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THE LOCAL EFFECTS OF GROUNDWATER PUMPAGE WITHIN A FAULT-INFLUENCED GROUNDWATER BASIN, ASH MEADOWS, NYE COUNTY, NEVADA, U.S.A.

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ABSTRACT

Rojstaczer, S., 1987. The local effects of groundwater pumpage within a fault-influenced groundwater basin, Ash Meadows, Nye County, Nevada, U.S.A. J. Hydrol., 91: 319–337.

Large-scale groundwater pumpage and water-level decline data are used in a preliminary attempt to identify the hydraulic connection between several wells and Devils Hole, a small pond in Nye County, Nevada, U.S.A. Results indicate that despite the discontinuous nature of the local aquifers, many wells have good hydraulic connection with Devils Hole. Hydraulic connection between the wells and Devils Hole exhibits a complex spatial variability typical of carbonate terrane. Zones or directions of minimal hydraulic connection may result from fault-controlled structural discontinuities. Zones or directions of enhanced hydraulic connection point to the presence of large-scale groundwater flow through fractures or conduits. The orientation of water-bearing fractures or conduits inferred from this study is qualitatively consistent with the major orientation of local and regional structural features.

INTRODUCTION

The ability of faults and fractures to serve as barriers or conduits for groundwater flow has been observed for decades. Large-scale failure planes can influence regional trends in groundwater flow (Winograd and Thordarson, 1968). At the other end of the spectrum, dense networks of small-scale failure planes can cause a groundwater system to have a highly variable character on a local scale (Horne and Rodriguez, 1983). In some places the local character of groundwater flow can be related to local deviations in structural trends (Vecchioli et al., 1969). In areas where faults and fractures are dense and have a dominant orientation on a local and regional scale, it is possible that the same structural trends that affect regional groundwater flow also will have an identifiable influence on the local character of groundwater flow. In this paper, the groundwater hydrology of the discharge zone of a regional groundwater flow system in carbonate terrane is examined. Large-scale groundwater pumpage and water-level decline data are used in a preliminary attempt to identify the hydraulic connection between several water wells and Devils Hole, a small

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pond in Nye County, Nevada, U.S.A., and to determine whether some of the apparent hydraulic heterogeneity of the local groundwater system can be related to the dominant structural trends within the region.

HYDROLOGY OF THE STUDY AREA

The study area is located within Ash Meadows, a gently sloping terrain within the Amargosa Desert in southwestern Nevada (Fig. 1). Winograd and Thordarson (1975) provide a thorough description of the regional hydrology. Waddell (1982) made a quantitative study of the regional groundwater system. Bateman et al. (1972) made a preliminary quantitative assessment of the local hydrogeology. Dudley and Larson (1976) performed a detailed analysis of the local hydrogeology of Ash Meadows. The information below is largely a synopsis of these descriptions.

Ash Meadows, which contains large-discharge springs, is the discharge zone for the Ash Meadows groundwater basin, a regional groundwater flow system whose principal aquifer is composed of Lower Paleozoic carbonate rocks (Fig. 1). Numerous faults are found within the groundwater basin, some of which serve as barriers to flow within the Lower Paleozoic carbonate aquifer. The barrier faults demarcate parts of the boundary of the Ash Meadows groundwater basin. The eastern boundary of the basin is largely defined by the Gass Peak thrust fault. The southwestern boundary is defined by a buried unnamed normal fault that is discussed in greater detail in the following sections.

A part of the Lower Paleozoic carbonate aquifer forms prominent ridges which demarcate the eastern boundary of Ash Meadows. Devils Hole, a small pond (roughly 3 m wide and 20 m long) formed by failure and dissolution along a local northeast-trending Cenozoic fault, is located at the western base of these northwest-trending hills (Fig. 2). Within Ash Meadows, the Lower Paleozoic carbonate aquifer is overlain largely by at least several hundred meters of Tertiary and Quaternary lacustrine, alluvial, and volcanic deposits. Most of the Tertiary and Lower Quaternary material is poorly permeable. The Upper Quaternary, however, does contain discontinuous zones of highly permeable travertine and continental limestone as well as some sand and gravel deposits. The Quaternary carbonate rocks serve as the major source of groundwater for the area. Surface water is derived mainly from the above-mentioned springs, which are aligned in a northwest trend and discharge from circular pools developed in Quaternary playa, lacustrine, and travertine deposits. These springs apparently owe their origin to a buried northwest-trending high-angle fault that acts as a barrier to groundwater flow in the Paleozoic carbonate rocks. The chemistry, temperature, and hydraulic head of the major springs and water wells clearly demonstrate that the springs and Quarternary aquifers are fed by upward or lateral groundwater flow from the buried and eastern-flanking, fault-terminated, Lower Paleozoic carbonate aquifer.

Historic records show that spring discharge, hydraulic head, water temperature and water chemistry are not significantly affected by yearly vari-

