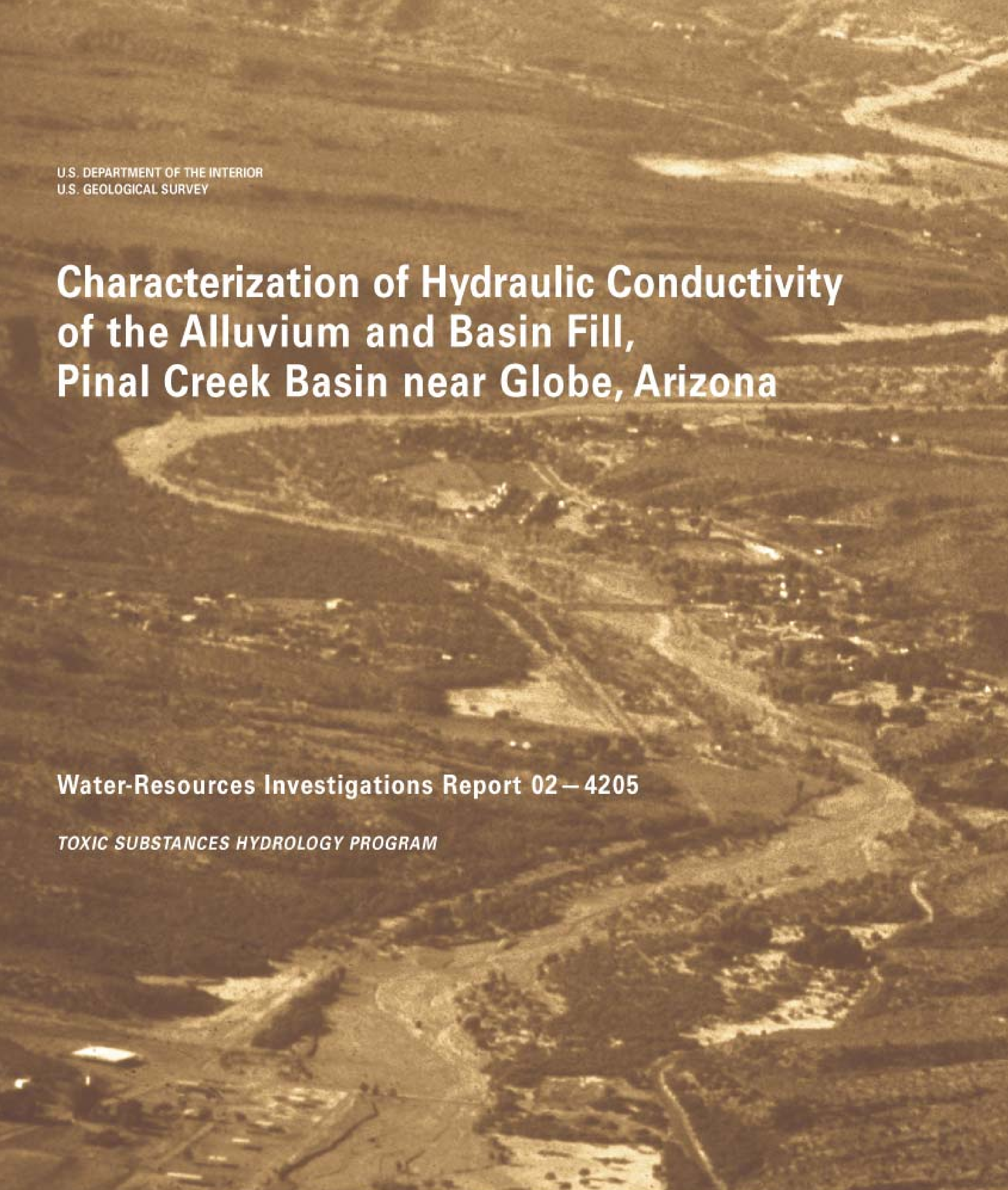

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Characterization of Hydraulic Conductivity of the Alluvium and Basin Fill, Pinal Creek Basin near Globe, Arizona

Water-Resources Investigations Report 02—4205

TOXIC SUBSTANCES HYDROLOGY PROGRAM

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By Cory E. Angeroth

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Tucson, Arizona
2002

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
meter (m)	1.094	yard
square meter (m^2)	10.76	square foot
square centimeter (cm^2)	0.1550	square inch
pounds per square inch (psi)	6,895	pascal
meter per day (m/d)	3.281	foot per day
meter squared per day (m^2/d)	10.76	foot squared per day

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8°C)+32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). **Altitude**, as used in this report, refers to distance above or below NGVD 29

Characterization of Hydraulic Conductivity of the Alluvium and Basin Fill, Pinal Creek Basin near Globe, Arizona

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Abstract

Acidic waters containing elevated concentrations of dissolved metals have contaminated the regional aquifer in the Pinal Creek Basin, which is in Gila County, Arizona, about 100 kilometers east of Phoenix. The aquifer is made up of two geologic units: unconsolidated stream alluvium and consolidated basin fill. To better understand how contaminants are transported through these units, a better understanding of the distribution of hydraulic conductivity and processes that affect it within the aquifer is needed.

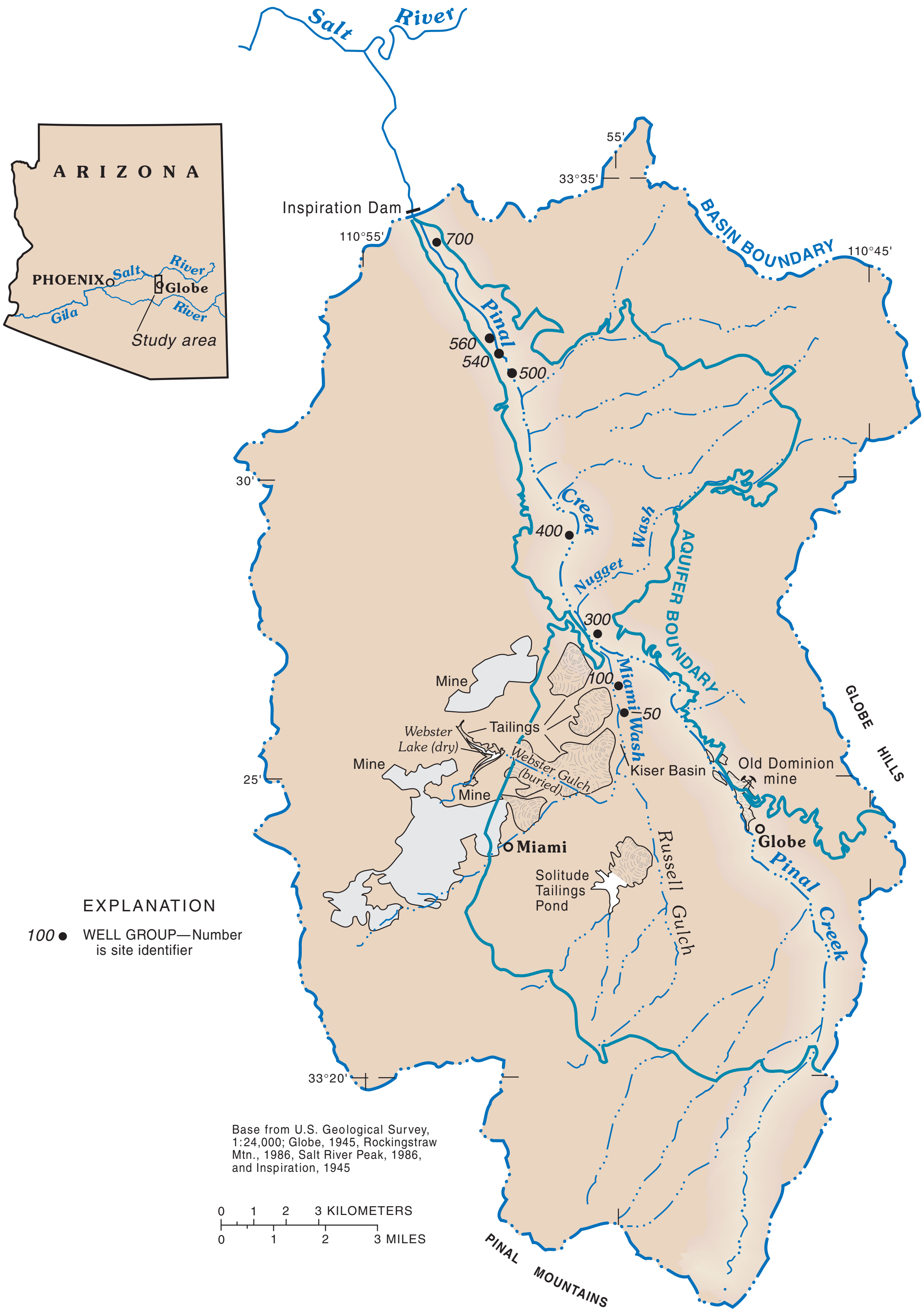
Slug tests were done in September 1997 and October 1998 on 9 wells finished in the basin fill and 14 wells finished in the stream alluvium. Data from the tests were analyzed by using either the Bouwer and Rice (1976) method, or by using an extension to the method developed by Springer and Gellhar (1991). Both methods are applicable for unconfined aquifers and partially penetrating wells. The results of the analyses show wide variability within and between the two geologic units. Hydraulic conductivity estimates ranged from 0.5 to 250 meters per day for the basin fill and from 3 to 200 meters per day for the stream alluvium. Results of the slug tests also show a correlation coefficient of 0.83 between the hydraulic conductivity and the pH of the ground water. The areas of highest hydraulic conductivity coincide with the areas of lowest pH, and the areas of lowest hydraulic conductivity coincide with the areas of highest pH, suggesting that the acidic water is increasing the hydraulic conductivity of the aquifer by dissolution of carbonate minerals.

INTRODUCTION

The principal aquifer in the Pinal Creek Basin near Globe, Arizona, is contaminated with acidic waters that contain elevated concentrations of dissolved metals (Neaville and Brown, 1993) and has been studied by the U.S. Geological Survey (USGS) since 1984. To better understand how ground water and dissolved contaminants in the ground water are transported through the aquifer, better information on the distribution of hydraulic conductivity in the aquifer is needed.

Purpose and Scope

The purpose of this study, as part of the larger research study, was to determine the distribution of hydraulic conductivity and the processes affecting it along the alluvial channel from Kiser Basin to the outlet of Pinal Creek at Inspiration Dam (**fig. 1**). The primary objectives were to collect and analyze slug-test data from as many USGS wells as possible and create a cross-section of hydraulic-conductivity distribution along the axis of the valley on the basis of test results.



Base from U.S. Geological Survey, 1:24,000; Globe, 1945, Rockingstraw Mtn., 1986, Salt River Peak, 1986, and Inspiration, 1945

Figure 1. Location of study area, Pinal Creek Basin, Arizona.

This report presents the magnitudes and distribution of hydraulic conductivity developed from aquifer testing and discusses some of the chemical processes that may be affecting them.

