.

Three semi-permanent micrometeorological stations were set up and operated by the U. S. Geological Survey to quantify the evapotranspiration rate at those points in Owens Valley. Site 2 was the northernmost station, Site 5 was located south of Big Pine, and as the southern-most station, Site 10 was located south of Independence. Each of these sites was equipped with instrumentation capable of calculating potential evapotranspiration via the Penman combination method and actual evapotranspiration by means of the Bowen ratio method. Actual evapotranspiration was also measured via the eddy correlation method using a mobile instrumentation set-up at these sites and at four additional sites (See Duell and Nork, 1985 and Simpson and Duell, 1984 for thorough descriptions of techniques and instrumentation, respectively). Because instrumentation necessary for use of the Penman combination method was in operation for all but about one week per month, hourly evapotranspiration data examined herein is the calculated potential evapotranspiration rate for Site 2. Due to extensive instrumentation employed at the micrometeorological stations, it is difficult to determine the overall instrument precision. Hence, the error in evapotranspiration rate calculation is taken to be ±0.01 millimeter per hour, based on the precision of the data collection devices. As with barometric pressure data, these units were also converted to equivalent feet of water.

Air temperature measurements were also collected at each of the micrometeorological stations. Like the previously mentioned data, the hourly temperature values pertaining to this work also apply to Site 2, and the temperature measurement precision is taken to be ±0.01°C.

Pumping test data were provided by the U. S. Geological Survey in conjunction with LADWP. The data are from an aquifer test conducted in December, 1983 at Site 12, located approximately 0.75 miles north of Site 2 (3.8 miles from the Bishop airport). Due to the close proximity of these sites, it was believed that data from Site 2 and the Bishop airport were applicable to Site 12.

4.0 ANALYSIS OF WATER LEVELS NEAR BISHOP, CALIFORNIA

Much of the data collection for the cooperative effort of establishing a water management plan for Owens Valley began in October, 1983. In order to become aware of the relationship between the water table and those factors that exploit it, it was desirable to be able to examine groundwater levels throughout Owens Valley over at least one entire growing season (early spring through late summer). Fortunately, data for the 1984 and 1985 growing seasons were available for this portion of the overall study. Figure 3 depicts this period of record for the water level at Site 2, near Bishop; the seasonal pattern is characteristic of water levels throughout the valley. As can be seen in Figure 3, the water level begins to rise in mid- to late fall when losses due to evapotranspiration are small and as winter storms begin. The rise continues throughout the winter and into early spring when recharge to the groundwater basin is at its maximum. As contributions from precipitation dwindle and as plants impose an increasing transpirative demand, the water level starts to recede in mid-spring, reaching a minimum in late summer to early fall.

On a diurnal scale as well, shallow water tables fluctuate in response to evapotranspirative demands. Troxell (1936) pointed out that in vegetated areas, water levels responding to evapotranspiration effects are commonly highest in the mid-morning when there are minimum transpirative losses. In late

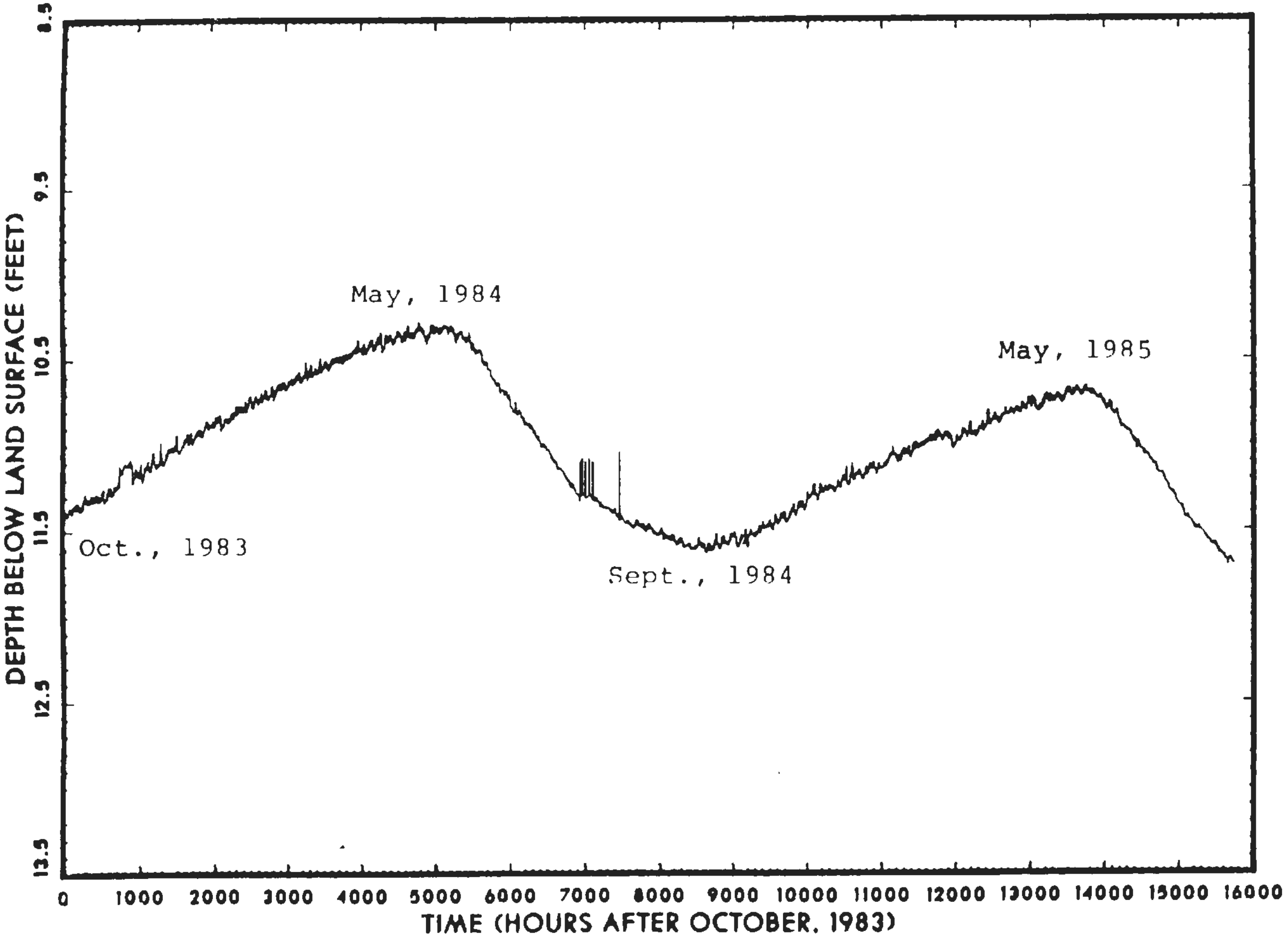

Figure 3. Water level depth measured at Site 2, October, 1983 through July, 1985.

afternoon when daily temperature is at its peak, water levels are at their lowest.