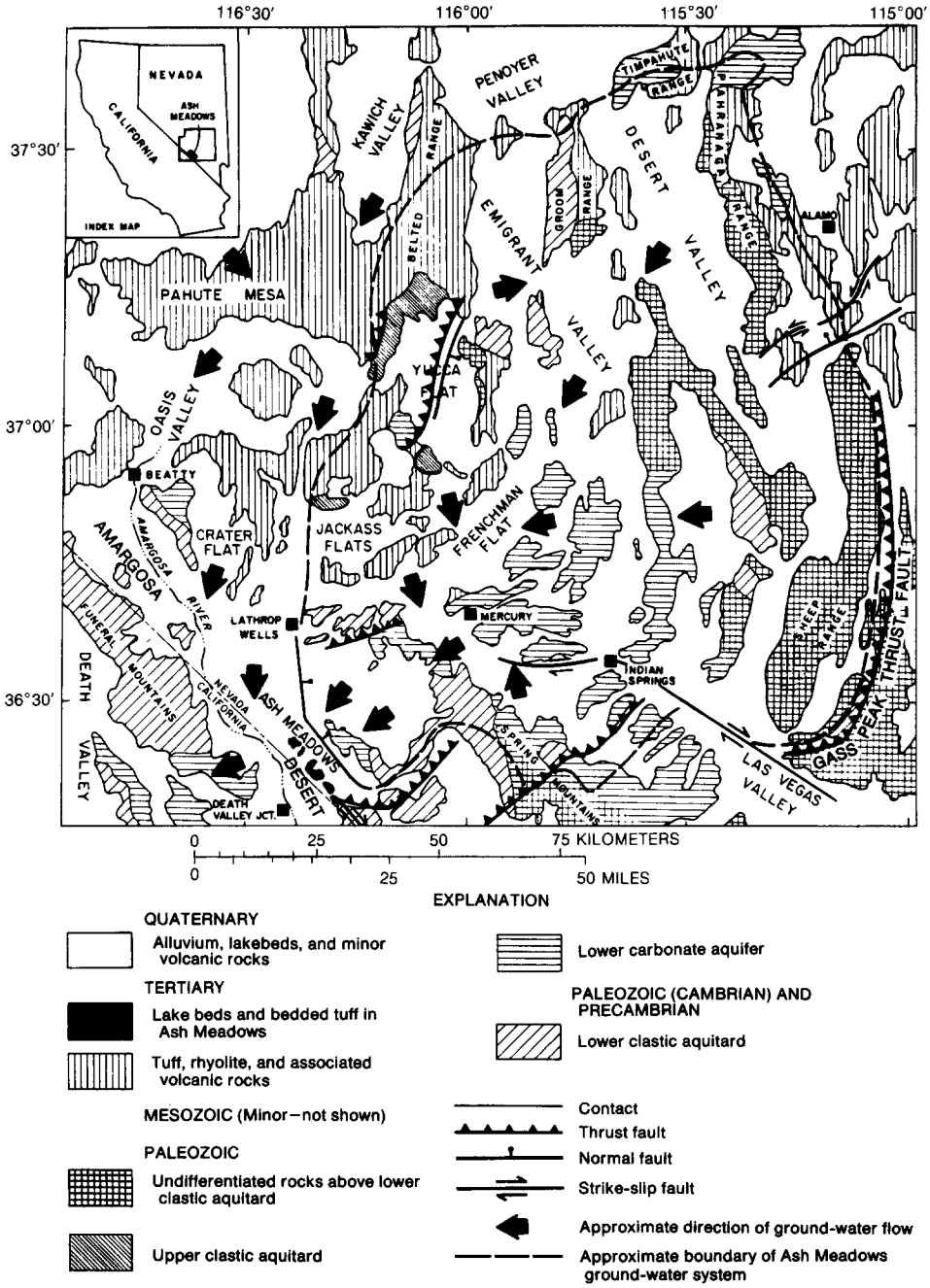

Fig. 1. General hydrogeology and major faults present within Ash Meadows groundwater basin, Nevada (adapted from Dudley and Larson, 1976; Burchfiel et al., 1983; Winograd and Thordarson, 1975).

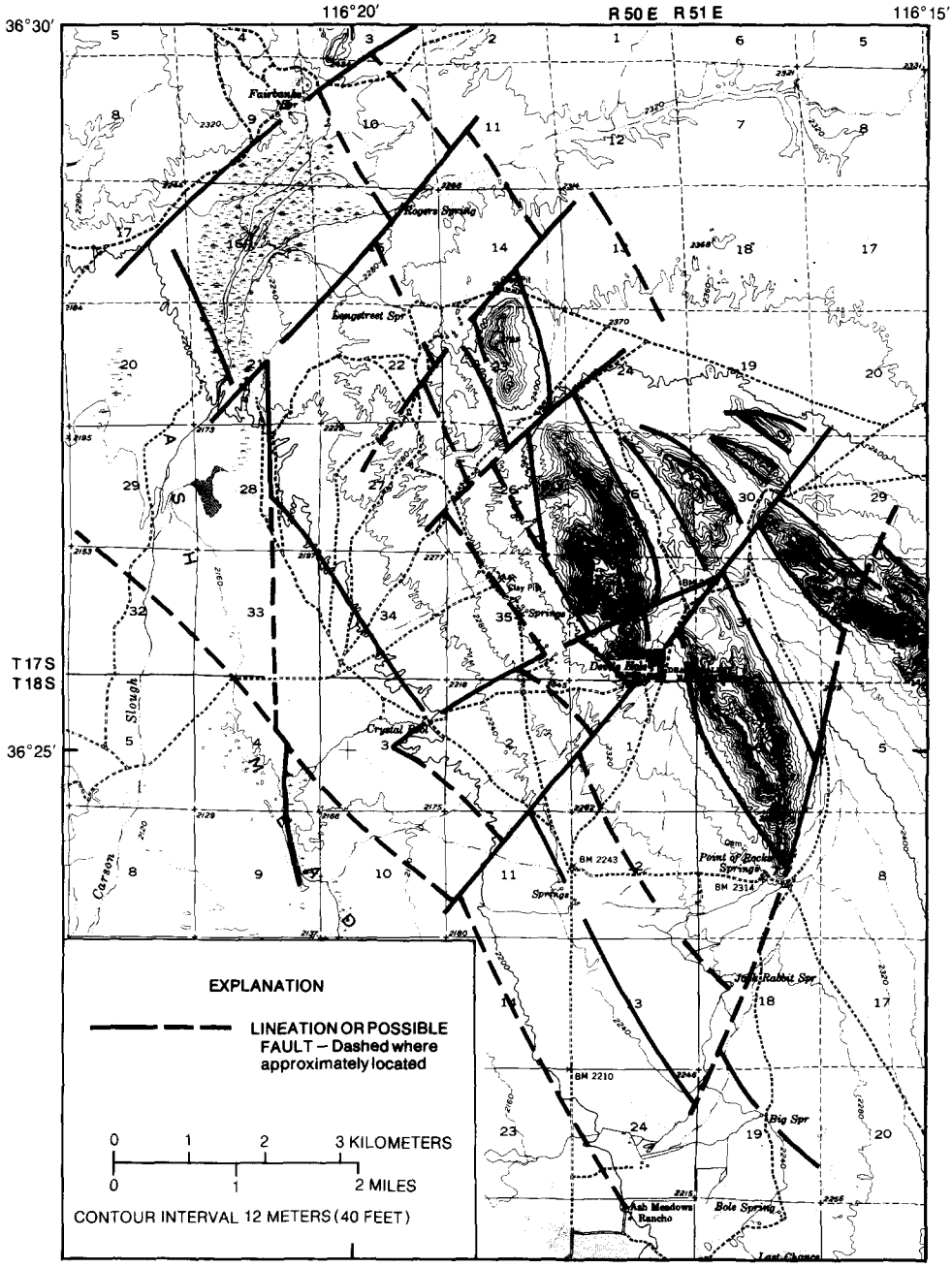

Fig. 2. Topography of Ash Meadows, with lineations and faults noted by Dudley and Larson (1976).

ations in climate. Major hydrologic changes occur only in response to groundwater pumpage. Volumetric spring discharge totals about 58,000 m^3 day^{-1} when the local aquifers are not pumped, a rate which has varied less than 20% since 1915. Groundwater levels, as evidenced by stage monitoring in Devils Hole, were constant between 1956 and 1968, a period when little groundwater was utilized. The water temperature and chemistry of the major springs have been constant since at least 1932.