Previous Investigations

The USGS, private consulting firms, and other government agencies have extensively studied the hydrogeology of the Pinal Creek Basin. The presence of contaminated ground water has long been recognized in the basin, but was not studied until 1979 (Envirologic Systems, Inc., 1983). Since that time, many studies have been completed.

Ransome (1903) and Peterson (1962) produced reports that emphasize the mineral resources in the area. Hazen and Turner (1946) documented initial hydrologic studies of the area, reported water-level and well-inventory information, and provided a description of the hydrogeologic system. The basin was selected as a research site for the USGS Toxic Substances Hydrology Program in 1984. Since that time, the research study has produced reports and journal articles that document the controls on contaminant migration. A complete bibliography is available online at http://toxics.usgs.gov/bib/bib-pinal.html (accessed December 4, 2001). Also under this program, Neaville and Brown (1993) produced a report on the hydrogeology and hydrologic system that presents findings on the hydraulic conductivity and storage properties of the alluvial aquifer in the Pinal Creek Basin. Pool and Eychaner (1995) used gravity methods to determine storage properties of the stream alluvium in the basin.

Mining companies, consulting firms, and local government agencies have produced reports documenting, primarily, the hydrogeology of the contaminated area of the creek. Several of these (Hydro Geo Chem, 1989a, b; C.G. Taylor, environmental engineer, Magma Copper Corporation, written commun., 1987) presented hydraulic conductivity and storage property values for the basin fill and stream alluvium.

Site Description

Pinal Creek Basin is in Gila County, Arizona, about 100 km east of Phoenix (fig. 1). Nearly 18,000 people inhabit the basin (U.S. Bureau of Census, 1991), most residing in the communities of Globe and Miami. Copper mining began in 1874 and is still the predominant industry in the basin. Vegetation in the basin is typical of the transition zone between the mountains of central Arizona and the hot, arid desert region of the southwestern part of the State (Peterson, 1962, p. 4; Hazen and Turner, 1946, p. 5). Climate in the basin generally is arid and mild but varies considerably with elevation and season.

The geology of the basin is typical of many in the Basin and Range province as reported by Wilson and Moore (1959). Basin structure is dominated by north-northwestward- and north-northeastward-trending normal faults that created structural troughs that were subsequently filled with alluvium (Neaville and Brown, 1993). These alluvial deposits constitute the regional aquifer in the basin.

The aquifer is made up of two geologic units. Unconsolidated stream alluvium containing about 0.3 percent carbonate is incised in consolidated to semiconsolidated basin fill, which contains about 1.5 percent carbonate (Eychaner, 1989) that occurs mostly as a coating on grains and as cement between grains. Igneous and metamorphic bedrock bounds the aquifer laterally and at depth. The thickness of the aquifer varies from about 1,300 m near the Solitude Tailings pond to zero at the lateral boundaries. Stream alluvium overlying the basin fill ranges in thickness from about 35 m near the confluence of Miami Wash and Pinal Creek to 5 m at Inspiration Dam.

Activities related to large-scale copper mining have contaminated the regional aquifer and perennial streamflow with metal-rich, low-pH waters. The most acidic ground water currently has a pH of between about 3.6 to 5.0 and is partially neutralized by reactions with carbonate minerals as it moves through the aquifer. Neutralized contaminated water in the aquifer has a pH of about 6, and neutralized contaminated water in perennial streamflow has a pH of about 8. Contaminated ground-water is underlain by uncontaminated ground water which has a pH near 7. Carbonate minerals are present in the basin fill and the neutralized zone of the contamination plume, whereas in the acidic portion of the plume most, if not all, of the carbonate minerals have been dissolved (Brown and others, 1999, p. 143).

The USGS has installed 34 monitoring wells at 11 sites within the basin (**fig. 1**). Each site has 1 to 6 wells screened at different depths (**table 1**).

Table 1. Well-construction data

Well	Date completed	Drilling method	Hole depth (m)	Well depth (m)	Depth to water at time of slug test (m)	Screened interval (m)	Geologic unit
51	10–11–1984	Rotary, bentonite	33.5	33.4	16.6	32.4–33.3	Basin fill
52	10–12–1984	Rotary, bentonite	20.1	19.8	16.6	18.8–19.7	Alluvium
53	10–12–1984	Rotary, bentonite	28.0	27.8	16.6	26.8–27.7	Basin fill
101	10–10–1984	Rotary, bentonite	36.3	36.1	16.9	35.1–36.0	Basin fill
103	10–11–1984	Rotary, bentonite	19.2	25.3	15.1	18.1–19.0	Alluvium
105	05–22–1986	Rotary, bentonite	49.1	48.8	15.1	47.2–48.1	Basin fill
301	10–07–1984	Rotary, bentonite	59.4	59.1	12.6	58.1–59.0	Basin fill
302	10–08–1984	Rotary, bentonite	36.0	35.8	12.5	34.8–35.7	Alluvium
304	05–24–1986	Rotary, bentonite	48.8	30.3	14.7	28.7–29.6	Alluvium
401	10–09–1984	Rotary, bentonite	34.4	34.2	13.2	33.2–34.1	Basin fill
402	10–10–1984	Rotary, bentonite	21.0	20.9	13.2	19.8–20.7	Alluvium
403	10–10–1984	Rotary, bentonite	13.1	13.0	10.7	12.0–12.9	Alluvium
404	09–04–1986	Cable tool	55.5	55.3	10.7	53.7–54.6	Basin fill
501	05–22–1986	Rotary, bentonite	17.1	17.0	3.5	15.4–16.3	Alluvium
502	05–22–1986	Rotary, bentonite	38.1	38.0	3.5	36.5–37.4	Basin fill
503	05–22–1986	Rotary, bentonite	73.2	25.3	3.6	23.4–24.1	Alluvium
504	07–24–1986	Cable tool	69.5	69.2	2.2	67.6–68.6	Basin fill
505	12–17–1988	Hollow-stem auger	22.2	21.6	3.5	15.5–21.6	Alluvium
541	02–22–1997	Hollow-stem auger	24.7	12.6	5.8	11.1–12.6	Alluvium
542	02–22–1997	Hollow-stem auger	20.9	19.8	5.9	18.3–19.7	Alluvium
561	02–23–1997	Hollow-stem auger	17.1	15.3	5.1	13.8–15.3	Alluvium
701	05–11–1990	Hollow-stem auger	8.5	4.7	1.8	3.8–4.7	Alluvium
702	05–11–1990	Hollow-stem auger	8.1	7.3	1.9	6.4–7.3	Alluvium

Most of the wells were constructed using 10.2-cm diameter polyvinyl chloride (PVC) well casing and 0.9-m long PVC screens made from 1,470 factory-cut slots 3.6 cm long by 0.64 mm wide. Most of the boreholes were constructed using normal-circulation rotary drilling with bentonite mud, the other holes were drilled with an auger or cable tool. Because of different drilling methods, the boreholes have diameters that range from 15 cm to 25 cm. Every borehole annulus was filled with washed pea gravel to 0.5 m above the top of the screen. A layer of bentonite was placed from about 0.5 to 1.5 m above the screen. The hole was then backfilled with drill cuttings and a concrete seal was placed at the surface (fig. 2). The wells were developed by jetting air into the well screen under high pressure to agitate the gravel pack and formation and to airlift water and fine sediments from the well (Eychaner and others, 1989).

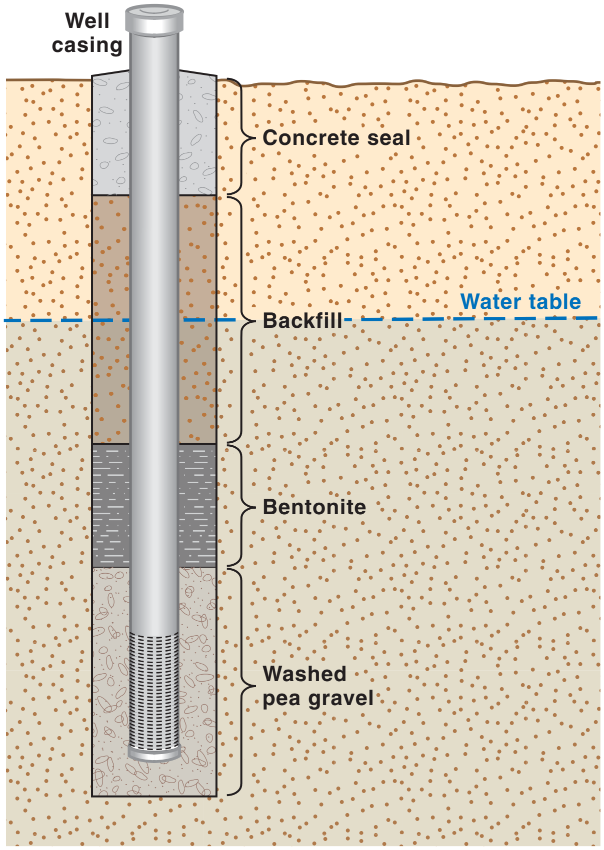


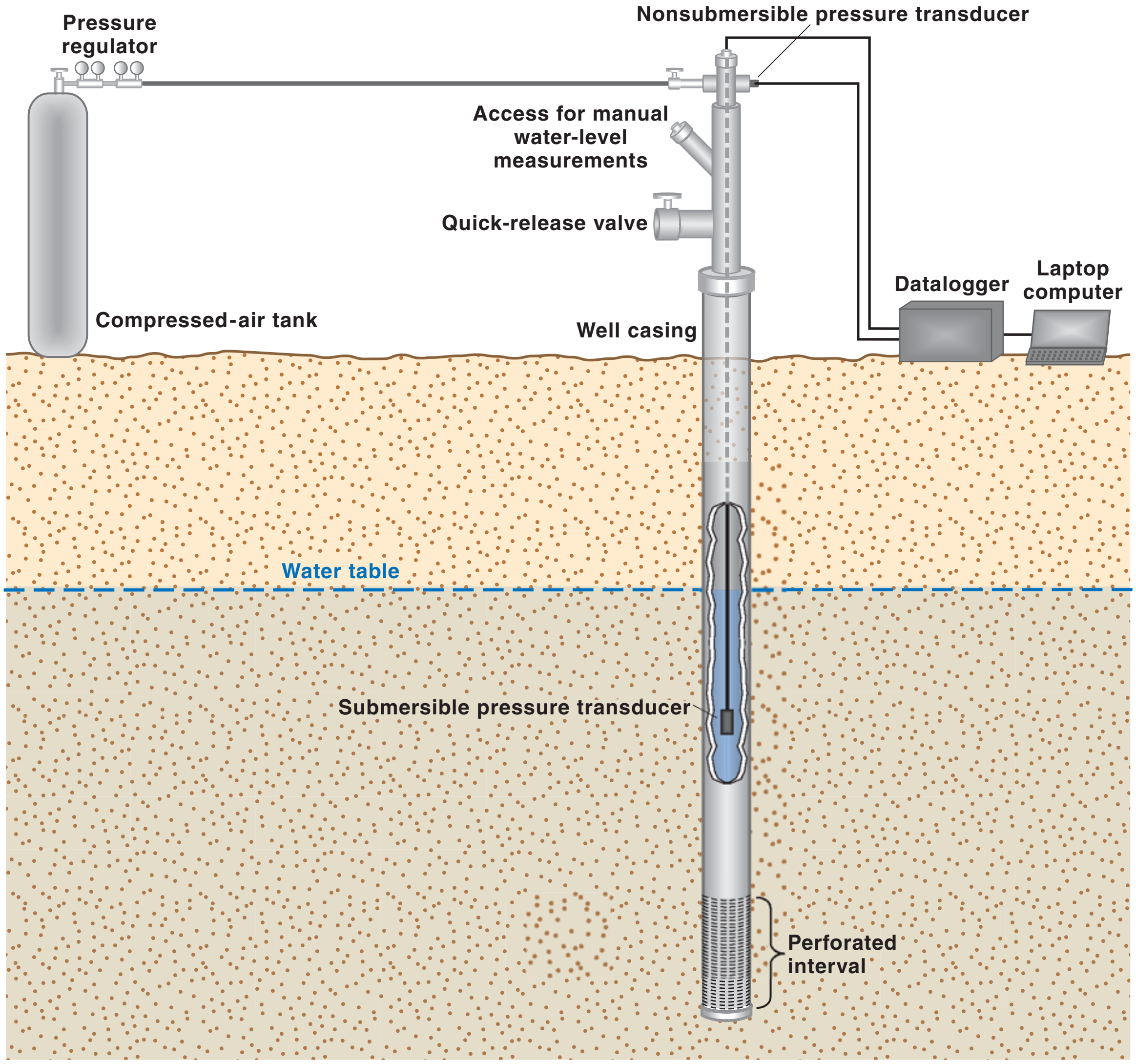
Figure 2. Generalized monitor-well construction.