Diurnal water level fluctuations due to barometric pressure effects behave quite differently. Turk (1975) noted that in areas where vegetation is sparse or nonexistent, water levels tend to be at their daily maximum in late afternoon and at their lowest in mid-mornings. Figure 4 illustrates water level occurrences in the vicinity of Bishop for March 11 through March 13, 1984, when the water table was approximately 10.45 feet below land surface. Because the daily maximum water level elevations occur in late afternoon rather than mid-morning, it is reasonable to assume that pressure effects are more influential than evapotranspiration effects early in the growing season and when the water table lies at such a depth.

There may be a water table depth below which barometric pressure effects are dominant and above which temperature and plant water use demands dominate the fluctuations. This latter situation characterizes water level changes in southern Owens Valley where the water table is frequently less than one-half foot below land surface at the onset of the growing season in the early spring.

Table 1 presents the magnitude of fluctuations for the changes in water level and the factors considered to be influential in producing those changes at Site 2, near Bishop.

In order to examine the detailed water level response of a shallow, unconfined aquifer to the combined effects of

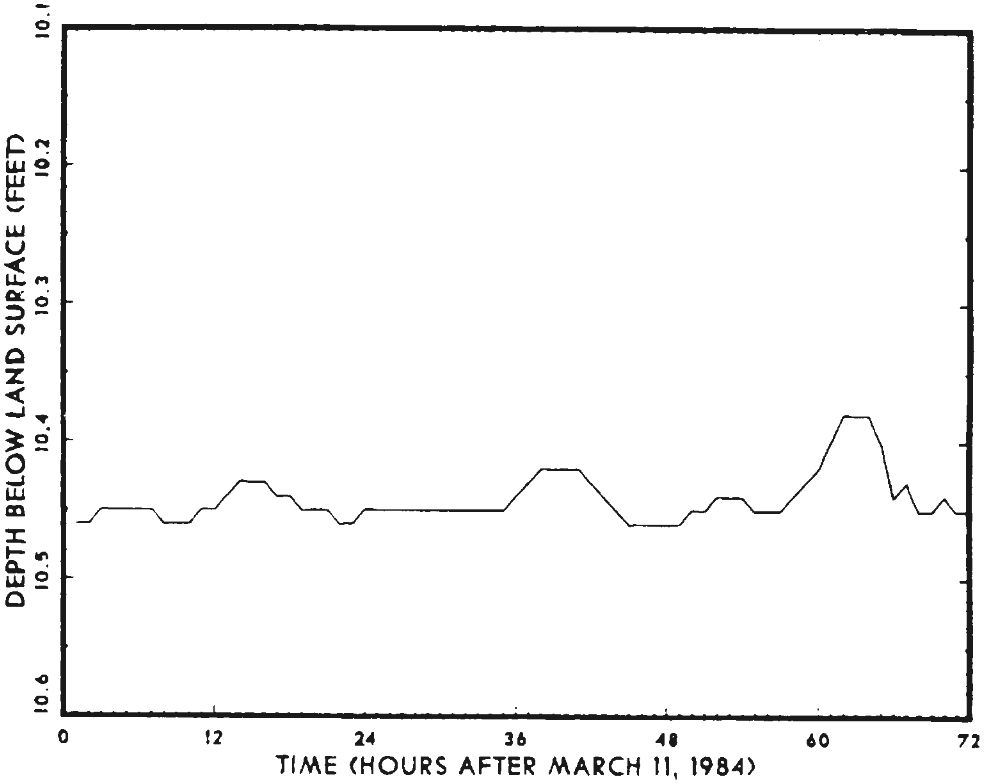

Figure 4. Diurnal water level fluctuations at Site 2, March 11-13, 1984.

Table 1. Magnitude of fluctuations at Site 2, near Bishop, California.

	WATER LEVEL (feet)	BAROMETRIC PRESSURE (feet of water)	EVAPO-TRANSPIRATION (feet/hour)	TEMPERATURE (degrees Celsius)
Spring (3/11-13/84)	8.00×10^{-2}	4.10×10^{-1}	2.00×10^{-3}	2.62×10
Summer (8/19-21/84)	5.00×10^{-2}	1.80×10^{-1}	4.00×10^{-3}	2.01×10
Fall (11/5-7/84)	7.00×10^{-2}	4.40×10^{-1}	2.00×10^{-3}	2.53×10
Winter (1/28-30/85)	3.00×10^{-2}	2.30×10^{-1}	1.00×10^{-3}	1.63×10

barometric pressure, evapotranspiration, and temperature, three situations were analyzed: (1) the actual response observed during March 5 to March 9, 1985; (2) the actual response observed in a well in which a pumping test was conducted during December 7 through December 8, 1983; and (3) an artificially generated response to a fictitious pumping test for the period of May 24 through May 25, 1985. In all situations, the water level was examined both before and after removal of the effects of the natural forces. For the two cases involving pumping test data, hydrologic characteristics of the aquifer (i.e., transmissivity, hydraulic conductivity, and specific yield) were compared to those calculated after removal of the effects of the natural forces on the water level.

4.1 Actual Water Level Response

4.1.1 Water Level at Site 2, March 5 - 9, 1985

The period of March 5 through 9, 1985 was chosen to depict the unconfined aquifer's water level response to barometric pressure, evapotranspiration, and temperature for two reasons: (1) it represents a transition from late winter precipitation into the generally drier months of spring; and (2) it occurs at the start of the growing season when vegetation is just beginning to actively transpire. The upper trace of Figure 5 shows the water level record for Site 2 over this period.