LOCAL STRUCTURAL FEATURES

Denny and Drewes (1965) mapped the geology of the Ash Meadows quadrangle, the northeast part of which includes Ash Meadows. Their work primarily focused on the stratigraphy and geomorphology of Cenozoic rocks, and the structural geology of the area was not treated in detail. The general geology of the area is included in the geologic map of Nevada (Stewart and Carlson, 1978). Burchfiel et al. (1983) studied the structural geology of the Montgomery Mountains and the northern one-half of the Nopah and Resting Spring Ranges. The study area treated in this paper, while not included in their detailed mapping, was included in their general structural analysis. Dudley and Larson (1976) detailed the lineaments and faults within Ash Meadows. The following description is a brief compilation of information from the above reports.

Ash Meadows is part of the Montgomery thrust plate, a Mesozoic structure whose fault trace can be found roughly 18 km southeast of the Point of Rocks Springs. The carbonate ridges that demarcate the eastern boundary of Ash Meadows are apparently a part of the northwest-plunging Ash Meadows anticline; this structure predates the Montgomery fault. Cenozoic structures in the region southeast of Ash Meadows are generally oriented northwest–southeast, and numerous northwest-trending high-angle faults are present. This prevailing northwest orientation also is present in the faults and failure planes local to Ash Meadows (Figs. 2 and 3). Cenozoic west or northwest extension has produced right-lateral and normal slip along these high-angle faults. The buried high-angle fault which controls spring discharge in Ash Meadows is probably the only fault within Ash Meadows with large-scale displacement. It may represent one edge of a complex pull-apart structure which is responsible for the formation of Ash Meadows and the Amargosa Valley. The northwest-trending faults present in Paleozoic carbonate ridges rarely have displacements in excess of 65 m.

APPROACH USED TO ASSESS HYDRAULIC CONNECTION

Beginning in 1968, groundwater supplies within the local Ash Meadows aquifers were used extensively for irrigation until 1972, when pumping was restricted by U.S. District Court order (Dudley and Larson, 1976). The production wells are between 45 and 240 m deep (Fig. 4); only well 7 produced water directly from the Paleozoic carbonate aquifer. Groundwater pumping during this time was accompanied by declines in groundwater levels and spring dis-

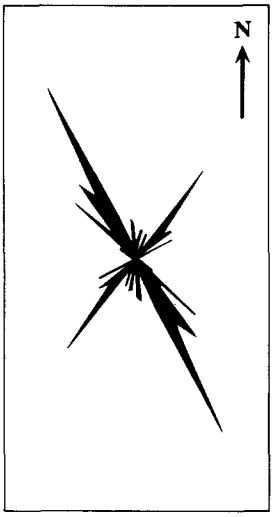

Fig. 3. Rose diagram summarizing the orientation of lineations and faults in Fig. 2.

charge within Ash Meadows. The stage of Devils Hole, which had been virtually constant for at least a decade, also fell in response to pumping; over the 32 months from June 1969 (when the stage had virtually recovered from groundwater pumping in the fall of 1968) to January 1972, the 10-day mean stage declined more than 60 cm. Groundwater pumpage on a monthly basis from the wells used during this time is shown in Table 1.

Dudley and Larson (1976) examined the stage declines in Devils Hole and the coincident groundwater pumpage data from each well and made a qualitative assessment of the hydraulic connection between each well and Devils Hole. They also performed pump tests on wells, using neighboring wells to observe groundwater level declines. The pump test data, which superficially seemed amenable to standard pump test analysis, generally yielded questionable values for the permeability and storage coefficient of the material between the pumping well and the observation well. Consequently, the pump-test data were not used as an accurate measure of aquifer properties; rather, they were used to assess qualitatively the hydraulic connection between local wells. The results of the overall analysis indicated that the hydraulic connection among the wells themselves and between the wells and Devils Hole was complex and that few spatial trends could be identified.

In this paper standard groundwater hydraulics theory is used in a preliminary attempt to explain the larger scale response of Devils Hole to groundwater pumpage. The stage declines of Devils Hole from June 1969 to January 1972 and the accompanying groundwater withdrawals are treated as a large-scale pump test. The reasons for employing such an approach are: (1) the influence of structural trends not apparent at the scale of the local pump tests may become identifiable at this somewhat larger scale; and (2) trends not identifiable through visual inspection of these data may be masked because it is difficult for