SLUG TESTS

Twenty-three of the wells were pneumatically slug tested to determine the range in hydraulic conductivity for the aquifer material. Tests were not done at 11 wells because the wells were dry, improperly constructed, or damaged. For conditions at Pinal Creek, pneumatic slug testing has several advantages over other more conventional methods. The most important advantage is that this method most closely approximates an instantaneous slug of water, which is critical for wells in which the water levels recover quickly (water levels in several wells fully recovered in less than 10 seconds). Also, the conventional method of adding or removing a column of water could alter the aquifer chemistry, which is the primary focus of research at this site. Last, with this method only a submersed pressure transducer is in contact with the contaminated water, reducing the amount of decontamination needed between sites (fig. 3; Greene and Shapiro, 1995).

Procedure

The equipment and procedures used in this study are described in Greene and Shapiro (1995) and will be summarized here. The equipment needed includes a wellhead apparatus, pressure source, and pressure monitoring equipment (fig. 3). The wellhead apparatus is an air-tight enclosure that attaches to the well casing. The apparatus includes a release valve and standard fittings for the pressure source and monitoring equipment. A compressed-air tank was used to apply pressures to the wells of between 1.5 and 5.6 psi, which equate to an initial displacement of the water level between 1.09 and 3.95 m. A two-stage regulator was used to control the pressure accurately within the casing. For the tests done in 1997, two factory-calibrated 15-psi relative-pressure transducers were used: one to measure air pressure within the casing and a second, generally submerged 3 m below the water surface, to measure the water pressure. For the tests done in 1998, two lab-calibrated, 10-psi relative-pressure transducers were used with the same set up as described above. A datalogger was used to record and store the data. Transducers and logging equipment capable of acquiring data several times per second provided the resolution needed for analysis of rapidly changing water levels.



Modified from Greene and Shapiro, 1995

Figure 3. Diagram of equipment used in pneumatic slug tests.

After the equipment was in place, the transducers were activated and the static condition was recorded for a short time to ensure that the water level had recovered from the installation of the transducer. To start each slug test, the release valve was closed and the casing was pressurized and maintained at a constant air pressure. When the readings from the submerged transducer stabilized, the release valve was opened quickly, and the pressurization source was isolated. Recovery was deemed complete when the readings from the submerged transducer stabilized at the pre-test value. For most wells, the procedure was then repeated two more times with the last test using an initial displacement similar to that of the first test, as recommended by Butler and others (1996). A logging rate of eight times per second was used in wells in which water levels recovered in less than 1 minute, and a logging rate of once per second was used when more than 1 minute was required for water-levels to recover completely.

Analytical Methods

Analysis of the slug test data was done by using the Bouwer and Rice method (1976), or by using an extension to the method developed by Springer and

Gelhar (1991). The methods are applicable to response data from wells that fully or partially penetrate an unconfined aquifer. Two key assumptions of the methods are that (1) the effect of elastic storage mechanisms can be ignored, and (2) the position of the water table does not change during the course of the test (Butler, 1997).

The analytical solution by Bouwer and Rice (1976) can be written as:

$$\ln\left[\frac{H(t)}{H_0}\right] = -\frac{2K_r bt}{r_c^2 \ln\left(\frac{R_e}{r_w{}^*}\right)}, \qquad (1)$$

where

$H(t)$ = head in the well at time t, [L];

H_0 = initial head displacement, [L];

K_r = radial component of hydraulic conductivity, [L/T];

b = screen length [L];

t = time, [T];

r_c = radius of well casing, [L];

$\ln\left(\frac{R_e}{r_w{}^*}\right)$ = empirical parameter estimated as described in Bouwer and Rice (1976) and Butler (1997) [dimensionless].

An important feature of this solution is that the plot of the logarithm of normalized head versus time is a straight line. The Bouwer and Rice (1976) method involves calculating the slope of the straight line fit to the response data and using that value to estimate the hydraulic conductivity of the formation. The method, as outlined in Butler (1997, p. 107), essentially consists of five steps:

1. The logarithm of the normalized response data is plotted versus the time since the test began.
2. A straight line is fit to the data plot either by visual inspection or an automated regression routine.
3. The slope of the fitted line is calculated. If the time lag, T_0 (time at which a normalized head of 0.368, the natural logarithm of which is -1, is obtained), is used in this calculation, the slope, when written in terms of the natural logarithm, becomes $-1/T_0$.
4. Values for the anisotropy ratio and the effective radius parameter are estimated for the particular well-formation configuration, these values are incorporated into the empirical parameter as described by Butler (1997). Unless information exists to the contrary, the anisotropy ratio is assumed equal to one.
5. The radial component of hydraulic conductivity is estimated with an expression obtained by rearranging equation 1 and rewriting it in terms of the slope calculated using T_0:

$$K_r = \frac{r_c^2 \ln[R_e/r_w{}^*]}{2bT_0}, \qquad (2)$$

where

T_0 = time at which normalized head of 0.368 is obtained.

An example of the use of this method using the results from the second test at well 502 (**fig. 4** a) is shown below. Using the line fitted to the recovery data through the T_0 point, well-construction information, and an estimate of 2.534[1] for the empirical parameter, produces a hydraulic conductivity (using equation 2) of:

$$K_r = \frac{(0.05\,\text{m})^2(2.534)}{2(0.9\,\text{m})(23.1\,\text{s})}$$

$$K_r = 1.5 \times 10^{-4}\ \text{m/s} = 13.2\ \text{m/day}.$$

This method is efficient but has been shown by Kipp (1985) to be invalid for high permeability formations. In these types of formations, the water-level response is at times oscillatory. These oscillations are caused by the inertia of the quickly recovering water column. The solution described by Bouwer and Rice (1976) does not account for inertia and is not valid for this type of response.

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[1] Value determined by using equations 6.4a through 6.5c in Butler (1997).

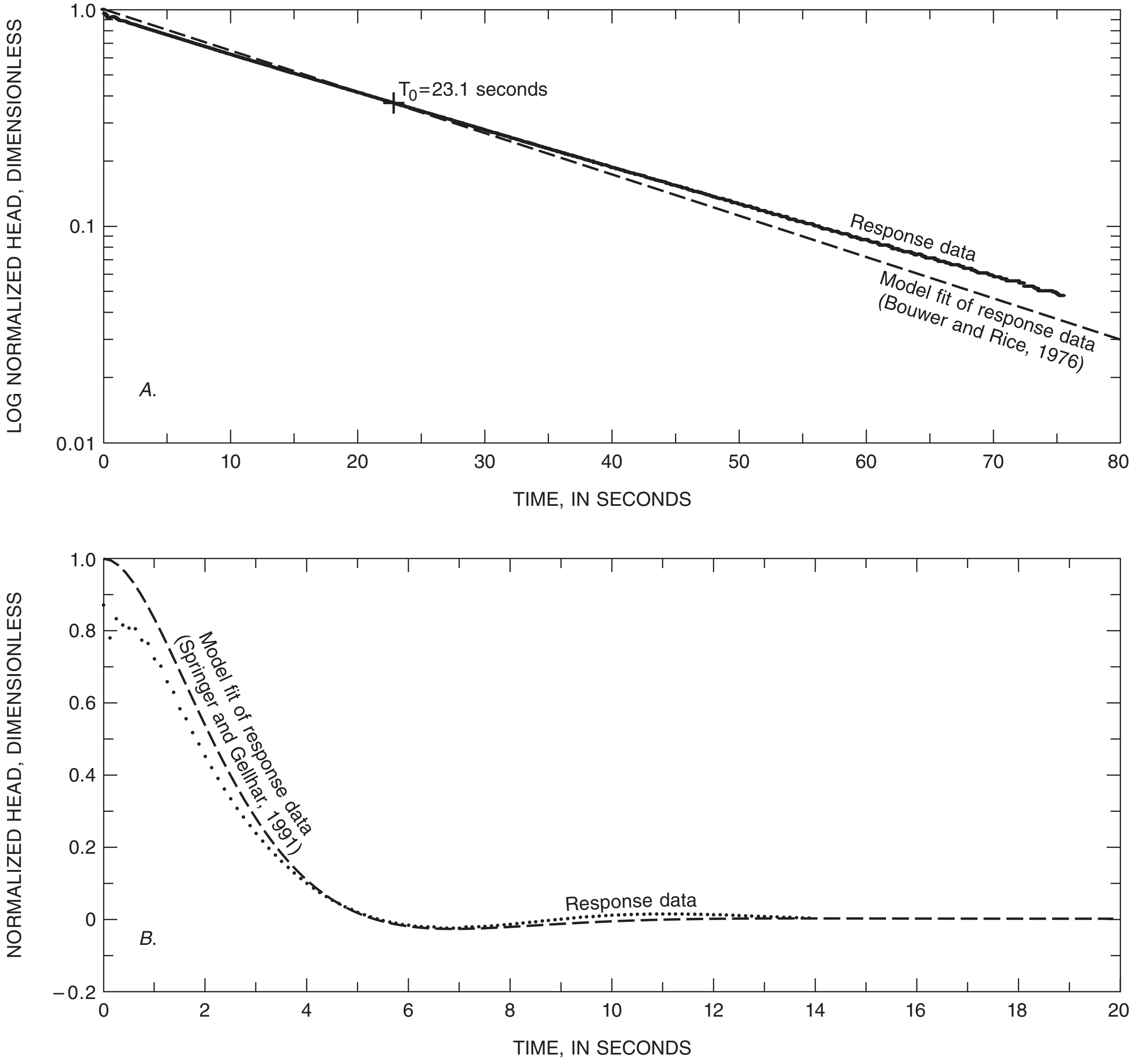

Figure 4. Composite plot of type curves and drawdown data from pnuematic slug tests for: *A*, Straight-line method and data from second test at well 502. *B*, Oscillatory type-curve matching method and data from second test at well 51.