Water level data were collected from a 25-foot deep well located at Site 2 and measured with a Fischer-Porter water

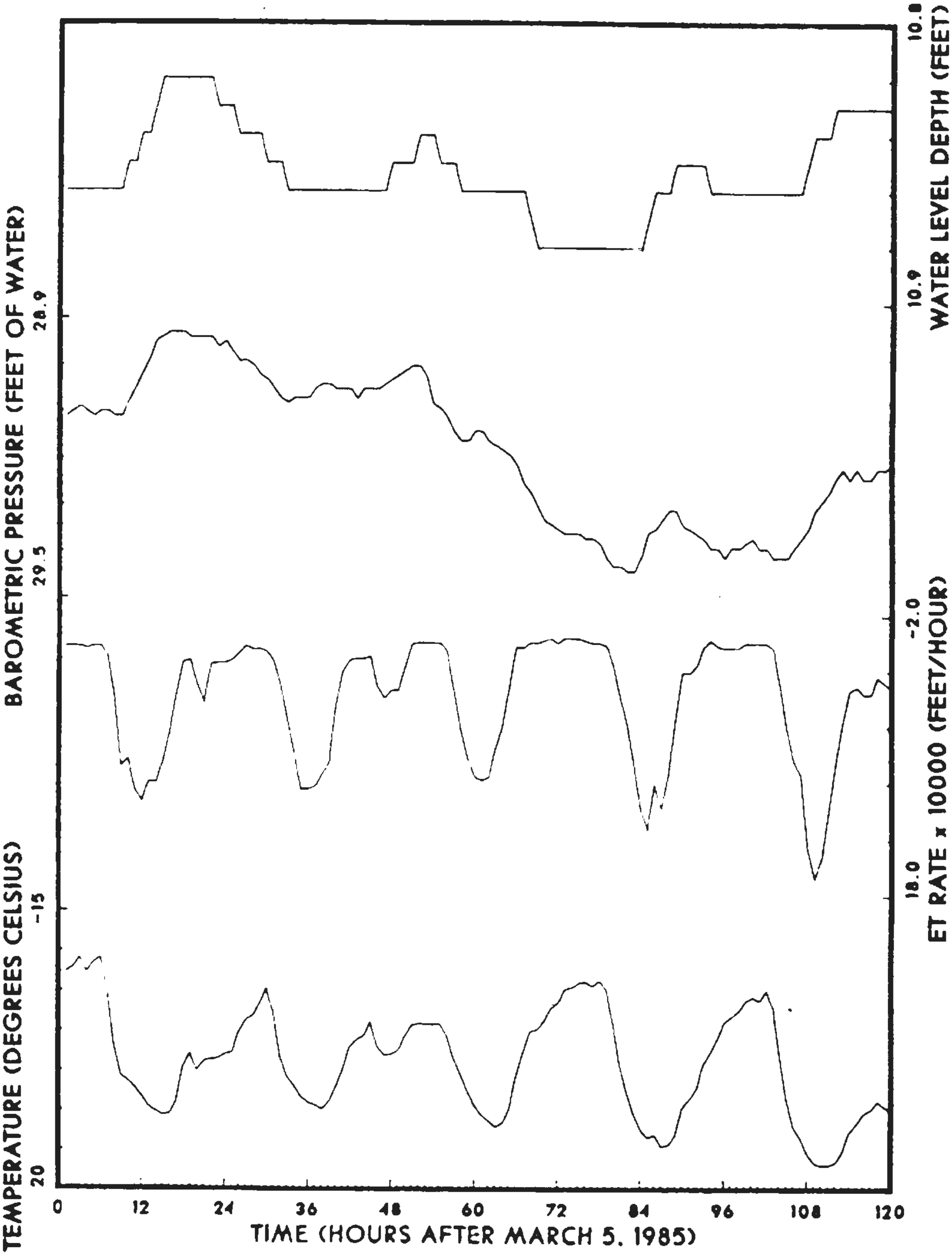

Figure 5. Water level depth, barometric pressure, evapotranspiration, and temperature measured at Site 2, March 5-9, 1985.

recorder. These data represent hourly averages of 15-minute readings and are accurate to ±0.01 feet. Therefore, it should be noted that the mechanical appearance of the water level shown on Figure 5 is a reflection of the instrument sensitivity. The other traces shown on Figure 5 depict hourly values of barometric pressure, evapotranspiration, and temperature for the same period of record. With the exception of barometric pressure, all of the traces show a distinct diurnal pattern. However, the peaks and troughs of the pressure trace correlate well with those of the water level data and do indicate a diurnal pattern to some degree.

In order to examine the water level pattern without the effects of the three natural forces, a concept based on barometric efficiency was used to remove signatures of the forces from the water level record. This means that an "efficiency" was calculated for each data set by the following relationships:

$$\frac{\text{change in WL}}{\text{change in BP}} \; ; \; \frac{\text{change in WL}}{\text{change in ET}} \; ; \; \frac{\text{change in WL}}{\text{change in T}} \; ,$$

where WL is the water level in feet (ft), BP is the barometric pressure in ft of water, ET is the evapotranspiration rate in ft, and T is temperature in degrees Celsius (°C) for the same period of record. In short, a weighted percentage of the water level fluctuations was attributed to each of the natural forces. Additionally, hourly values of barometric pressure were adjusted to a mean standard pressure calculated for the elevation at the

Bishop airport (4145 ft). Assuming that the density of air remains constant and considering the atmosphere as a static fluid (Daugherty and Franzini, 1977), the mean standard barometric pressure was calculated to be 28.83 ft of water.

The other two data sets were similarly corrected to minimum standard values below which neither the evapotranspiration rate nor the temperature would reasonably occur. For example, with a "temperature efficiency" of 1.00×10^{-3} ft/°C and a minimum standard temperature correction of -12.00 °C, an hourly temperature reading of 6.25 °C was revised as follows:

$$[1.00 \times 10^{-3}\ \mathrm{ft/^{o}C}) \times 6.25^{o}\mathrm{C}] - [(1.00 \times 10^{-3}\ \mathrm{ft/^{o}C}) \times -12.00^{o}\mathrm{C}] = 1.83 \times 10^{-2}\ \mathrm{ft}.$$

An "evapotranspiration efficiency" of 1.50×10 ft/ft and a minimum standard evapotranspiration correction of 0.00 ft yielded the following revision for an hourly reading of 8.37×10^{-4} ft:

$$[(1.50 \times 10\ \mathrm{ft/ft}) \times (8.37 \times 10^{-4}\ \mathrm{ft})] - [(1.50 \times 10\ \mathrm{ft/ft}) \times 0.00\ \mathrm{ft}] = 1.26 \times 10^{-2}\ \mathrm{ft}.$$

Similar calculations were performed to revise the barometric pressure data set. Table 2 presents the values used in these revisions, and Figure 6 shows the actual measured water level and the adjusted water level that was obtained from the subtraction of each of the "revised" natural forces.

As can be seen in Figure 6, the adjusted water level is significantly different from actual measurements. It is

Table 2. Efficiencies and standard corrections for barometric pressure (BP), evapotranspiration (ET), and temperature (T) at Site 2, March 5-9, 1985.