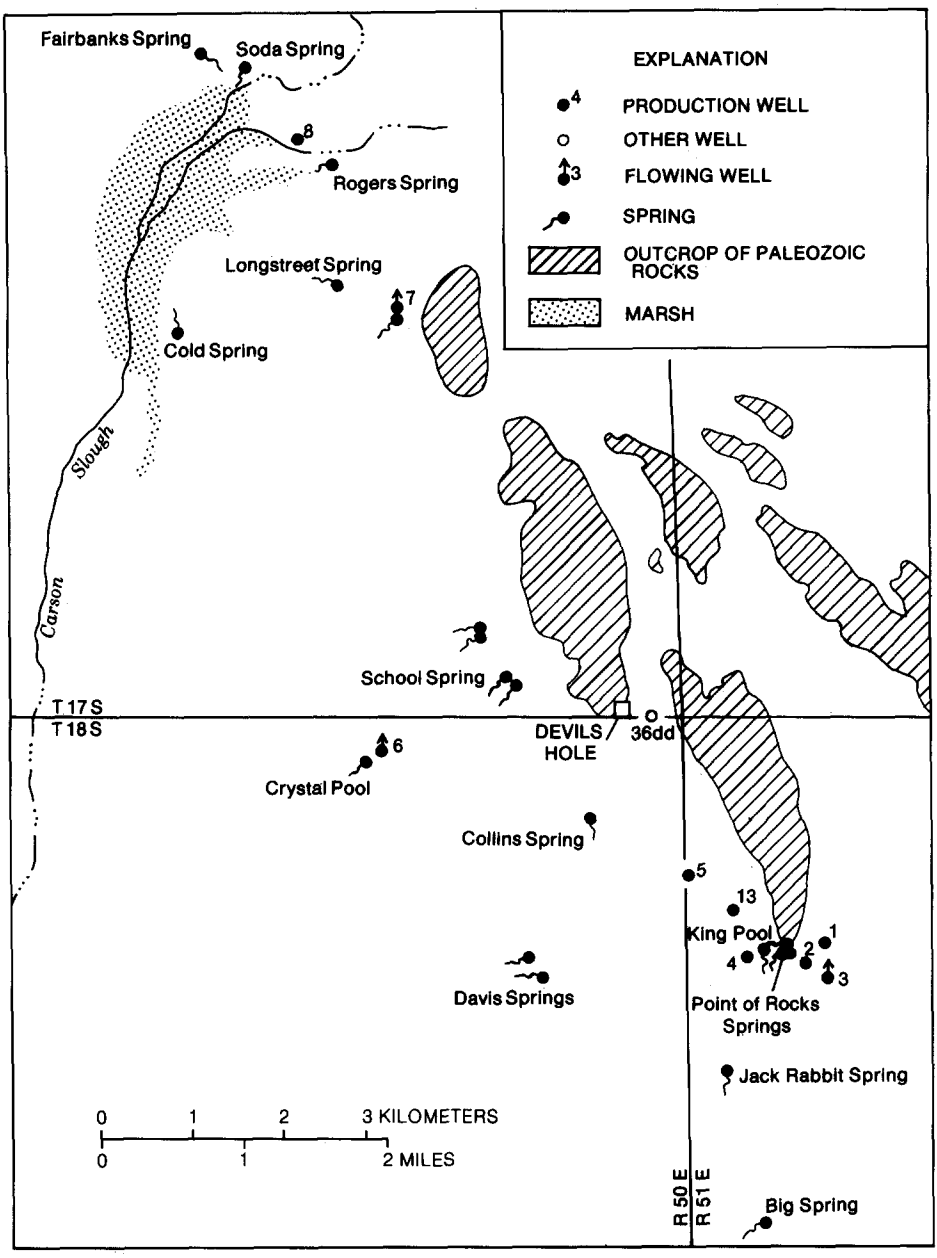

Fig. 4. Location of wells utilized for significant groundwater supply and water-level observation from June 1969 to January 1972. Wells indicated as flowing are those wells which flowed prior to being used for water supply (adapted from Dudley and Larson, 1976).

TABLE 1

Estimated monthly pumpage, in 10^{-4} km^3, for wells considered in this study, from June 1969 to January 1972

Month	Well No.								
	1	2	3	4	5	6	7	8	13
1969									
June	1.9	0	0	0	0	0	0	0	0.5
July	1.8	0	0	0	0	0	0	0	0.5
August	1.1	0	0	0	0	0.5	0	–*	0.7
September	0.4	1.1	0	0.1	0	0	0	1.0	0.6
October	1.7	0.8	0	1.7	0	0.2	0	0	0.7
November	1.6	1.1	0	1.4	0	0.2	0	1.2	0.6
December	0.2	0.4	0	0.1	0	0.2	0	–*	0.4
1970									
January	0	–*	0	0	0	0	0	0	0
February	0	–*	0	0.4	0	0	0	0	0
March	0	–*	0	0.2	0	0	0	0	0
April	0.1	0.7	0.7	0.9	0	0	0	0	0
May	2.5	0.9	1.5	0.8	4.2	0	0	0	0
June	2.3	1.0	1.4	1.5	4.1	0.3	0	0	0
July	2.2	1.0	0.9	1.5	3.0	0.3	0	1.5	0
August	2.6	1.5	2.0	1.5	3.7	0.3	0	0.9	0
September	2.3	1.4	2.0	1.4	3.3	0.3	0.3	0.2	0
October	2.5	1.6	1.4	1.0	3.6	–*	–*	1.7	0
November	2.3	1.2	0.6	1.5	3.3	0	0.2	1.7	0
December	0.9	1.4	0.1	0.9	1.4	0	0	0.7	0
1971									
January	0	0	0.4	0.2	0.9	0	0	0	0
February	2.3	0	0	0.4	1.6	0	0.1	0.1	0
March	1.8	0	0.6	0.5	0.5	0	0.7	0	–*
April	1.5	0.8	0.9	0.5	0.6	0.4	0.50	0	–*
May	1.8	0.4	0	0.5	1.5	0.7	0.4	0.2	0
June	3.0	1.1	1.0	1.5	1.2	0.1	0.5	1.1	0.1
July	2.6	1.4	2.0	1.2	1.5	1.7	0.9	1.1	0.2
August	2.6	1.6	2.0	0.9	1.5	2.2	0.8	1.0	0.2
September	2.5	1.6	1.9	0.2	0.4	0.5	0.2	0.2	0.2
October	2.5	1.6	2.0	0	0	0	0.5	0.4	0.4
November	2.2	1.5	2.0	0	0	0	0.7	0.6	0
December	2.5	0.8	1.7	0	0	0	0.7	1.1	0
1972									
January	1.2	0	0	0	0	0	0	1.1	0

* Less than 5×10^{-6} km^3 was pumped.

a visual approach to separate a response due to large volumes of pumpage from a response due to good hydraulic connection.

In employing pump-test methodology, it is assumed that Devils Hole behaves like an observation well in response to groundwater pumpage from the sur-

rounding sites. The validity of this assumption is indicated by several observations. Inspection of the stage fluctuations of Devils Hole indicates that Devils Hole responds to external stresses, such as atmospheric pressure and earth tides, like a water well tapping a confined aquifer (Fig. 5). The stage of Devils Hole also responds to surface waves induced by near and distant earthquakes. Finally and most important, the response of Devils Hole to pumping from 1971 to 1973 was similar to the response of a 75 m deep observation well which taps a local aquifer 275 m east of Devils Hole (well 36dd in Fig. 4; Dudley and Larson, 1976; Larson, 1975). This similarity in response indicates not only that Devils Hole behaves like a well in response to surrounding pumpage, but also that Devils Hole is in good hydraulic connection with the nearby Quaternary valley fill.

Also implicit in this application of pump-test methodology is the assumption that the response of the Lower Paleozoic carbonate aquifer and local aquifers to pumpage either will be governed by the true permeability, thickness, and elastic storage of the aquifers or can be quantitatively described using apparent values of permeability, thickness, and elastic storage for the aquifers. While such an assumption cannot be applied to all carbonate aquifers (White, 1969), it appears to be valid for this study. As previously noted, pump tests of the local aquifers indicated that aquifer response can at least be simulated using well-hydraulics theory. The author also has analyzed pump-test data (Winograd and Thordarson, 1975) for the Lower Paleozoic carbonate aquifer and has found that the aquifer response to pumpage can be approximated through the use of well-hydraulics theory established for porous-fractured media (Streltsova-Adams, 1978).