Springer and Gelhar (1991) extended the Bouwer and Rice (1976) method to account for inertial effects. Their extension has been incorporated into a spreadsheet solution (Butler and Garnett, 2000) for analysis of highly permeable formations. The spreadsheet generates type curves, which are then superimposed on a plot of the response data. A dimensionless damping parameter, C_d, and a value that adjusts the dimensionless times (termed the modulation factor) are adjusted through trial and error until a close match between the type curve and response data exists. The spreadsheet calculates the hydraulic conductivity based on the C_d value, modulation-factor value, and well-construction information. For example, the type curve that produces the best match for the second test at well 51 occurs when the C_d value equals 1.5 and the modulation factor is set to 1.45 (fig. 4b). This produces a hydraulic conductivity estimate of 140 m/d. For this study, the spreadsheet method was used first, and if the C_d value required to approach a match became greater than about 5, as suggested by Kipp (1985), then the straight-line method was used.

The matches of the models and data are shown in the **appendix** of this report. The straight-line method was used to solve for hydraulic conductivity at 12 of the 23 wells tested; the spreadsheet method was used for the remaining 11 wells. The range of hydraulic conductivity estimates determined by using the straight-line method was 33 to 0.5 m/d. The range from the spreadsheet method was 250 to 28 m/d. Generally, the results of analysis of repeated tests were in close agreement and are adequate for producing estimates. In some cases the solution is good over only a portion of the data. In these cases the straight-line solutions were fit through the T_0 point and the oscillatory solutions were fit through the first trough in the oscillatory response.

An inverse relation exists between the size of the slug, H_0, and the K value (table 2). This relation is typical for highly permeable formations and commonly is seen as a result of non-Darcian flow losses (Butler and others, 1996). When doing slug tests, it is best to use a small slug size (H_0) because the K value determined from using the smaller H_0 probably is closer to the actual value.

Table 2. Slug-test results

Well_test number	Test date	Initial head displacement (H_0), in meters	Damping parameter (C_d)	Analysis type	Hydraulic conductivity value, in meters per day	Hydraulic conductivity value used for contouring, in meters per day
51_2	10–07–1998	2.080	1.50	Spreadsheet	140	
51_3	10–07–1998	1.355	1.36	Spreadsheet	170	170
51_4	10–07–1998	2.182	1.50	Spreadsheet	140	
52_1	10–07–1998	1.974	1.95	Spreadsheet	180	
52_2	10–07–1998	1.334	1.85	Spreadsheet	200	200
52_3	10–07–1998	2.049	1.95	Spreadsheet	180	
53_1	10–07–1998	2.197	1.40	Spreadsheet	210	
53_2	10–07–1998	1.279	1.15	Spreadsheet	250	250
53_3	10–07–1998	2.191	1.40	Spreadsheet	210	
101_1	10–09–1998	1.982	2.20	Spreadsheet	83	
101_2	10–09–1998	1.254	1.98	Spreadsheet	92	90
101_3	10–09–1998	1.942	2.20	Spreadsheet	83	
103	09–04–1997	1.760	1.70	Spreadsheet	130	130
105	09–04–1997	1.751	>10	Straight line	.8	.8
301	10–09–1998	1.417	>10	Straight line	.5	.5
302	09–03–1997	3.950	>10	Straight line	30	30
304_1	10–09–1998	1.878	1.30	Spreadsheet	170	
304_2	10–09–1998	1.282	1.18	Spreadsheet	190	190

Table 2. Slug-test results—Continued

Well_test number	Test date	Initial head displacement (H_0), in meters	Damping parameter (C_d)	Analysis type	Hydraulic conductivity value, in meters per day	Hydraulic conductivity value used for contouring, in meters per day
304_3	10–09–1998	1.899	1.30	Spreadsheet	170	
401_1	10–08–1998	1.976	>10	Straight line	9.5	
401_2	10–08–1998	1.524	>10	Straight line	10	10
401_3	10–08–1998	2.028	>10	Straight line	9.3	
402_1	10–08–1998	2.039	2.70	Spreadsheet	84	
402_2	10–08–1998	1.420	2.40	Spreadsheet	100	100
402_3	10–08–1998	2.070	2.70	Spreadsheet	92	
403	09–05–1997	1.266	4.20	Spreadsheet	110	110
404	09–04–1997	2.780	>10	Straight line	1.2	1.2
501_1	10–08–1998	1.756	>10	Straight line	27	
501_2	10–08–1998	1.093	>10	Straight line	32	32
501_3	10–08–1998	1.772	>10	Straight line	18	
502_1	10–08–1998	1.825	>10	Straight line	12	
502_2	10–08–1998	1.140	>10	Straight line	13	13
502_3	10–08–1998	1.922	>10	Straight line	13	
503_1	10–08–1998	1.922	>10	Straight line	11	
503_2	10–08–1998	1.284	>10	Straight line	14	14
503_3	10–08–1998	1.959	>10	Straight line	11	
504	10–08–1998	1.856	>10	Straight line	7.1	7
505_1	10–08–1998	1.832	>10	Straight line	7.0	
505_2	10–08–1998	1.287	>10	Straight line	10	10
505_3	10–08–1998	1.829	>10	Straight line	7.4	
541_1	10–08–1998	1.479	1.60	Spreadsheet	42	
541_2	10–08–1998	1.091	1.55	Spreadsheet	41	41
541_3	10–08–1998	1.597	1.65	Spreadsheet	42	
542_1	10–08–1998	1.845	1.65	Spreadsheet	37	
542_2	10–08–1998	1.318	1.45	Spreadsheet	36	36
542_3	10–08–1998	1.711	2.00	Spreadsheet	37	

Table 2. Slug-test results—Continued

Well_test number	Test date	Initial head displacement (H_0), in meters	Damping parameter (C_d)	Analysis type	Hydraulic conductivity value, in meters per day	Hydraulic conductivity value used for contouring, in meters per day
561_1	10–08–1998	1.837	2.00	Spreadsheet	35	
561_2	10–08–1998	1.223	1.60	Spreadsheet	34	34
561_3	10–08–1998	1.940	2.00	Spreadsheet	28	
701	09–02–1997	1.423	>10	Straight line	3.3	
701_1	10–07–1998	1.698	>10	Straight line	2.8	
701_2	10–07–1998	1.171	>10	Straight line	3.1	3
702	09–01–1997	3.669	>10	Straight line	3.1	3

RESULTS AND DISTRIBUTION OF HYDRAULIC CONDUCTIVITY

Nine of the wells used in the study are screened over short intervals in the upper part of the basin fill. Analyses of the data from these wells produced hydraulic conductivity estimates that ranged from 0.5 m/d at well 301 to 250 m/d at well 53 (table 2). An analysis of aquifer properties in alluvial basins throughout the Southwest produced a hydraulic conductivity range of 0.3 to 30 m/d for basin fill (Anderson and others, 1992), which is significantly lower than some values measured in this study. Slug tests done in 14 wells screened in the unconsolidated stream alluvium produced hydraulic conductivity values that ranged from 3 m/d at the 700 group wells to 200 m/d at well 52 (table 2).

On the basis of particle sizes at or near the screened interval, all wells are finished in zones that contain more than 89 percent sand and gravel, except for well 501, which is finished in a zone that contains 33 percent sand and gravel. Although some studies show a relation between particle size and hydraulic conductivity, the small variation in particle size at this site does not suggest a large range in hydraulic conductivity. Perhaps the hydraulic conductivity is determined not by particle size but by the amount of cementation and variations in bedding and deposition in the downstream direction as illustrated by the low values for the 700 group wells.

The vertical and horizontal distribution of hydraulic conductivity along the axis of the valley was contoured (**fig. 5**a) using the slug-test results. The pattern of the distribution of hydraulic conductivity is similar to that of the distribution of ground-water pH (fig. 5b, **table 3**), with the higher hydraulic conductivity units associated with the lower pH areas. Statistical analysis of the relation of hydraulic conductivity to the hydrogen-ion concentration, which is the inverse log of the negative pH, in water from the wells produced a correlation coefficient of 0.83 (**fig. 6**). The largest values of hydraulic conductivity were in the acidic part of the contaminant plume and likely reflect changes to the aquifer caused by contaminated ground-water flow. Chemical analyses of aquifer sediments has indicated that in the acidic core of the plume, all the carbonate minerals, coatings, and cement were completely consumed by neutralization reactions (Brown and others, 1999). Loss of this carbonate evidently resulted in an increase in the hydraulic conductivity of the aquifer in the areas of lowest pH. Because the percentage of carbonates in the alluvium is about one-fifth that in the basin fill, 0.3 compared to 1.5, the effects of acidic contamination produced a larger range of hydraulic conductivity in the basin fill than in the alluvium.