	EFFICIENCY	MINIMUM STANDARD CORRECTION	"EFFICIENT" CORRECTION
BP	1.30×10^{-1}	2.88×10 ft of water	3.75
ET	1.50×10	0.00 ft	0.00
T	1.00×10^{-3}	-1.20×10 °C	-1.20×10^{-3}

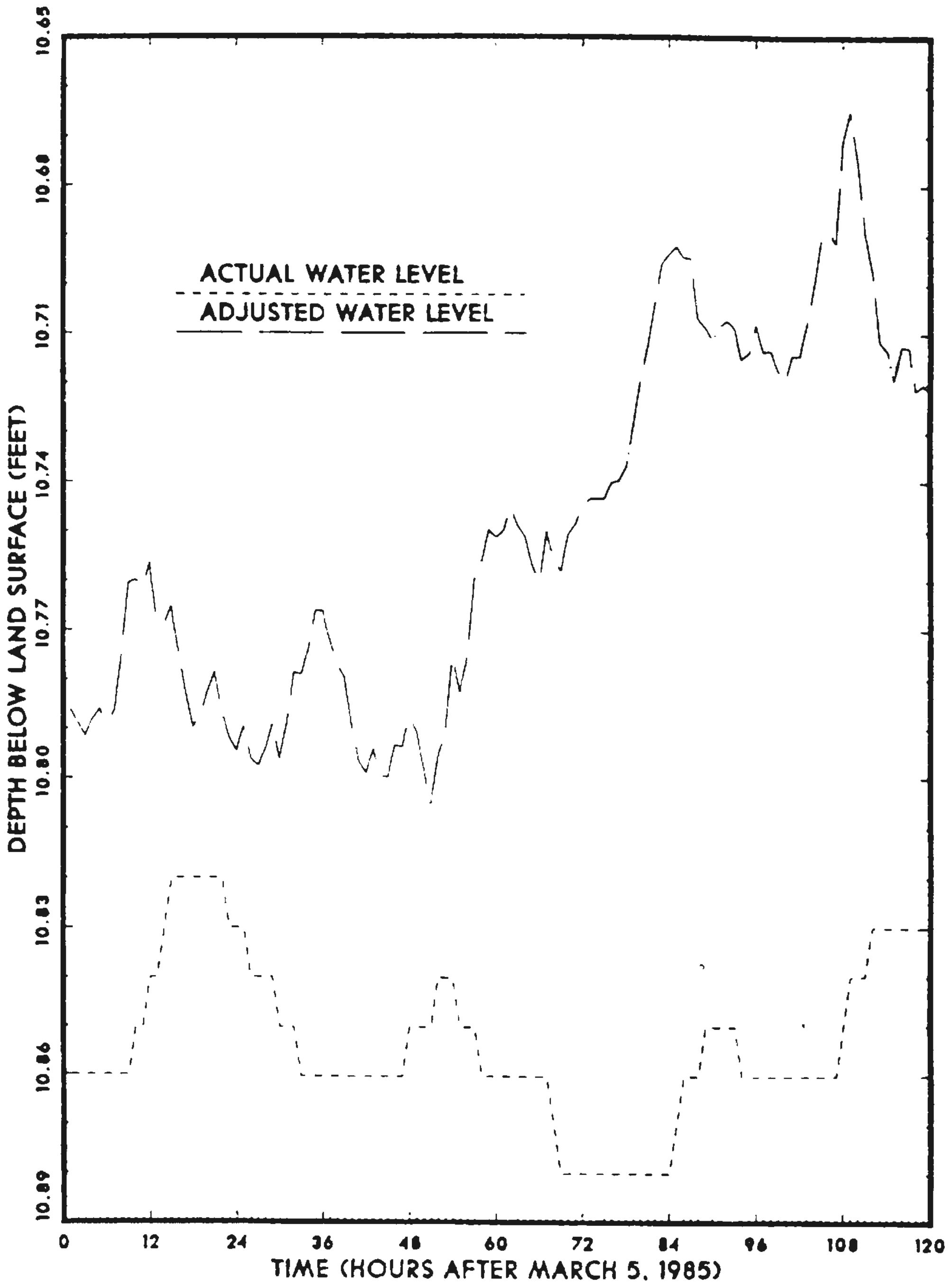

Figure 6. Actual and adjusted water level depth at Site 2, March 5-9, 1985.

shallower than the actual water level, albeit by less than two inches even at the traces' most significant deviations of March 8 and 9. Also, the adjusted water level exhibits slopes that are more variable than those seen on the mechanical trace of the actual water level. In fact, rising and falling actual water levels are not necessarily correlated with the increasing and decreasing slopes of the adjusted trace for the same time periods, thus implying a suppression or enhancement of the water level due to the natural forces.

Upon removal of the natural forces, it was noticed that the magnitude of contributions toward the water level fluctuations was greatest for the barometric pressure data set. This is supported by the actual water level exhibiting a daily maximum in the late afternoon on March 5, 8, and 9, as would be expected for a water level that is strongly influenced by changing pressure. (The early peak water level values on March 6 and 7 could be due to errors in the water level recorder, the fact that each hourly value is an average of four 15-minute readings, or an anomalously lagged manifestation of the true water level.) The adjusted water level, however, consistently exhibits a daily maximum that occurs at or very near to noon for every day shown on Figure 6.

Perhaps the most noticeable difference between the two traces is the marked increasing trend of the adjusted water level that begins on March 7. It is possible that such a water level increase was not apparent in the actual data due to the counterbalancing influence of the three natural forces serving to depress the water level at a rate approximately equal to the rate of the overall water level rise. This increase that becomes apparent only after removal of the effects of the natural forces may be due to plants with extensive roots actually pulling water up from the water table at the onset of the growing season. The water level rise might otherwise be due to a direct addition of moisture to the unconfined aquifer. For instance, it might result from precipitation that occurred at Site 2 on March 6 or 7. Since the main period of precipitation in Owens Valley occurs from October to February, it seems more likely, however, that the water level increase is due to recharge resulting from the accumulation of snow and rain at higher elevations and on the valley itself. Therefore, removal of the effects of barometric pressure, evapotranspiration, and temperature could possibly result in Figure 3 depicting a peak water level at an earlier time.

4.1.2. Pumping Test at Site 12, December 7-8, 1983

Data from early December, 1983 were examined to show an unconfined aquifer's water level response to the three natural forces during a pumping test. The particular period of December 7 - 8 was studied because the pumping test conducted at that time was one of the few tests performed in northern Owens Valley that obtained water from the unconfined zone. Furthermore, examination of these data provided an excellent opportunity to see if removal of the effects of barometric pressure, evapotranspiration, and temperature from the water level could significantly change values of the hydrologic characteristics that are normally calculated from such data.

The well in which the pumping test was conducted is owned by the U.S. Geological Survey and is located at Site 12. It is 98 feet deep with 10-inch diameter steel casing extending from 2 to 48 feet; the casing is perforated from 8 to 48 feet. The material in which the well was drilled is composed of alternating layers of clay, silty clay, silty sand, and silty, sandy gravel. The completed well extends to a 48-foot depth, where a two-foot silty clay layer was encountered. The constant discharge portion of the pumping test extended from December 7, 1983 through December 8, 1983 and was run at a discharge rate of 81 gallons per minute (gpm). LADWP performed the test and recorded the water level changes. Observation well G is located 33 feet northwest of the production well and was also monitored during the pumping test. It was drilled to a 56-foot depth and is lined with 8-inch diameter plastic casing from 2 to 56 feet; perforations exist from 16 to 56 feet. Like the production well, well G terminates in a mixed layer of clay and silty clay.