MATHEMATICAL MODELS OF THE PHYSICAL SYSTEM

In this paper, three simple mathematical models are employed in a preliminary attempt to describe the relation between groundwater pumpage within Ash

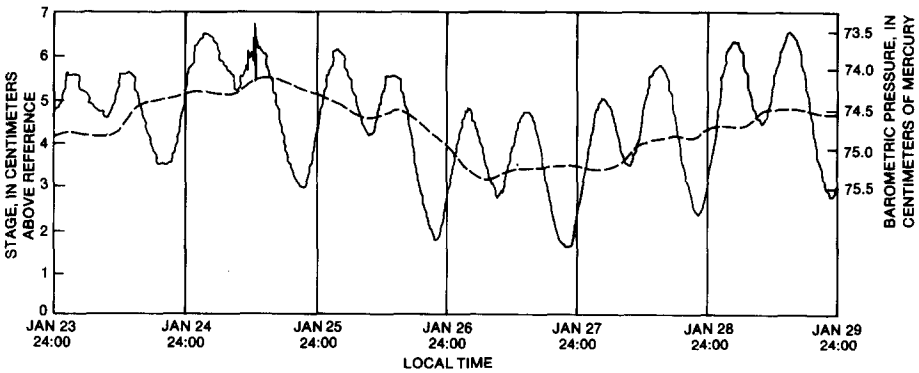

Fig. 5. Six-day record of stage and air-pressure fluctuations at Devils Hole during January 1953. Solid line is stage record, dashed line is air-pressure record, spike during January 25 is stage response to a distant earthquake.

Meadows and stage declines in Devils Hole. In the first model (referred to as the isotropic-homogeneous model), it is assumed that the local aquifers tapped by the wells are in good hydraulic connection with each other and that it is possible to lump them together into one equivalent, homogeneous, isotropic, areally extensive aquifer. The relation between stage declines and groundwater discharge under conditions of horizontal flow is then described by:

$$s = \sum_{i=1}^{n} \frac{1}{4\pi T} \int_0^t \frac{Q_i(t-\tau)}{\tau} \exp\left(\frac{-Sr_i^2}{4T\tau}\right) \mathrm{d}\tau \tag{1}$$

where:
s is the stage decline,
n is the number of wells,
i is the well identification number,
T is the lumped aquifer transmissivity,
t is time,
Q_i is the volumetric rate of pumpage from the ith well,
τ is a dummy variable,
S is the aquifer storage coefficient, and
r_i is the radial distance from the ith pumping well to Devils Hole (Theis, 1935).

In the second model (referred to as the anisotropic-homogeneous model), it is assumed that much of the apparent local hydraulic variability within the Quaternary valley fill of Ash Meadows can be attributed to the presence of large-scale anisotropy within an equivalent areally extensive aquifer. The relation between stage declines and groundwater discharge for this model (under conditions of horizontal flow) is described by:

$$s = \sum_{i=1}^{n} \frac{1}{4\pi\sqrt{T_{xx}T_{yy} - T_{xy}^2}} \int_0^t \frac{Q_i(t-\tau)}{\tau} \exp\left[\frac{-S}{4\tau}\left(\frac{T_{xx}Y_i^2 + T_{yy}X_i^2 - 2T_{xy}X_iY_i}{T_{xx}T_{yy} - T_{xy}^2}\right)\right] \mathrm{d}\tau \tag{2}$$

where T_{xx} and T_{yy} are the principal horizontal transmissivities of the transmissivity tensor, T_{xy} is the deviatoric transmissivity, and X_i and Y_i are the distances from the ith well to Devils Hole along prescribed orthogonal axes (Papadopulos, 1965).

Finally, in the third model (referred to as the heterogeneous model), the hydraulic connection between each well and Devils Hole is allowed to be unique and independent of any large-scale trends. It is assumed that simple well-hydraulics theory (which, despite the presence of small-scale heterogeneities, is able to simulate the results of interference tests in Ash Meadows over distances of several hundred meters after long periods of time) is able to simulate aquifer behavior over distances of several kilometers. The relation between groundwater discharge and stage declines is:

$$s = \sum_{i=1}^{n} \frac{1}{4\pi T_i} \int_0^t \frac{Q_i(t-\tau)}{\tau} \exp\left(\frac{-S_i r_i^2}{4T_i\tau}\right) \mathrm{d}\tau \tag{3}$$

where S_i and T_i are the apparent transmissivity and storage coefficient of the material between the ith well and Devils Hole.

The degree of hydraulic connection between the wells and Devils Hole is determined by applying each model to the groundwater pumpage data from Table 1 and solving for the aquifer characteristics which yield the best fit to the contemporaneous stage-decline data for Devils Hole. The parameters which best fit the data were obtained using the solution technique described in the Appendix.

The three simple models employed here encompass the range of behavior that might be expected in the local portion of this groundwater system. In the first two models the physical system is assumed to be homogeneous; in the third model the physical system is assumed to be heterogeneous. Which, if any, of these models is an appropriate description of the physical system is dependent on: (1) whether the model provides a good fit to the data; (2) whether a more complex model can fit the data significantly better; and (3) whether the model parameters that fit the data make physical sense.

DISCUSSION OF RESULTS

The ability of the three models to fit the stage-decline data is shown in Fig. 6. The parameters determined from the models are shown in Table 2. Although both the homogeneous-isotropic and homogeneous-anisotropic models are able to follow the major trends in the Devils Hole hydrograph, they are unable to provide an accurate fit. In both of the homogeneous models, stage declines in response to periods of large quantities of groundwater withdrawal during 1970 and 1971 are too great; peaks and troughs in the two homogeneous model hydrographs appear to be slightly out of phase with the actual hydrograph; and, finally, stage response during the period from June 1969 to May 1970 is too small (this is also true of the heterogeneous model). It is believed that these deficiencies are the result of: (1) errors in groundwater withdrawal data for 1969 and/or differences between the processes that govern early time response and those which are responsible for middle and late time responses; and (2) significant local hydraulic heterogeneity that makes these lumped homogeneous models deficient as accurate descriptions of the local groundwater system.

