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LETTER REGARDING REVIEW OF THE INTERIM MEASURE WORK PLAN FOR SITE 11
NSB KINGS BAY GA
11/1/1993
U S DEPARTMENT OF THE INTERIOR

United States Department of the Interior

GEOLOGICAL SURVEY
Water Resources Division
Peachtree Business Center, Suite 130
3039 Amwiler Road
Atlanta, Georgia 30360-2824

November 1, 1993

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Mr. Ed Lohr
Southern Division
Naval Facilities Engineering Command
2155 Eagle Drive, P.O. Box 190010
North Charleston, South Carolina 29419-9010

Dear Ed:

Review of the Interim Measure work plan for Site 11 at Kings Bay sub base (work plan dated September 1993) by ABB Environmental Services (ABB) is nearly complete. Most comments thus far are in regards to the aquifer tests and, in particular, the anticipated pumping rates to be used for the single-well test at well RW1. Comments about the aquifer tests are in this letter. Comments about other parts of the work plan will be transmitted in a few days, after completion of the review.

The pumping rates that ABB anticipate for the aquifer test, as given on page 4-3 of the work plan, range from 7 to 15 gallons per minute (gal/min), and the highest yielding pump ABB plans to use has a maximum rate of 20 gal/min. ABB does not state in the work plan how these anticipated pumping rates were determined.

A method of aquifer-test analysis was used by the USGS to estimate: (a) the pumping rates necessary to produce 1 foot of drawdown in the observation wells nearest to the planned RW1 pumping well after 1 day of pumping, and (b) expected drawdowns at these nearest observation wells after pumping for 1 day at the range of pumping rates given in the ABB work plan. Descriptions of the method of analysis, and details of the analysis, are given on the enclosed pages.

The results of the computations for pumping rates show that, if hydraulic-conductivity data from slug tests of wells are used to compute the anticipated pumping rates, the rates needed to cause 1 foot of drawdown in the observation wells after 1 day are about 2 to 4 times greater than those rates anticipated by ABB. Only the data from the ABB hydrocone tests show hydraulic conductivities low enough to fall within the anticipated pumping range given by ABB. The hydrocone data cannot be evaluated because water-level recovery data and examples of the method of analysis were not given in the work plan or in previous ABB reports received by the USGS.

The computed drawdowns in the nearby observation wells, using the range of pumping rates given in the ABB work plan and hydraulic-conductivity values from slug tests of wells, range from about 0.2 to about 0.8 feet. These drawdowns are considered to be somewhat small for an aquifer test.

The results of the computations are shown in the enclosure, and are transmitted for consideration by you and ABB. ABB may have anticipated these small drawdowns in observation wells after considering well losses and large drawdowns in the pumping well, or perhaps anticipated them for other reasons. However, the information given in the work plan in regards to how the range of anticipated pumping rates was determined, and what hydraulic conductivity values were used in making the determinations, was insufficient for the USGS to provide an evaluation.

Sincerely,

Bud Zehner

Bud Zehner
Hydrologist

Enclosure

ESTIMATES OF PUMPING RATES DURING PLANNED AQUIFER TESTS AT KINGS BAY SUBMARINE BASE

Pumping rates were estimated by using the aquifer-test method described by Neuman (1975). The method is summarized in the textbook by Freeze and Cherry (1979), and copies of the two pertinent pages from the textbook are enclosed.

The Neuman method applies to unsteady-state conditions in an unconfined aquifer with a fully penetrating pumping well. To use the method for estimating pumping rate, as applied to conditions at Kings Bay, the specific yield and transmissivity are estimated, and a series of theoretical type curves are used to obtain a solution to a function called the "unconfined well function." Values for this function are given in the textbook by Kruseman and de Ridder (1991), and U.S. Geological Survey (USGS) computer-generated plots of these values were used to obtain more accurate solutions than are possible by use of the Freeze and Cherry (1979) plot.

The Neuman method involves:

(1) using values of distance (r) from the pumping well to an observation well, saturated thickness (b) of the aquifer, hydraulic conductivity in the vertical (KZ), and hydraulic conductivity in the horizontal (KX) to compute a value N; the N is determined by the product of the ratios (r-squared/b-squared)*(KZ/KX), and represents one curve in a suite of theoretical type curves.

(2) using values of specific yield (SY), time (t) after pumping started when the drawdown (s) is measured at the observation well, and transmissivity (T) to compute a value (UB); the UB is determined by the ratio of (r-squared*SY)/(4*T*t). The value of UB is used, in combination with the value of N, to determine a solution to the "unconfined well function" W(UB,N) from the theoretical type curve.