Recordings of barometric pressure, evapotranspiration, and temperature were not made at Site 12. Therefore, pressure data from the Bishop airport and micrometeorological data collected at Site 2 were used to analyze the water level's response to the natural forces. However, the instrumentation necessary for calculation of evapotranspiration and temperature was inoperative from December 7 through the early part of December 8. In order to examine data for this period, techniques of time series analysis were employed to estimate mathematical models capable of producing time series that are statistically indistinguishable from available hydrological series (Bras and Rodriguez-Iturbe, 1985). A summary of the theory of time series analysis used in this study is described in the appendix. The analysis technique of autoregressive integrated moving average (ARIMA) modeling was used to generate temperature and evapotranspiration time series based on actual hourly values from December 5 - 6, 1983. The use of barometric pressure data also presented a problem: pressure readings for December, 1983 were not available for examination. Therefore, ARIMA modeling was also used to generate a barometric pressure time series for December 7 - 8, 1983 that was based on hourly data from December 7 - 8, 1984.

The effects of the three natural forces were removed from the water level data set in exactly the same manner as described for the March, 1985 data. Unlike the March water level data set, the values of depth to water that were measured during the pumping test at well G comprise the water levels from which the natural forces were removed. Table 3 contains the corrections used to revise the barometric pressure, evapotranspiration, and temperature time series.

Table 3. Efficiencies and standard corrections for barometric pressure (BP), evapotranspiration (ET), and temperature (T) at Site 12, December 7-8, 1983.

C	EFFICIENCY	MINIMUM STANDARD CORRECTION	"EFFICIENT" CORRECTION
BP	2.00×10^{-1}	2.88×10 ft of water	5.77
ET	4.46×10	0.00 ft	0.00
T	2.00×10^{-3}	-3.00×10 °C	-6.00×10^{-2}

Figure 7 presents the depth to water measured at observation well G both before and after the removal of the natural forces. As with the March, 1985 data, barometric pressure contributes the greatest effect of the natural forces acting on the water level. This is not surprising considering that temperatures are generally low in December, and evapotranspiration is virtually nonexistent. Nevertheless, because of the combined effects, the adjusted water level is shallower than the actual water level by two to four inches. This magnitude is greater than the deviations for the March, 1985 data, but the overall effect of pumping (i.e., a two-foot water level drop) generally diminishes the intensity of smaller fluctuations. Thus, Figure 7 depicts an overwhelming decline of the natural water surface rather than smaller deviations that would have been apparent in the absence of pumping.

The slopes between values of the adjusted water level are similar to those of the actual water level in most instances. Clearly the adjusted trace exhibits the same water level decline followed by a stabilizing trend as does the actual water level trace.

To determine whether these seemingly minor differences between the actual and adjusted water levels have any effect on the calculated values of the aquifer's hydrologic properties, values of the drawdown measured at well G were examined. Table 4 presents the actual drawdown and the drawdown adjusted

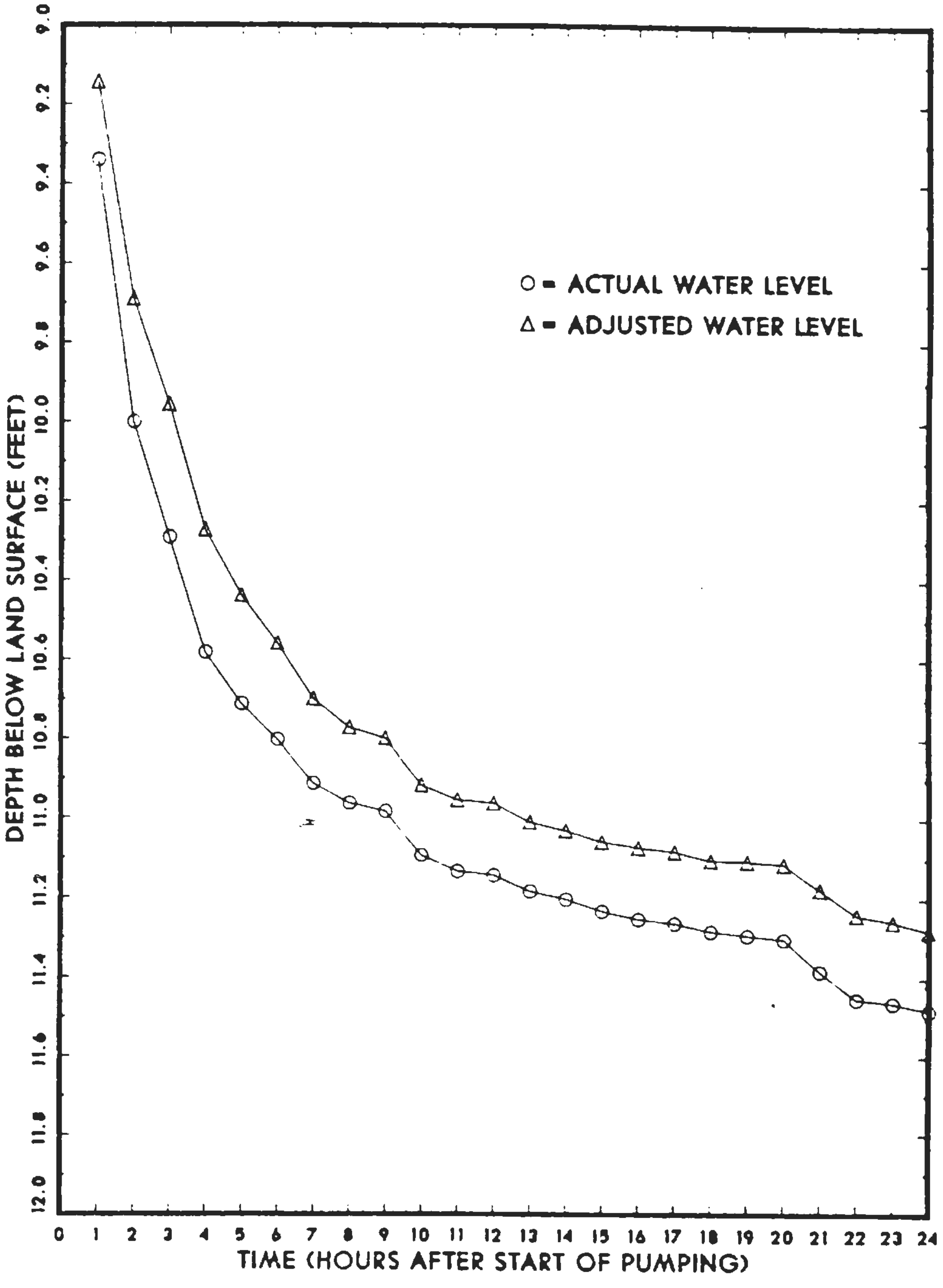

Figure 7. Actual and adjusted water level depth measured at Observation Well G, Site 12, December 7-8, 1983.