Dudley and Larson (1976) estimate that their data for monthly groundwater withdrawals (the data used in this study) are as much as 20% in error during 1969. The poor fit of the homogeneous models (as well as the heterogeneous model) to the early portion of the hydrograph may indicate that this error estimate is too small. Groundwater withdrawals during 1969 may have been significantly larger than the estimates of Dudley and Larson (1976). Alter-

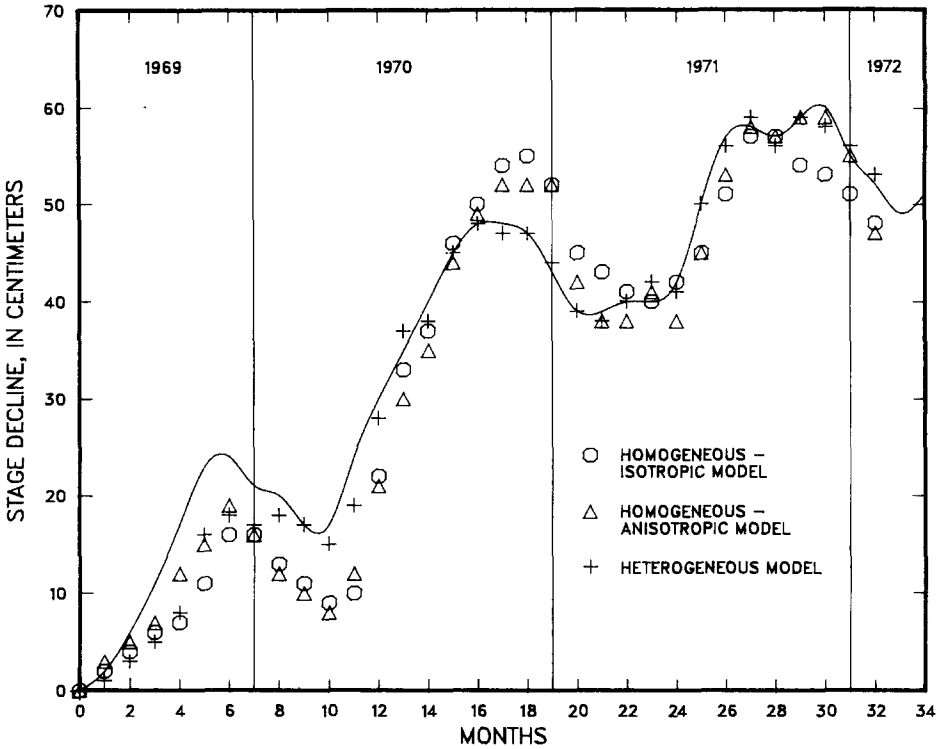

Fig. 6. Comparison of measured stage decline at Devils Hole (based on a 10-day mean) with model results. Hydrograph is denoted by the solid line.

TABLE 2

Parameter values determined from models

Homogeneous isotropic model	$T = 1.2 \times 10^3$	$S = 9 \times 10^{-2}$
Homogeneous anisotropic model	$T_{xx} = 5.8 \times 10^5$ (oriented N34° W)	$S = 1 \times 10^{-2}$
	$T_{yy} = 1.8 \times 10^0$ (oriented N56° E)	
Heterogeneous model	$T_2 = 3.5 \times 10^4$	$S_2 = 2 \times 10^{-4}$
	$T_3 = 9.8 \times 10^3$	$S_3 = 4 \times 10^{-5}$
	$T_4 = 2.3 \times 10^3$	$S_4 = 4 \times 10^{-2}$
	$T_5 = 9.6 \times 10^2$	$S_5 = 1 \times 10^{-1}$
	$T_8 = 1.1 \times 10^3$	$S_8 = 6 \times 10^{-3}$
	$T_{13} = 1.1 \times 10^4$	$S_{13} = 4 \times 10^{-2}$

Anisotropic transmissivity oriented in principal directions, hence $T_{xy} = 0$. Heterogeneous model indicated that wells 1, 6, and 7 were isolated from Devils Hole. Transmissivity (T) values are in units of centimeters squared per second. Storage coefficient (S) values are dimensionless.

natively, errors in the early part of the model hydrographs may indicate that there is some fundamental physical difference between the initial and subsequent response of the local groundwater system to prolonged periods of groundwater withdrawal. This possibility is discussed in some detail below.

Errors in data are less likely to explain the lack of fit of the homogeneous models to the 1970 and 1971 autumn portions of the actual hydrograph because Dudley and Larson (1976) indicate that the electrical power consumption of each well, from which groundwater pumpage data were derived, was monitored closely during this time. The inability of these models to accurately match the middle and late parts of the Devils Hole hydrograph indicates that they are, at best, crude quantitative representations of the local hydrogeology.

Although the homogeneous models are not precise descriptions of the local hydrogeology, they may yield some qualitative information about the general degree of hydraulic connection within the study area. The lumped transmissivity and storage coefficient determined from both the isotropic and anisotropic-homogeneous models are large. These models yield values for aquifer characteristics which are about one order of magnitude larger than those obtained from small-scale interference tests (Dudley and Larson, 1976). One theory to explain the apparent scale dependence in aquifer characteristics is that during long periods of sustained groundwater withdrawal (on the order of months or greater), the local confined aquifer(s) are significantly influenced by vertical recharge from above or below. Under these conditions, the long-term aquifer response would be sluggish in comparison to the long-term response which would be observed under conditions of purely horizontal flow. Small-scale interference tests (which are generally run only for several days or less) would not be run long enough to detect the influence of vertical recharge; as a result, aquifer response would appear to be governed by a transmissivity and storage coefficient which is smaller than the apparent aquifer characteristics which govern long-term response. If the local aquifers were only in limited connection with the overlying or underlying source of recharge, the dampening effects of vertical influx may not be detected for many months or longer; under these conditions, the characteristic aquifer response, through at least the first few months of groundwater withdrawal, would differ from the aquifer response during later periods.

This theory is attractive in that it is able to explain the apparent scale dependence of the aquifer characteristics and possibly explains the poor fit of the models to the early part of the hydrograph. Although there is no direct evidence that the local aquifers are being influenced by vertical recharge during periods of prolonged pumpage, such a process would be in agreement with the long-established theories of groundwater basin response to extended periods of groundwater withdrawal (Theis, 1938, 1940). An attempt was made to account for the possibility of vertical recharge by including (in the homogeneous models) a recharge term derived by Hantush and Jacob (1955) for "leaky aquifers". Inclusion of this term, however, served only to degrade the

fit to the hydrograph, indicating that if vertical recharge is present, it cannot be represented through the use of simple "leaky-aquifer" theory.