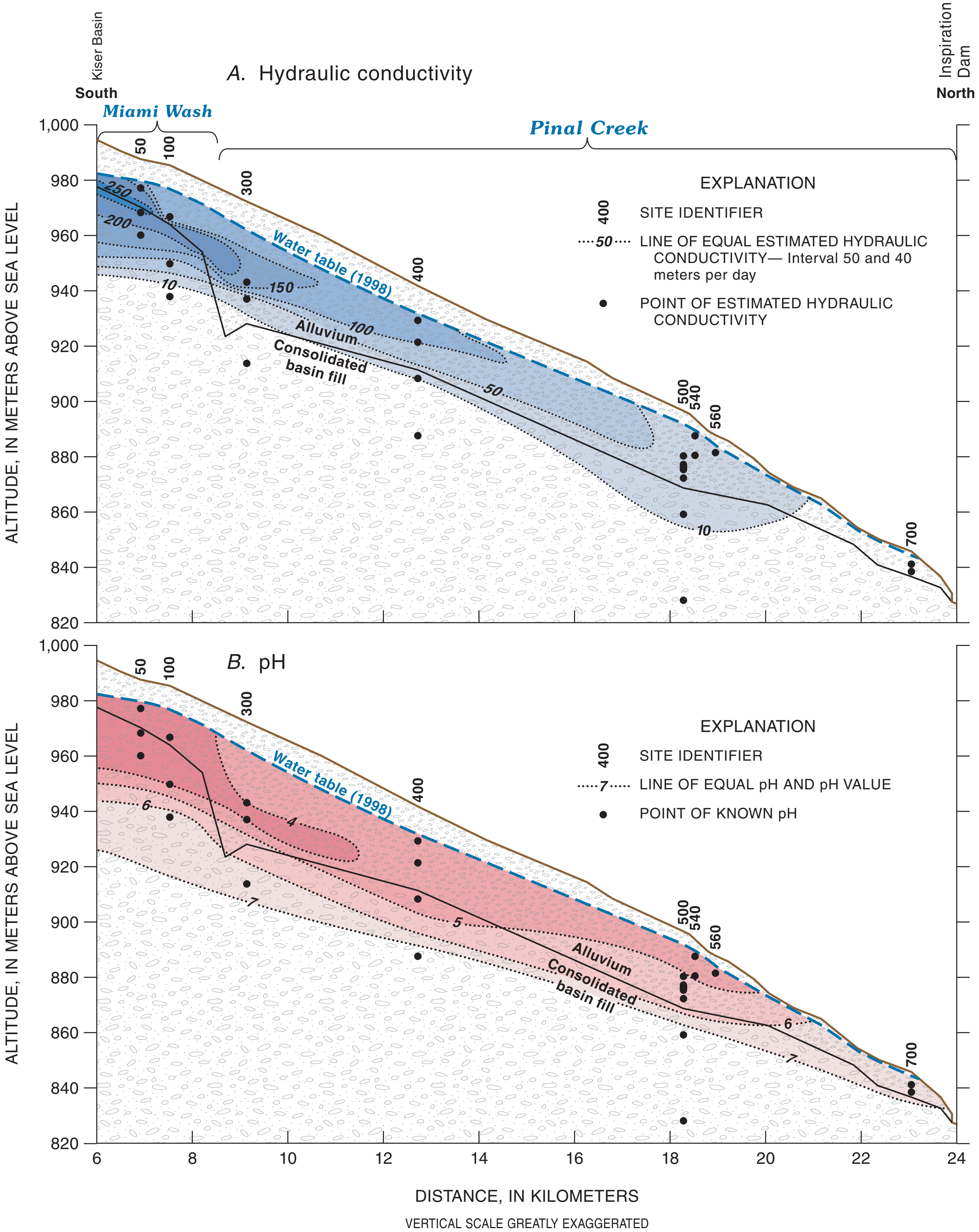

Figure 5. Graph showing line of section approximating the principal ground-water flow line from Kiser Basin to Inspiration Dam along the channels of Miami Wash and Pinal Creek. *A*, Distribution of hydraulic conductivity. *B*, Distribution of pH.

Table 3. Ground-water pH

Well	pH (standard units)	Date	Well	pH (standard units)	Date
51	4.0	11–06–1998	404	7.6	06–08–1998
52	3.9	11–05–1998	501	5.5	11–03–1998
53	3.9	11–06–1998	502	7.3	11–03–1998
101	4.0	11–06–1998	503	5.3	11–03–1998
103	3.9	11–06–1998	504	7.6	06–09–1998
105	6.2	11–07–1997	505	5.8	05–02–2001
301	6.3	11–05–1998	541	4.4	11–04–1998
302	4.0	11–05–1998	542	4.4	11–04–1998
304	4.1	11–05–1998	561	4.6	11–04–1998
401	4.4	11–05–1998	701	6.9	11–02–1998
402	4.3	11–05–1998	702	7.0	11–02–1998
403	4.5	11–06–1997			

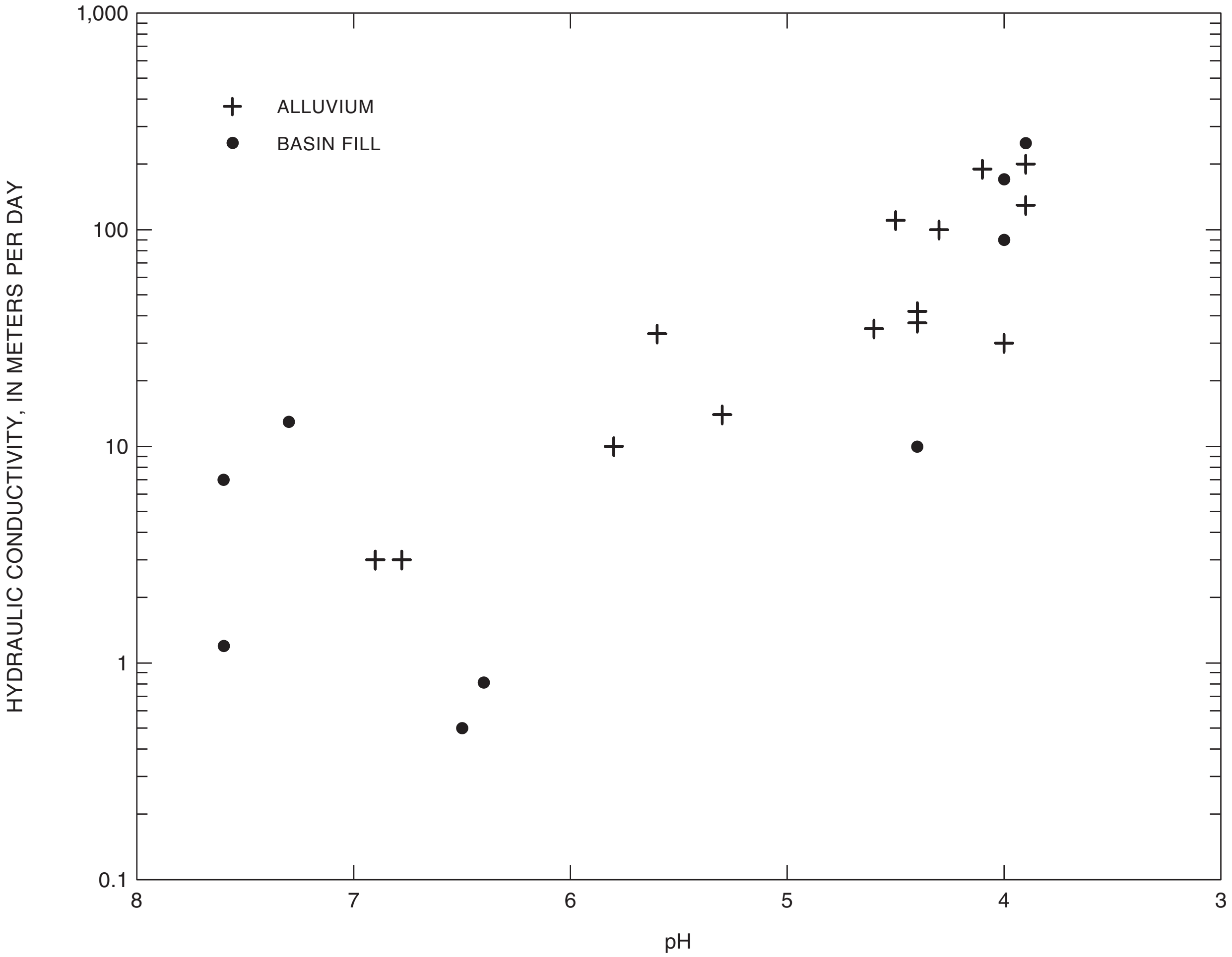

Figure 6. Relation between pH and hydraulic conductivity in ground water in the alluvium and in ground water in the basin fill.

SUMMARY

The Pinal Creek Basin has been contaminated by acidic waters containing elevated concentrations of dissolved metals. To better understand how the contaminants are transported through the regional aquifer, the distribution of hydraulic conductivity and the chemical processes affecting the hydraulic conductivity need to be better understood.

Pneumatic slug tests were done in 23 wells that are screened over small intervals. The data from the slug tests were analyzed by using the Bouwer and Rice (1976) method, or by using an extension of the method developed by Springer and Gelhar (1991). Both methods are applicable for unconfined aquifers and fully or partially penetrating wells, conditions that apply in the Pinal Creek Basin. The tests provide point values of hydraulic conductivity at various depths and locations along Pinal Creek. Results of the slug tests indicate that hydraulic conductivity ranges from 200 to 3 m/d in the alluvium and ranges from 250 to 0.5 m/d in the basin fill.

In the unconsolidated stream alluvium and in the basin fill, the distribution of hydraulic conductivity is similar to the distribution of pH. Generally, for both geologic units, the lower the pH of the ground water, the higher the hydraulic conductivity. This increase is likely caused by the dissolution of aquifer material by low pH water, thereby causing an increase in the hydraulic conductivity. The hydrogen ion concentration and hydraulic conductivity have a correlation coefficient of 0.83.