Table 4. Actual drawdown measured at Observation Well G and adjusted drawdown after the removal of the influences of barometric pressure, evapotranspiration, and temperature.

ACTUAL DRAWDOWN (FT)	ADJUSTED DRAWDOWN (FT)	TIME
0.00	0.00	1300
0.66	0.55	1400
0.95	0.81	1500
1.24	1.13	1600
1.37	1.29	1700
1.46	1.41	1800
1.57	1.55	1900
1.62	1.63	2000
1.64	1.65	2100
1.75	1.77	2200
1.79	1.81	2300
1.80	1.82	2400
1.84	1.86	0100
1.86	1.88	0200
1.89	1.91	0300
1.91	1.93	0400
1.92	1.94	0500
1.94	1.96	0600
1.95	1.96	0700
1.96	1.97	0800
2.04	2.03	0900
2.11	2.09	1000
2.12	2.11	1100
2.14	2.14	1200

for the influences of barometric pressure, evapotranspiration, and temperature. As seen on Table 4, the values become essentially identical approximately five hours after the start of pumping.

Using these data, the transmissivity, hydraulic conductivity, and specific yield (S_y) were calculated and are presented in Table 5. Calculations are based on Neuman's (1975) method of analysis for unsteady-state flow in unconfined aquifers with delayed yield. The method is a refinement of Boulton's analysis (Kruseman and DeRidder, 1983) and employs a series of type curves. The early and late data referred to in Table 5 reflect the concept of delayed yield: if unconfined aquifers are pumped for a sufficiently long period, they frequently exhibit the characteristics of delayed yield resulting from gravity drainage (Neuman, 1975). Both before and after the delayed yield phase, the time-drawdown plot closely conforms to the Theis-type curve. Thus, the early data refer to drawdown values measured until the onset of delayed yield; late data refer to those values measured from the delayed yield phase until the end of the pumping test.

The storage terms calculated from the early data are an order of magnitude lower than those calculated from the late data. In fact, they seem to be less characteristic of an unconfined aquifer than a confined aquifer. This is typical of an unconfined aquifer with delayed yield and shows the danger

Table 5. Transmissivity (T), hydraulic conductivity (K), and storage terms (S, Sy) calculated for actual and adjusted water level data measured at Observation Well G.

	EARLY DATA			LATE DATA		
	T (ft^2/day)	K (ft/day)	S %	T (ft^2/day)	K (ft/day)	S_y %
ACTUAL	2.6×10^3	5.0 x 10	2.0	3.3×10^3	7.0 x 10	3.0 x 10
ADJUSTED	2.3×10^3	5.0 x 10	3.0	1.8×10^3	4.0 x 10	2.0 x 10

of assuming that the early data can predict long-term drawdowns of the water table (Kruseman and DeRidder, 1983).

Table 5 shows that the calculations for the adjusted data set are essentially identical to those for the actual data during the early phase of the pumping test. And although there is less similarity between the transmissivity values for the late data, these calculations are also quite similar.

While the values presented in Tables 4 and 5 appear to indicate that the removal of the influences of natural forces does not considerably affect the aquifer's calculable hydrologic properties, two considerations should be noted. As mentioned earlier, the alluvial material that comprises much of Owens Valley does not allow for easy classification of distinct, laterally continuous unconfined and confined aquifers. Secondly, the interpretation of both the actual and adjusted drawdowns can be somewhat subjective. In the case of the 24-hour pumping test performed at Site 12, the time-drawdown plots did not exhibit a very distinct delayed yield phase. In fact, the data could have equally as likely been analyzed with a Theis-type curve. Since the water-bearing zone could plausibly be classified as a semi-unconfined aquifer, there is no absolute indication that a pumping test analysis using a Theis-type curve would be extremely inaccurate. Perhaps if the test had run long enough to promote a distinct delayed yield phase, this would not have been the case. It was thought that the examination of time-drawdown data exhibiting an ideal delayed yield response could indicate the reliability that can be associated with this part of the overall analysis. The following section explores this possibility.

4.2 Artificial Water Level Response

4.2.1 Artificially Generated Pumping Test, May 24-25, 1985

Since actual data from pumping tests performed in Owens Valley did not conclusively imply whether or not water levels in unconfined aquifers significantly respond to the effects of natural forces, ideal artificially generated data for May, 1985 were examined. The time-drawdown data were derived from the Neuman-type curve with n equal to 0.4 (see Neuman (1975) for a thorough explanation of his procedure and constants). In doing so, the appearance of the data imply that: (1) a pumping test was conducted in a well penetrating a typical unconfined aquifer; and (2) the test was carried on long enough for the aquifer to exhibit delayed yield. With the time-drawdown data in this form, there was no possibility that a Theis-type analysis procedure could have properly calculated the aquifer's transmissivity, hydraulic conductivity, and specific yield.

Because evapotranspiration and temperature data were available for May, 1985 at Site 2 and barometric pressure was measured at the Bishop airport, it was assumed that the fictitious pumping test was conducted at Site 2. The period of May 24 through May 25, 1985 was studied because evapotranspiration rates calculated for that period at Site 2 were higher than at any other time during the 1984 and 1985 growing seasons. As with the actual pumping test that was conducted at Site 12 in December, 1983, the unconfined aquifer was assumed to be 48 feet thick. Also, the fictitious well was pumped at a rate of 81 gpm and the water level was monitored in an observation well located 33 feet from the pumped well. The effects of the natural forces were removed from the water level data set in the same way as described in the previous sections. The corrections used to revise the barometric pressure, evapotranspiration, and temperature data sets are presented in Table 6.

The depth to water measured in the observation well before the removal of the natural forces, and the adjusted values are presented in Figure 8. The similarity between the two traces is even more striking than with the December, 1983 data. In fact, the adjusted water level is only 0.24 to 0.60 inches shallower than the actual water level, and the slopes between consecutive values are identical. As with the December, 1983 data, the overall influence of the fictitious pumping produced a water level decline that obscured any diurnal or shorter duration fluctuations that are evident in the March, 1985 data. Also, even though the evapotranspiration rates measured during May 24 - 25, 1985 were an order of magnitude greater than those measured in December, 1983, barometric pressure was still the most influential of the natural forces in affecting the water level.