An alternative explanation for the apparent scale dependence in aquifer characteristics is that aquifers tapped by wells are in excellent hydraulic connection with the underlying Paleozoic carbonate aquifer. Under these conditions, the water-well response observed during small-scale interference tests essentially would be influenced by the effects of partial penetration (Hantush, 1961). Aquifer characteristics determined from these interference tests would likely be too small (unless the tests were run for extended periods of time and the influence of partial penetration was taken into account). The aquifer characteristics determined from the larger scale Devils Hole data, as a result of the distance between the pumping wells and the observation point, would not be influenced by the effects of partial penetration; they would represent approximately the lumped hydraulic properties of the entire thickness of material bounded by the top of the local aquifer and the bottom of the Paleozoic carbonate aquifer. This thickness is on the order of 1000 m (Dudley and Larson, 1976). Because transmissivity and storage coefficient are by definition proportional to thickness, the values of aquifer characteristics determined from these models would be reasonable for carbonate rock if the thickness of material stressed by pumpage was large. Based upon an aquifer thickness of 1000 m, the homogeneous isotropic model indicates that the hydraulic conductivity of the lumped aquifer is on the order of $10^{-2}\,cm^2\,s^{-1}$, and the specific storage is on the order of $10^{-6}\,cm^{-1}$. This theory is unable to account for the poor fit of the models to the early part of the hydrograph.

The difference between the foregoing theories may be slight if the source of vertical recharge invoked in the first theory is wholly or partly the Lower Paleozoic carbonate aquifer. Underlying both these theories is the idea that, although groundwater pumpage occurs largely within the local aquifers, the stress imposed by the pumpage is shared by other sources of groundwater.

The degree to which local pumpage affects the Lower Paleozoic carbonate aquifer is unknown; however, there probably is at least fair hydraulic connection between the regional aquifer and local aquifers. The large volumes of spring flow in the area previously noted as having water quality similar to that of the Lower Paleozoic carbonate aquifer point to the possibility of good vertical hydraulic connection. Except for one well (well 8, Fig. 4), the average temperature of water produced from the wells is at least 9°C higher than the mean annual air temperature (Dudley and Larson, 1976), which may indicate that there is significant upward flow from the deeper Paleozoic carbonate rock to the local aquifers.

Another explanation for the large values in aquifer characteristics is simply that the stage declines in Devils Hole represent water-table declines. The high transmissivity values obtained from these models would be explained by the presence of highly conductive fractures. The high values of storage coefficient would be the result of the unconfined nature of the fractured aquifer. This explanation, however, is not plausible. As previously noted, the stage in Devils

Hole is sensitive to earth tides and atmospheric-pressure fluctuations. Because this pond apparently responds not only to the semi-diurnal strains but also to long-term changes in atmospheric pressure (Fig. 5), the aquifers tapped can have only limited hydraulic connection with the water table (Bodvarsson, 1970; Weeks, 1979).

The aquifer characteristics determined from the homogeneous-anisotropic model also suggest that there is a great deal of spatial variability in the hydraulic connection between the wells and Devils Hole. As evidenced by the large difference in the horizontal components of the transmissivity tensor shown in Table 2, hydraulic connection appears to depend on orientation. Under the assumption that spatial variability in hydraulic connection can be adequately described through the use of a spatially-invariant transmissivity tensor, the orientation of greatest hydraulic connection is N34° W; this orientation is in good agreement with the principal orientation of faults and lineaments in Ash Meadows (Fig. 3). However, since this model yields only minor improvement in the fit to the hydrograph when compared to the fit of the homogeneous isotropic model, it would appear to be imprudent to place too much emphasis on the exact orientation of the maximum principal transmissivity determined from the model. It also would be imprudent to place a great deal of significance on the exact values of the model-aquifer parameters. The model parameters appear to qualitatively indicate that wells which are northwest or southeast of Devils Hole have a tendency to be in good hydraulic connection with the pool.

The presence of spatial variability in hydraulic connection is clearly indicated in the characteristics determined from the heterogeneous model; this model yields substantial improvement in the fit to the Devils Hole hydrograph. Qualitatively there are two major differences between the characteristics identified in this model and those identified from the homogeneous models. First, the storage coefficients identified for wells 2 and 3 are very small, indicating that pumping from these wells rapidly lowers the stage of Devils Hole. Second, wells 1, 6, and 7 are identified as having no hydraulic connection with Devils Hole. It should be noted that the characteristics from the heterogeneous model were identified by fitting the pumping data with only the last 21 months of the hydrograph. Inclusion of the early part of the hydrograph yielded unreasonable values for a few characteristics, indicating that the model was incapable of accurately fitting the initial parts of the hydrograph. This difficulty is further discussed in the Appendix.

The extremely rapid propagation of the effects of pumping from wells 2 and 3 to Devils Hole indicated by the model can only be explained by the presence of a relatively large-scale continuous network of fractures at depth. The existence of such channel-like continuity has been observed or inferred within Ash Meadows by others. Dudley and Larson (1976) noted that discharge from Jack Rabbit Spring was reduced just minutes after the onset of pumping from well 2, 1.6 km distant (Fig. 4). No other wells appeared to have a significant impact on discharge within this spring. Winograd and Pearson (1976) inferred from carbon-14 measurements that rapid groundwater flow to Crystal Pool occurred

through a continuous fracture network or channel at least 11 km long. Other springs within Ash Meadows apparently were not connected to this fracture network.

There is currently only circumstantial evidence which supports fracture- or conduit-enhanced hydraulic connection between wells 2 and 3 and Devils Hole. Both wells have nearly the same orientation relative to Devils Hole, indicating that only one fracture network may be necessary to produce enhanced hydraulic connection between Devils Hole and these wells. The orientation of these wells relative to Devils Hole (S36° E for well 2 and S38° E for well 3) is also qualitatively consistent with the dominant northwest–southeast orientation of fractures and lineaments within Ash Meadows and the surrounding region. Finally, the construction of these wells may make them more likely than other nearby wells to intersect fracture zones; both wells have casings which are perforated over nearly the entire depth of the wells. The casing of well 2 (91 m deep) is perforated from 18 to 91 m; the casing of well 3 (238 m deep) is perforated from 3 to 238 m. In contrast, perforations in the casing of other wells near the Point of Rocks Springs (Fig. 4) begin at depths of 30 m or greater. Since fractures tend to decrease in frequency and width with depth (Nur, 1982), wells perforated at shallow depths will have the greatest likelihood of intersecting and hydraulically stressing existing fracture zones.