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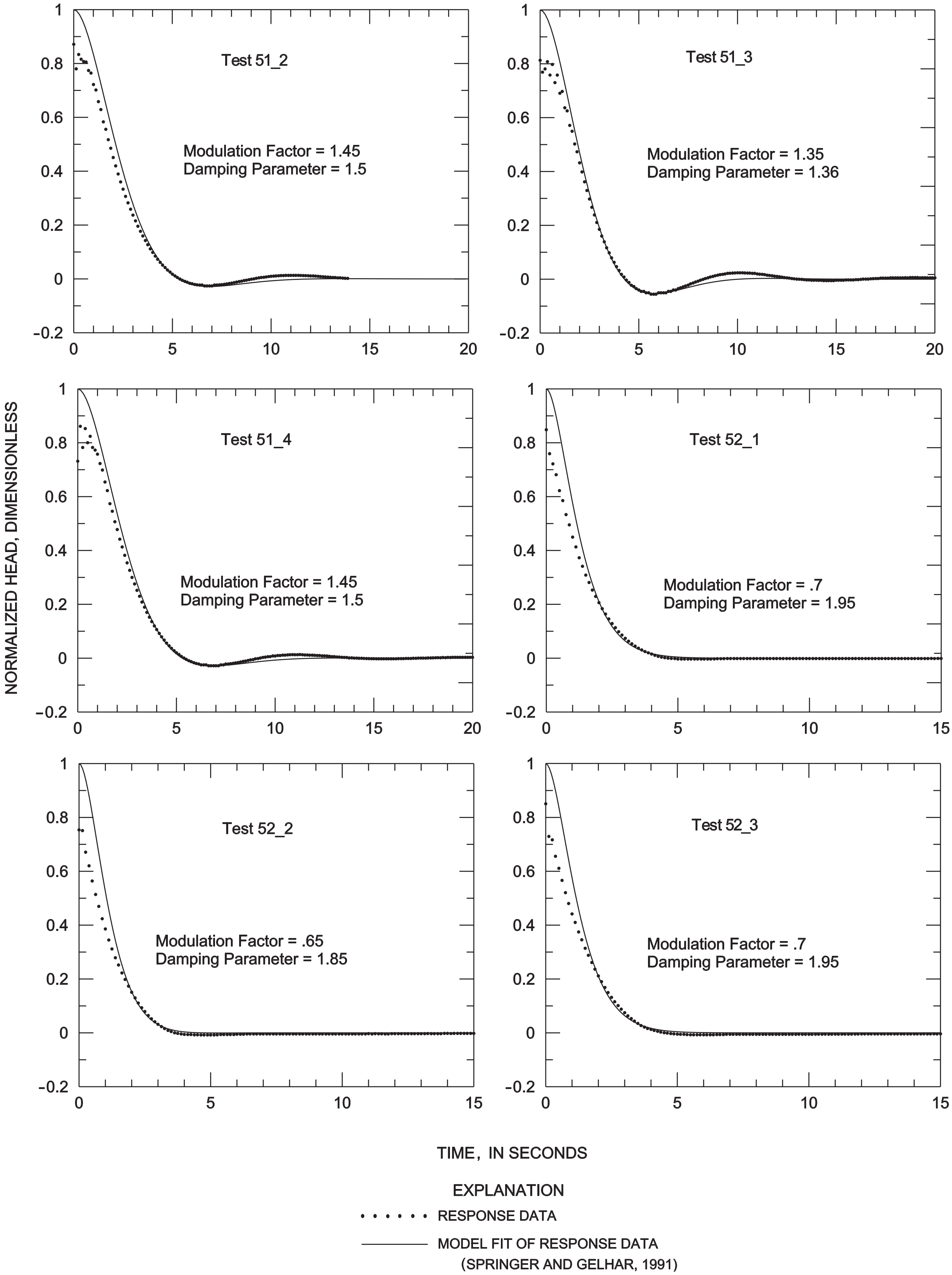
APPENDIX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5
10
15
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TIME, IN SECONDS
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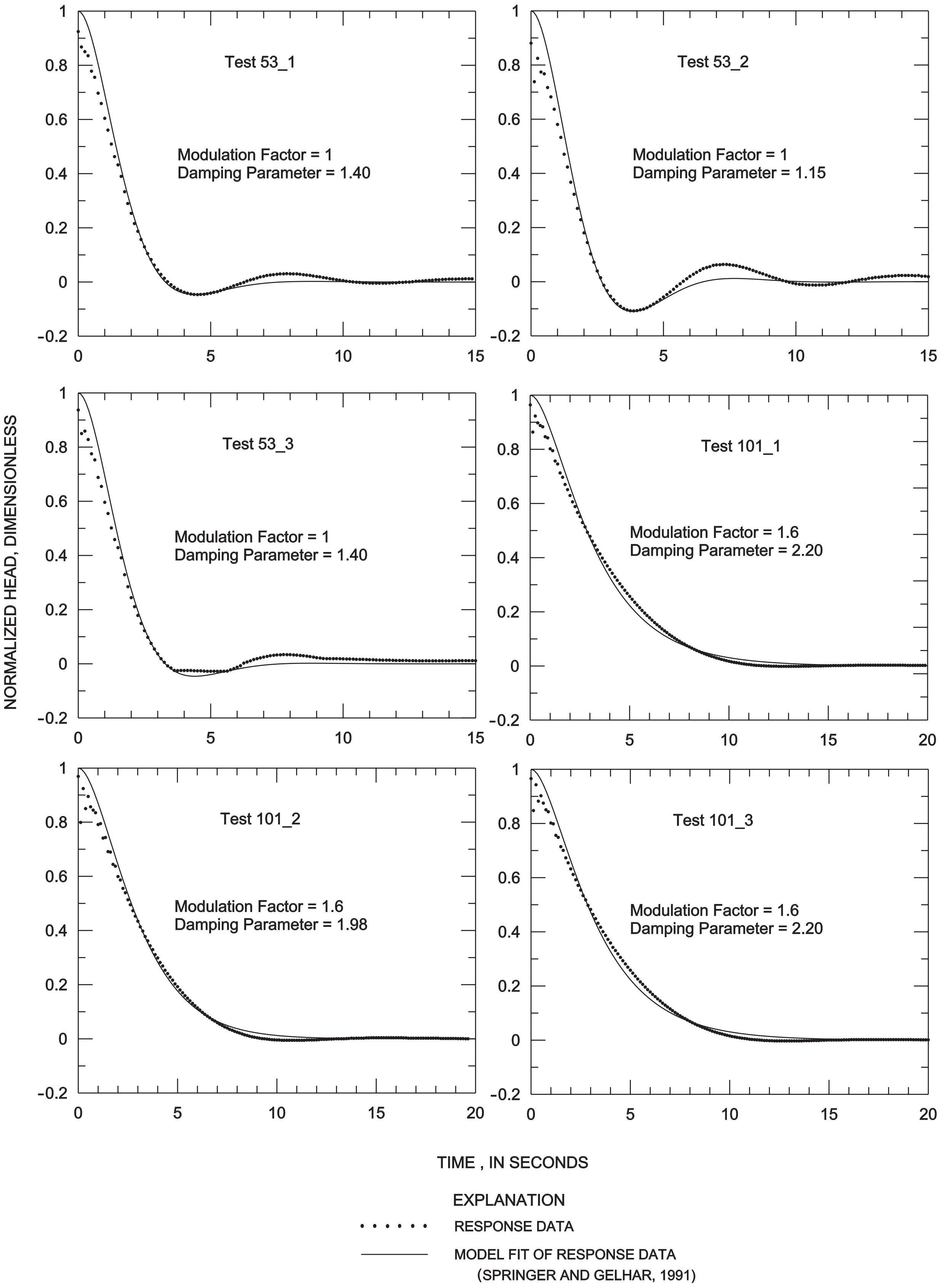
MODEL FIT OF RESPONSE DATA
(SPRINGER AND GELHAR, 1991)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0.6
0.4
0.2
0
-0.2
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5
10
15
20
EXPLANATION
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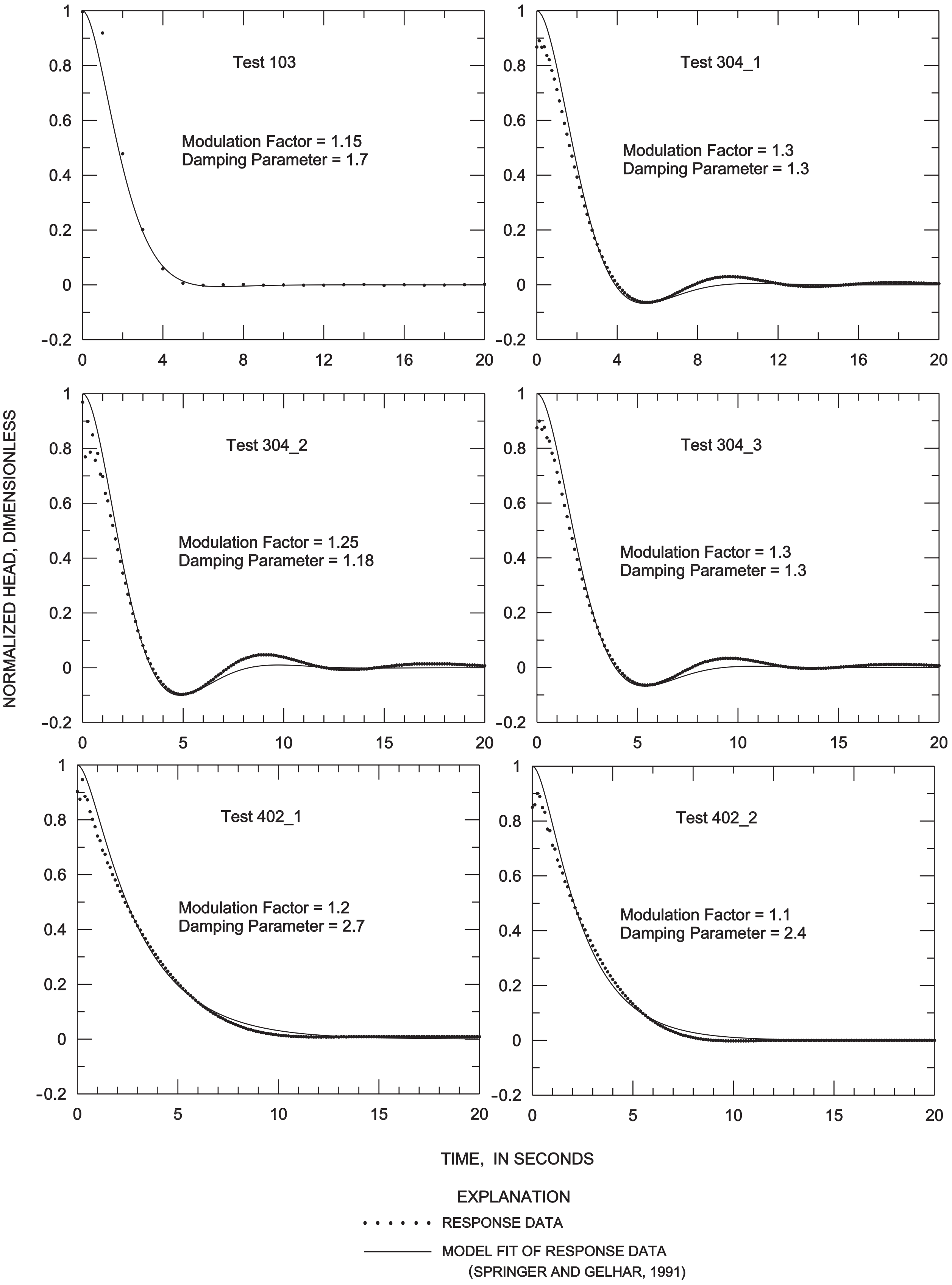
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0.2
0
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0