Table 6. Efficiencies and standard corrections for barometric pressure (BP), evapotranspiration (ET), and temperature (T) at Site 2, May 24-25, 1985.

	EFFICIENCY	MINIMUM STANDARD CORRECTION	"EFFICIENT" CORRECTION
BP	5.80×10^{-2}	2.88×10 ft of water	1.67
ET	2.95	0.00 ft	0.00
T	1.00×10^{-3}	1.75 °C	2.00×10^{-3}

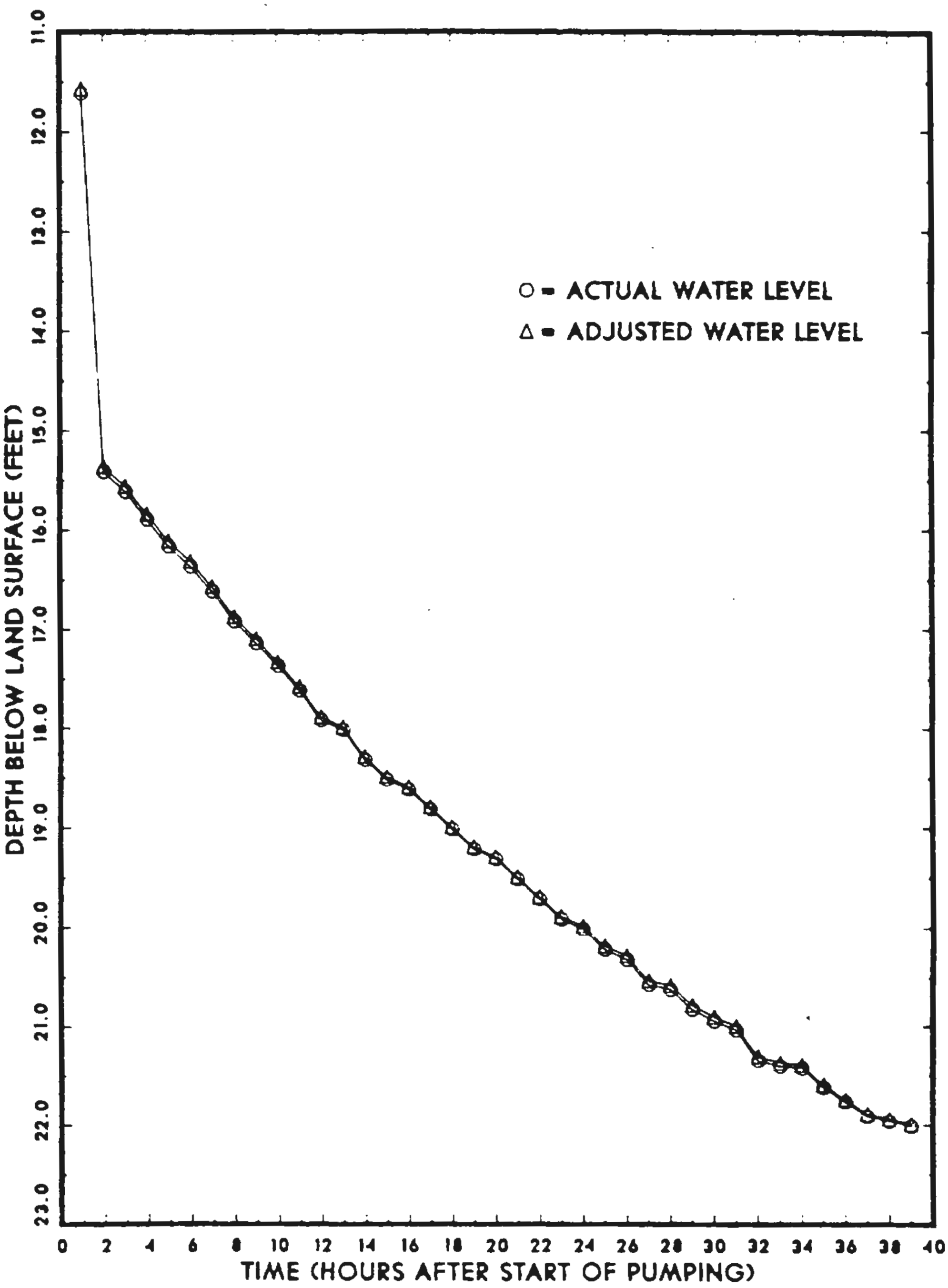

Figure 8. Artificially generated actual and adjusted water level depth at Site 2, May 24-25, 1985.

The hydrologic properties of the aquifer were calculated from the actual and adjusted water level measurements using Neuman's (1975) method of analysis. Table 7 shows that even after removal of the influences of the three natural forces, adjusted drawdown was quite similar to actual drawdown. Table 8 shows the transmissivities, hydraulic conductivities, and storage terms calculated from the artificially generated early and late drawdown values. Clearly, there is an agreement between the actual and adjusted calculations from both the early and late data. However, the storage terms calculated from the late data are two orders of magnitude greater than those calculated from the early data, and are typical of unconfined aquifers' specific yield values. Therefore, it does not appear that even ideal water level data observed during a pumping test of an unconfined aquifer are significantly influenced by barometric pressure, evapotranspiration, and temperature.

Table 7. Actual drawdown generated in an artificial pumping test and the adjusted drawdown after the removal of the influences of barometric pressure, evapotranspiration, and temperature.

ACTUAL DRAWDOWN (FT)	ADJUSTED DRAWDOWN (FT)	TIME
0.00	0.00	0800
3.80	3.79	0900
4.00	3.99	1000
4.28	4.27	1100
4.55	4.54	1200
4.75	4.74	1300
5.00	5.00	1400
5.30	5.30	1500
5.52	5.52	1600
5.75	5.75	1700
6.00	6.01	1800
6.30	6.31	1900
6.40	6.41	2000
6.70	6.71	2100
6.90	6.91	2200
7.00	7.02	2300
7.20	7.22	2400
7.40	7.42	0100
7.60	7.62	0200
7.70	7.72	0300
7.40	7.92	0400
8.10	8.12	0500
8.30	8.32	0600
8.40	8.41	0700
8.60	8.61	0800
8.70	8.71	0900
8.95	8.95	1000
9.00	9.00	1100
9.20	9.20	1200
9.32	9.32	1300
9.41	9.41	1400
9.72	9.72	1500
9.78	9.79	1600
9.80	9.81	1700
10.00	10.02	1800
10.15	10.17	1900
10.30	10.32	2000
10.35	10.37	2100
10.40	10.42	2200

Table 8. Transmissivity (T), hydraulic conductivity (K), and storage terms (S, Sy) calculated for the artificially generated actual and adjusted water level.