The apparent lack of hydraulic connection between well 1 and Devils Hole indicated by the model is surprising and questionable. Small-scale pump tests conducted by Dudley and Larson (1976) indicate that well 1 is in good hydraulic connection with nearby wells 2 and 3 and is in some degree of hydraulic connection with well 4, which is 0.8 km distant. Well 1 does appear to be hydraulically isolated from well 5, 1.7 km distant, but this is also true of wells 2 and 3 (Dudley and Larson, 1976).

The hydraulic isolation of wells 6 and 7 from Devils Hole as indicated by the model is in good agreement with the results of Dudley and Larson (1976) and Winograd and Pearson (1976). Pumping and spring-flow data as well as water-chemistry data indicate that well 6 is closely connected to nearby Crystal Pool, a spring which Winograd and Pearson (1976) infer is fed by a large-scale fracture network apparently unconnected to Devils Hole. Well 7 is a distant, shallow (30 m deep) well which yields relatively small quantities of water. However, if regional structural trends strongly influence hydraulic connection within Ash Meadows, the lack of hydraulic connection between well 7 and Devils Hole would be surprising; this well is N30° W of Devils Hole and taps the Lower Paleozoic carbonate aquifer. The poor hydraulic connection between well 7 and Devils Hole indicated by the model may point to the presence of a shallow hydraulic barrier between these sites.

The degree of hydraulic connection indicated by the heterogeneous model between each of the remaining wells (4, 5, 8, and 13) and Devils Hole is qualitatively similar to the degree of hydraulic connection shown in the homogeneous-isotropic model. Once again, model-aquifer parameters are about one order of magnitude larger than those derived from smaller scale interference tests. Possible explanations for this apparent scale dependence have been

previously noted. Qualitatively, the aquifer characteristics obtained from this model (as well as the characteristics obtained from the homogeneous models) serve to indicate that despite the discontinuous nature of the local aquifers, many wells have good hydraulic connection with Devils Hole.

CONCLUSIONS

This preliminary analysis of the response of Devils Hole to groundwater pumpage indicates that the local groundwater hydrology of Ash Meadows possesses a complexity typical of carbonate terrane. Some wells appear to have excellent hydraulic connection with Devils Hole, several kilometers distant; others appear to be hydraulically isolated from this pool. Zones or directions of enhanced hydraulic connection within Ash Meadows inferred from this study and by others can be explained only by groundwater flow through large-scale fracture networks or conduits. It is possible that the presence of such fracture networks is structurally controlled. Zones or directions of suppressed hydraulic connection also may be controlled by structural features such as faults.

Spatial trends in the variability of hydraulic connection are difficult to identify. Groundwater withdrawals, even from neighboring wells, can apparently have very different effects on the rate of stage decline in Devils Hole. Both the homogeneous-anisotropic model and the heterogeneous model point to the presence of an enhanced zone of hydraulic connection southeast of Devils Hole. This orientation is qualitatively consistent with the major orientation of lineations and failure planes within Ash Meadows and may indicate that there is a correspondence between spatial trends in structural features and spatial trends in hydraulic connection. However, the response of the local groundwater system to pumpage appears to possess a spatial variability which cannot be explained by regional structural trends alone.

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APPENDIX: METHOD OF SOLUTION

The homogeneous-isotropic model is used to explain the general method of solution which applies to all three models. Defining the stage decline at a given month k as s_k, the relation between stage declines and groundwater pumpage, assuming pumpage is at a constant rate for an entire month, is:

$$s_k = \sum_{i=1}^{n} \sum_{j=1}^{k} \frac{Q_{i,k+1-j}}{4\pi T} \int_{j-1}^{j} \frac{1}{\tau} \exp\left(\frac{-Sr_i^2}{4T\tau}\right) \mathrm{d}\tau \tag{4}$$

where $Q_{i,k+1-j}$ is the pumpage from the ith well during the $k + 1 - j$ month. In this paper, a least-squares approach was used to reduce the error ε between the model hydrograph and the actual hydrograph.

The following minimization problem was solved:

minimize:

$$\sum_{k=12}^{32} \varepsilon_k^2 \tag{5}$$

subject to:

$$\varepsilon_k = s_k(T, S) - h_k \tag{6}$$

and:

$$p \leqq T \leqq q \tag{7}$$

$$v \leqq S \leqq w \tag{8}$$

where h_k is the actual stage decline at the end of the kth month. The constants p, q, v, and w are bounds on T and S, the independent parameters. A bounds constrained quasi-Newton algorithm was used to solve the above minimization problem (Gill and Murray, 1976; Gill et al., 1983).

The lower and upper bounds placed on transmissivity were $1 \times 10^{-3}\,\mathrm{cm^2\,s^{-1}}$ and $4 \times 10^5\,\mathrm{cm^2\,s^{-1}}$, respectively. The lower and upper bounds placed on storage coefficient were 1×10^{-6} and 1×10^2, respectively. The wide ranges in transmissivity and storage coefficient were chosen to reflect the possibility that some of the wells were effectively hydraulically isolated from Devils Hole. Solution through the use of the quasi-Newton algorithm was a sequential process. The integral in eqn. 4 was initially computed through the use of five-point Gaussian quadrature with knots fixed at the bounds of the integral. The solution obtained by this method was compared with a solution obtained with finer spacing between knots. For both homogeneous models, the high-accuracy solution yielded only minor changes (beyond the second digit) in the parameter values. Solving for the parameters of the heterogeneous model proved more difficult — both the solution based on coarse spacing and the solution based on fine spacing contained storage-coefficient values which were so small that neither method of quadrature provided an accurate representation of the integral. The solution contained in this paper was obtained through a mixed method: Gaussian quadrature was used to compute the integral when previous solutions indicated that the ratio $Sr^2/4T$ was $\geqslant 0.001$; a series approximation to the integral (Gautschi and Cahill, 1964) was used when previous solutions indicated that the above ratio was < 0.001.

It should be noted that only the last 21 months of the hydrograph were used in the minimization procedure. It was found that for both homogeneous models, inclusion of the first 11 months of the hydrograph did not significantly change the solution, the characteristics were virtually unchanged, and there were only minor improvements in the fit. As previously noted, inclusion of the first 11 months of the hydrograph for the heterogeneous model produced unreasonable characteristic values for some wells. For example, the characteristics identified for well 8 were $4.0 \times 10^5\,\mathrm{cm^2\,s^{-1}}$ and 2.3 for transmissivity and storage coefficient, respectively, and the characteristics identified for well 6 were at their respective lower bounds. This indicated to the author that the model was incapable of accurately fitting the initial portions of the hydrograph.

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