4
8
12
16
20
0
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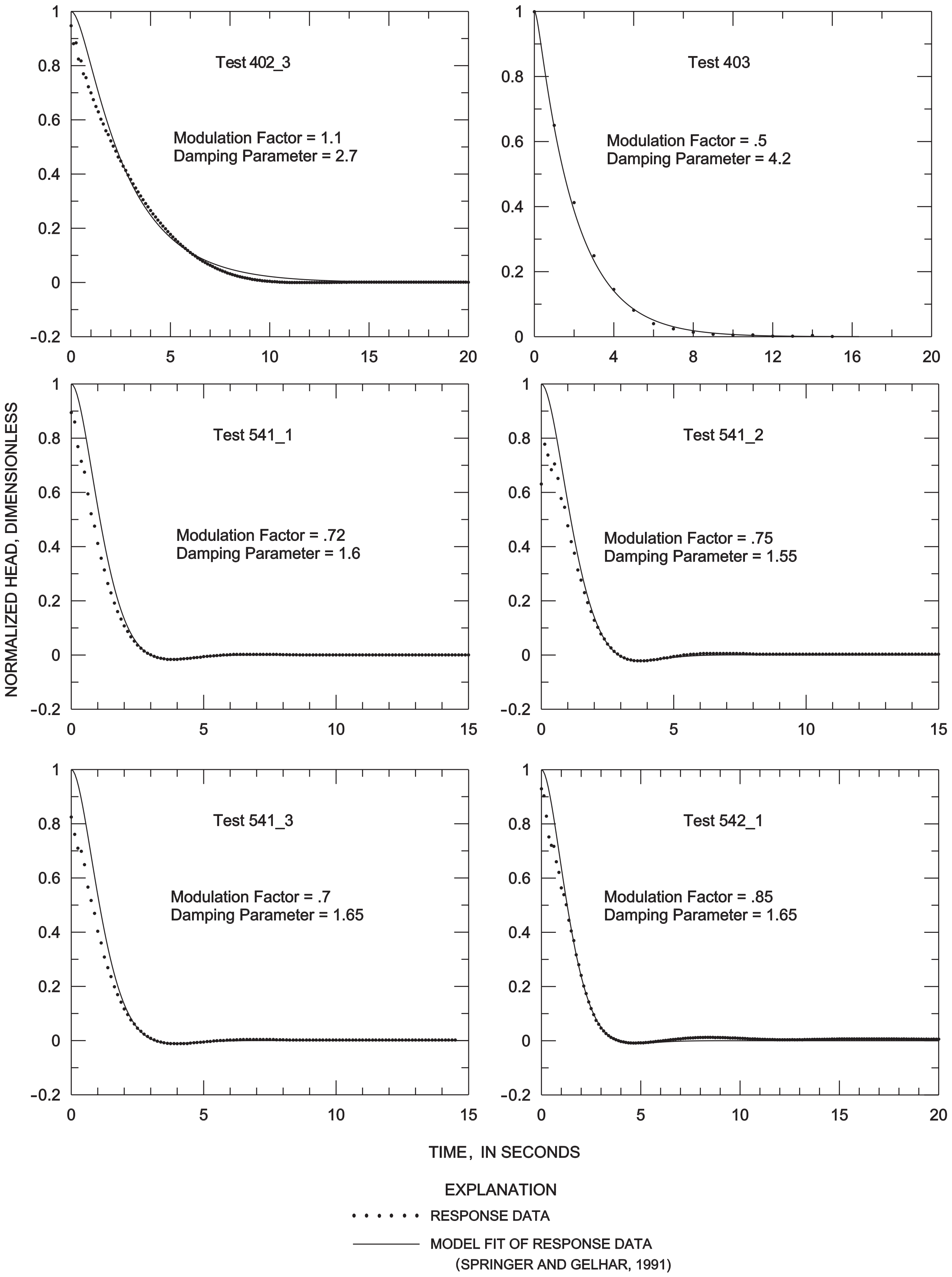
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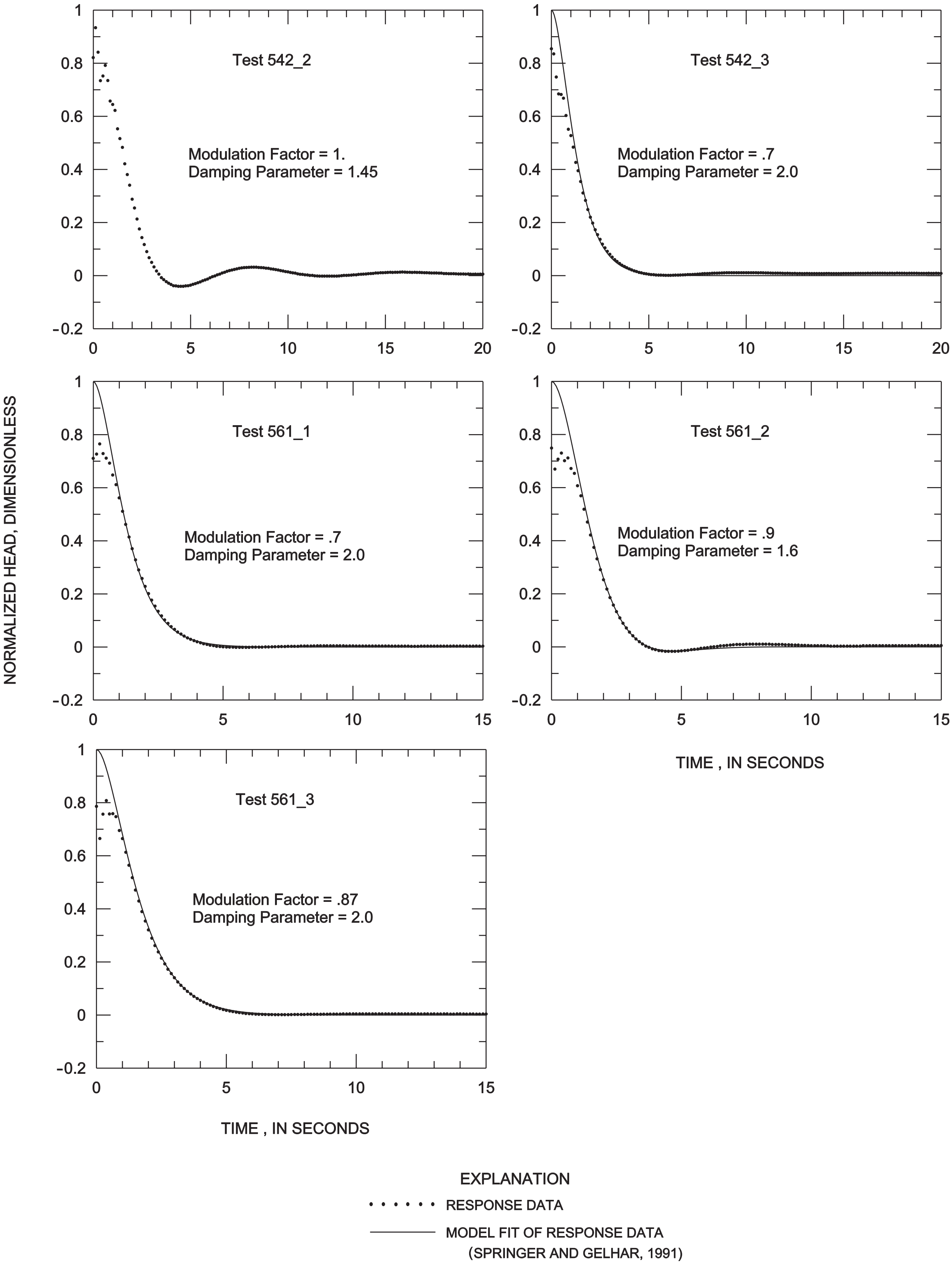
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15
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TIME , IN SECONDS
EXPLANATION
RESPONSE DATA
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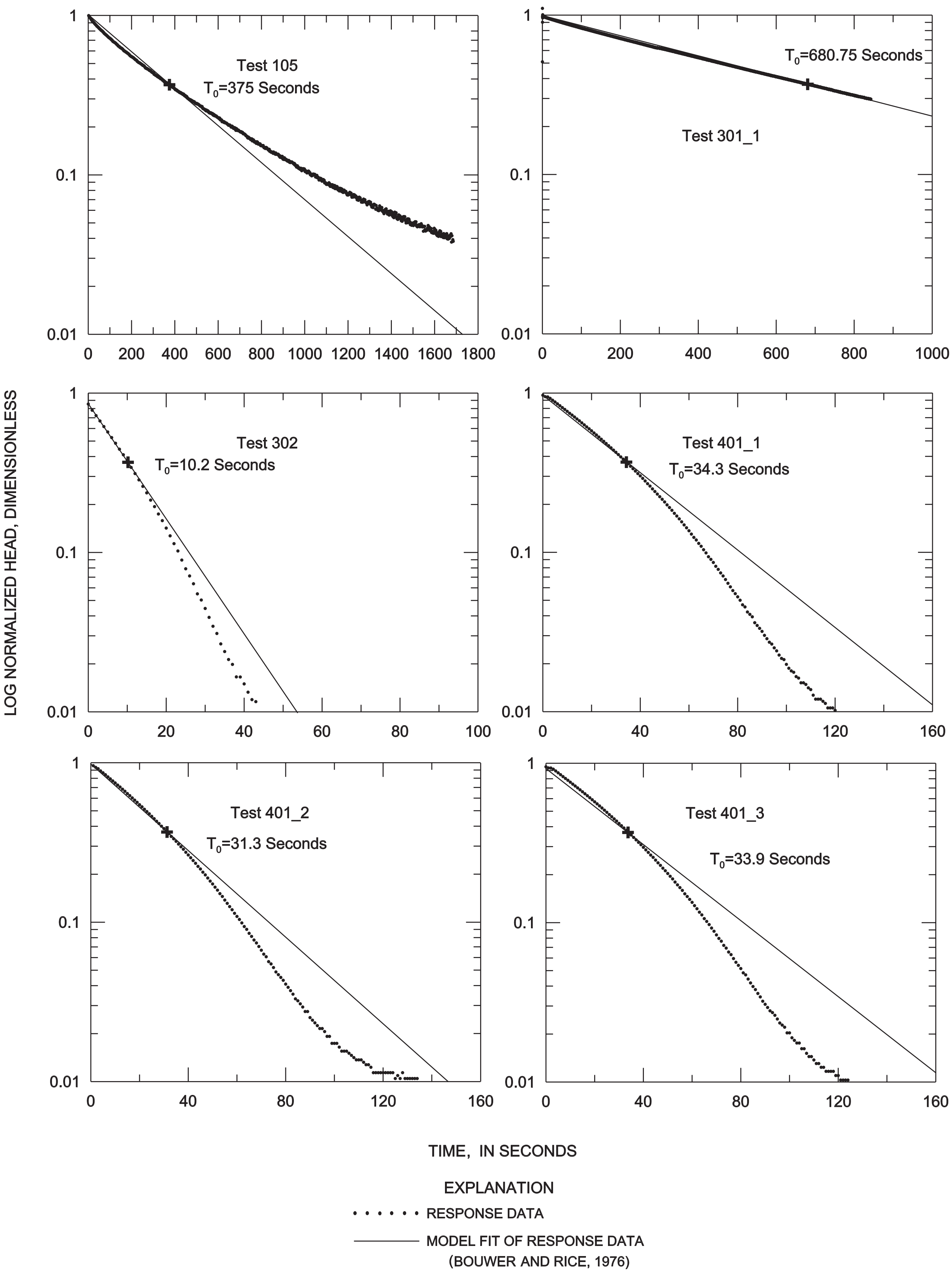Test 105
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Test 401_3
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0.01
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EXPLANATION
RESPONSE DATA
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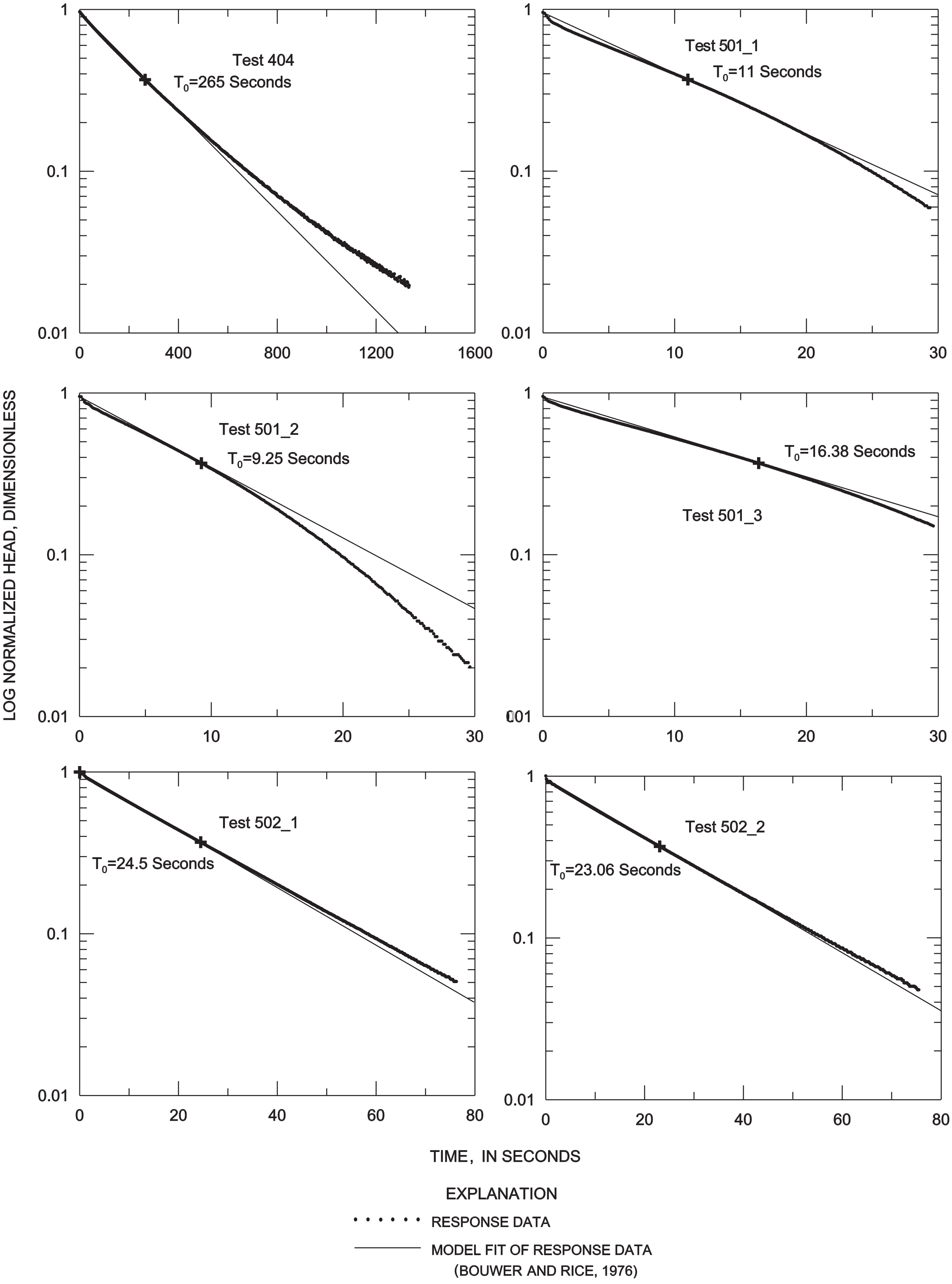