	EARLY DATA			LATE DATA		
	T (ft^2/day)	K (ft/day)	S %	T (ft^2/day)	K (ft/day)	S_y %
ACTUAL	2.1×10^2	5.0	1.3×10	2.3×10^2	5.0	1.2×10
ADJUSTED	2.3×10^2	5.0	1.3×10	2.4×10^2	5.0	1.2×10

5.0 CONCLUSIONS AND RECOMMENDATIONS

After examining the effects of barometric pressure, evapotranspiration, and temperature on the water level of a shallow, unconfined aquifer in Owens Valley, some conclusions regarding the value of isolating and removing these effects from the water level may be drawn.

Because of the relatively small cumulative influence of the three natural forces (on the order of 0 to 4 inches of water), their removal has no apparent effect on the calculations of transmissivity, hydraulic conductivity, or specific yield with respect to the data examined herein. In fact, these data imply that meticulous measurement of such forces and the correction of water levels monitored during pumping of the unconfined aquifer in northern Owens Valley are seemingly unnecessary.

This may not be the case in areas where the water table is closer to land surface, the unconfined aquifer material is more homogeneous, or during the advance or retreat of storm activity. It is therefore recommended that: (1) noticeable changes in atmospheric conditions be physically noted during pumping tests of unconfined aquifers; (2) thorough analyses of the aquifer material be carried out; and (3) accurate instrumentation be used for the monitoring of such natural forces whenever it is economically feasible.

It should be also noted that the removal of the effects of the three forces from a water level that is not stressed by pumping may indicate an otherwise suppressed manifestation of recharge--albeit by some small amount.

Of the three natural forces considered in this investigation, barometric pressure appears to have the greatest influence in causing water level fluctuations at any time of the year in the northern portion of Owens Valley, where the water table is about 10.5 feet below land surface. This is true even during periods where data sets for the natural forces were generated via time series modeling. In fact, the similar behavior of the actual pressure, evapotranspiration, and temperature data sets and the data sets generated by the ARIMA methodology lends favorable support for the use of ARIMA modeling of hydrologic data.

There are three main areas where more work should be done. The first would involve a similar analysis with water levels measured in a confined aquifer. Specifically with respect to pressure changes, an unconfined aquifer responds to pumping (i.e., a decrease in fluid pressure) by expansion of water in the aquifer, compaction of the aquifer material, and dewatering of the aquifer as water is withdrawn from soil pores. Therefore a change in pressure in an unconfined aquifer can be "absorbed" into the soil pores and into water level fluctuations that become evident in the well bore. Because confined aquifers cannot respond to such a change by accomodating it in soil pores, the entire effect is translated to water level fluctuations in the well itself and thus typically produces fluctuations of magnitudes greater than those produced in wells tapping unconfined aquifers. Therefore, through the examination of water levels measured in a confined aquifer, it might then be possible to determine an upper limit to the magnitude of the effects that the three natural forces impose on water levels; the analysis of unconfined aquifers serves as a lower limit.

Secondly, work could also be carried out by isolating and removing the effects of the three natural forces from the water level measured in an unconfined aquifer in an area with a much more shallow water table. In an area where the static water level is within two feet of the land surface, it might be possible to determine if the combined influences have a more significant effect on the hydrologic properties that are calculated from pumping test data. Site 10 in southern Owens Valley is characterized by a water table that is often less than one foot below land surface, and therefore would serve as an excellent study area.

As a third consideration, time series analysis in the frequency domain could be used as an alternate means of isolating and removing the signatures of barometric pressure, evapotranspiration and temperature from the water level data. Additionally, the analysis of both confined and unconfined aquifers could be broadened to include earth tidal effects.

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7.0 APPENDIX: A SUMMARY OF TIME SERIES ANALYSIS USING ARIMA MODELING

A large part of the statistical hydrological literature acknowledges natural processes as random phenomena that can be managed with the established concepts of random process theory (Box and Jenkins, 1976, Haan, 1977, Bowerman and O'Connell, 1979, and Bras and Rodriguez-Iturbe, 1985). The applicability of these concepts and the randomness itself may be intrinsic in the hydrologic process or may result from the scale of observation or from missing information.

Observed occurrences, or realizations, of a random process are called time series. Through the use of time series analysis, the statistical properties of the underlying random processes that lead to a physically observed series are estimated. This allows for the generation of mathematical models that are able to produce new time series which are statistically indistinguishable from the original.

There exist several types of models for the generation of hydrologic random processes, both in the time and frequency domains. This work follows the methodology described by Box and Jenkins (1976) in their comprehensive text on time series analysis in the time domain. Box and Jenkins developed a stochastic analysis technique based on the examination of the general class of ARIMA models. In random process theory, it is assumed that consecutive values of a time series are not related to each other, or are statistically independent. In practice, however, some values are statistically dependent on other values; this is known as autocorrelation. The ARIMA methodology makes efficient use of the autocorrelation, and thus produces models that have the potential to be extremely representative of the actual hydrologic phenomenon (Bowerman and O'Connell, 1979).

The adequate representation of a hydrologic time series by an ARIMA model is a multi-phased process. In the model identification phase, a class of models is selected based on the statistical properties of the original time series and a comparison of the theoretical behavior of those properties that can be obtained by the set of possible models. Parameter estimates are a product of the second phase. They are achieved by the iterative refinement of reasonable first estimates. The third phase is the diagnostic step in which the adequacy of the estimated models is checked. By either choosing a statistically significant model or eliminating all models, this verification phase examines the expected theoretical behavior of the model residuals, which represent uncorrelated random variables (Bras and Rodriguez-Iturbe, 1985).

The Minitab data analysis software package (Ryan, et al, 1982) was used to perform the computations necessary to decide on representative ARIMA models for the barometric pressure, evapotranspiration, and temperature time series analyzed in Chapter 4. The input to this statistical package consisted of a time series and certain directives as to the model type:

autoregressive (AR); moving average (MA); a combination of these two (ARMA); or an ARIMA-type. The output consisted of parameter estimates at each iteration, significance tests of the final parameter estimate, and a significance test to check the model's adequacy. Once the most adequate models were determined, a subroutine from the International Mathematical and Statistical Library (IMSL Reference Manual, 1982) was used to generate time series for the missing data for the period of December 7 - 8, 1983. These new time series were based on the models determined from the Minitab software.

There exists a considerable amount of literature on the mechanics of time series analysis in general, and ARIMA modeling in particular. A detailed explanation of such topics is quite beyond the scope of this work. Those interested in the detailed description of the theory of the analysis technique and/or examples using actual data are advised to examine the works of Yevjevich (1972), Box and Jenkins (1976), Bowerman and O'Connell (1979), and Bras and Rodriguez-Iturbe (1985).