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Test 501_3
Test 502_1
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Test 502_2
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0.01
0
400
800
1200
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10
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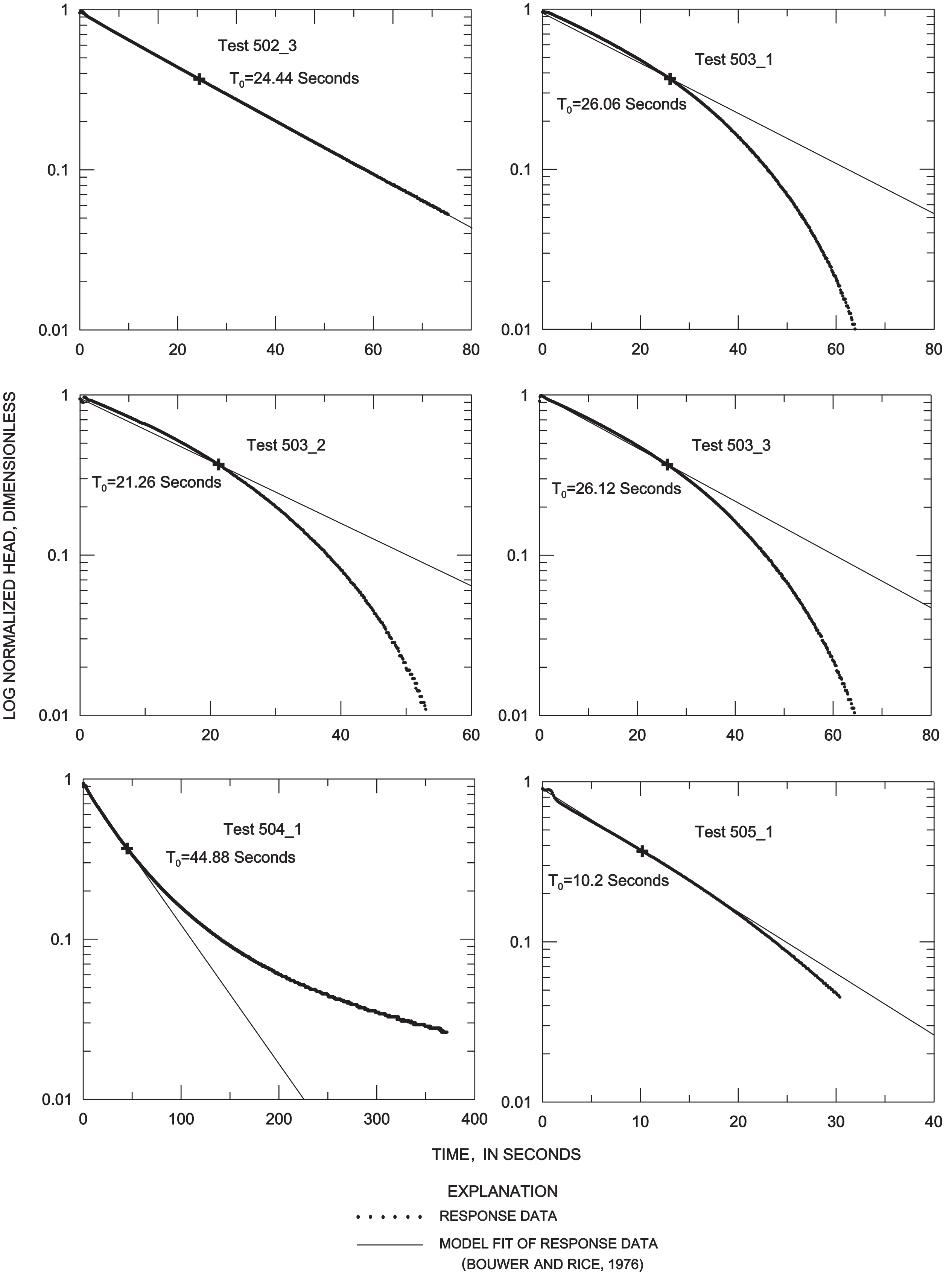
EXPLANATION
RESPONSE DATA
MODEL FIT OF RESPONSE DATA
(BOUWER AND RICE, 1976)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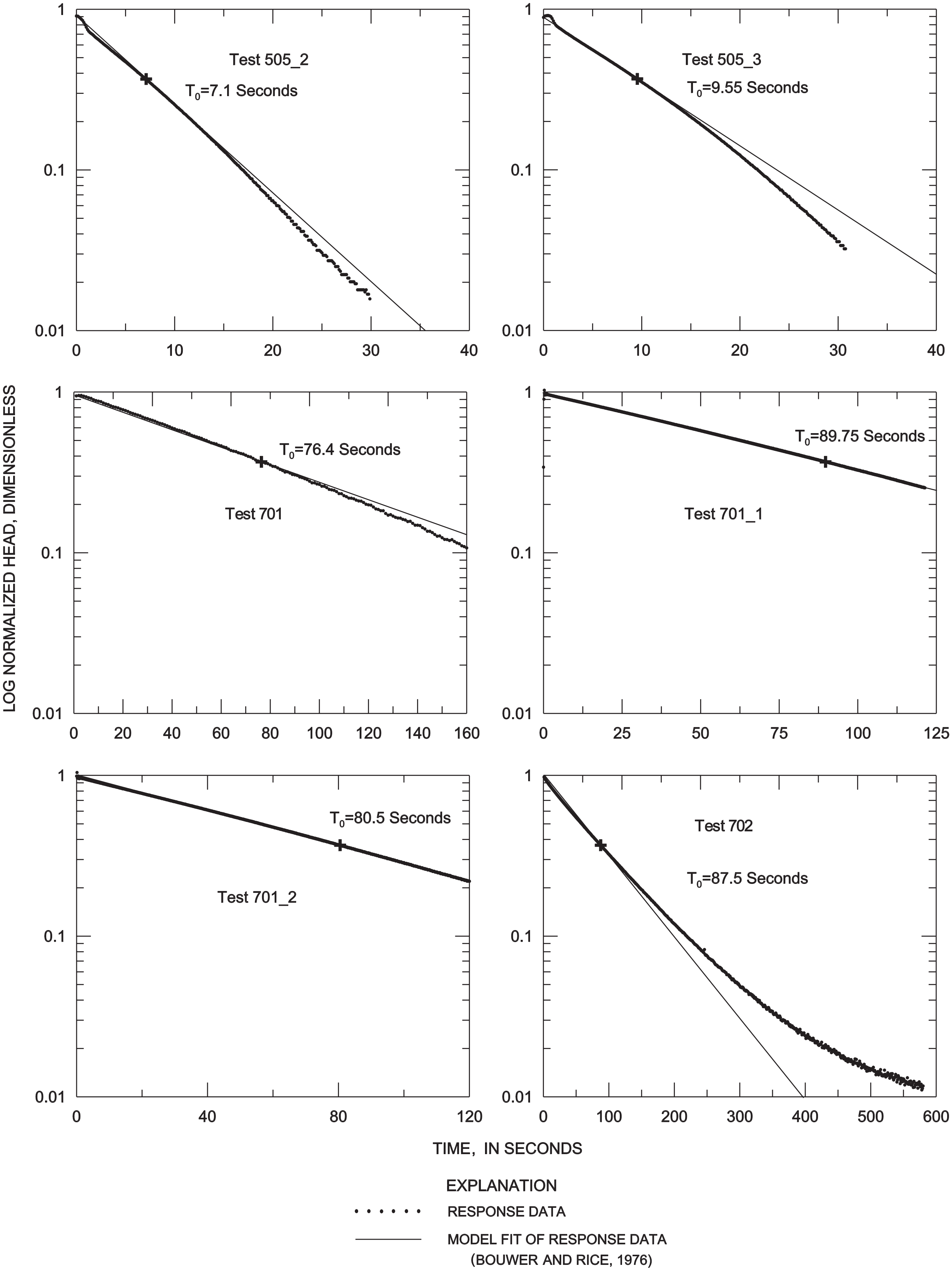
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160
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EXPLANATION
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