(3) and, computing pumping rate (Q) as the ratio of (s*4*3.142*T)/(W(UB,N)).

The pumping rates computed in this analyses are given in table 1. Values of aquifer parameters are also given in table 1, and explanations are given in following paragraphs as to how these values were estimated. The distance from the RW1 pumping well to nearby observation wells PS-2 and PS-3 is about 50 feet, as shown on figure 1-5 of the ABB work plan. The pumping rates are computed on the assumption that at least 1 foot of drawdown is to be observed in the two nearby observation wells one day after pumping is started.

Table 1. Assumed aquifer parameters and estimated pumping rates to cause 1 foot of drawdown in an observation well located 50 feet from a pumping well after 1 day of pumping.

KZ/KX	N	SY	1/UB	W(UB,N)	PUMPING RATE Q (GPM)	TRANSMISSIVITY KX*b (FT-squared/DAY)	FOOTNOTE
1/1	0.510	0.1	13.44	2.1	26	(12)*(70)=840	1
1/2	0.255	" "	" "	2.1	26	" "	"
1/3	0.170	" "	" "	2.1	26	" "	"
1/1	0.510	0.2	6.72	1.6	34	" "	"
1/2	0.255	" "	" "	1.7	32	" "	"
1/3	0.170	" "	" "	1.8	30	" "	"
1/1	0.510	0.3	4.48	1.3	42	" "	"
1/2	0.255	" "	" "	1.5	37	" "	"
1/3	0.170	" "	" "	1.7	32	" "	"
1/1	0.391	0.2	5.76	1.5	31	(9)*(80)=720	2,3
1/2	0.195	" "	" "	1.7	28	" "	" "
1/3	0.130	" "	" "	1.8	26	" "	" "
1/1	0.694	" "	4.32	1.2	29	(9)*(60)=540	2,3
1/2	0.347	" "	" "	1.4	25	" "	" "
1/3	0.231	" "	" "	1.6	22	" "	" "
1/2	0.195	" "	0.77	1.2	5.2	(1.2)*(80)=96	2,4
1/2	0.347	" "	0.58	0.85	5.5	(1.2)*(60)=72	" "
1/2	0.195	" "	1.73	1.3	11	(2.7)*(80)=220	2,5
1/2	0.347	" "	1.30	0.95	11	(2.7)*(60)=160	" "
1/2	0.195	" "	122	4.2	240	(190)*(80)=15200	2,6
1/2	0.347	" "	91.2	3.9	190	(190)*(60)=11400	" "
1/2	0.195	" "	700	5.4	1100	(1100)*(80)=88000	2,7
1/2	0.347	" "	530	5.3	810	(1100)*(60)=66000	" "

FT is feet, and GPM is gallons per minute. KZ is hydraulic conductivity (in feet per day) in the vertical and KX is hydraulic conductivity in the horizontal. N is: KZ/KX times the distance (in feet) to observation well (r)-squared, divided by the thickness (in feet) of the saturated aquifer (b)-squared. SY is specific yield (dimensionless). Transmissivity (T) is the product of KX*b. UB is the product of r-squared times SY, divided by 4Tt, in which t is the time at which drawdown is measured in the observation well. W(UB,N) is a function of T, pumping rate (Q), and drawdown; it is obtained from theoretical type curves.

FOOTNOTE EXPLANATIONS:

1 - KX value based on USGS analysis of ABB slug-test data, and is mean from wells 11-1, 11-3, 11-5, and 11-7, as shown in table 2 of USGS letter to Navy dated April 16, 1993. Value of b is mean of: 80-foot saturated aquifer depth and approximate 60-foot saturated depth of planned pumping well.

2 - Value of b based on 80-foot saturated aquifer depth or 60-foot saturated depth of planned pumping well.

Table 1 (continued).
FOOTNOTE EXPLANATIONS (continued):

3 - KX value based on mean of values computed by ABB from slug tests of wells 11-1,11-3,11-5, and 11-7, as given in: ABB letter to Navy dated May 24, 1993 (page 6, table 2), and; September 1993 RFI report (appendix pages G-1 through G-14).

4 - KX value based on median of 25 values. The 25 values were computed by ABB from hydrocone tests, as shown in September 1993 RFI report (appendix page G-15).

5 - KX value based on median of 99 values. The 99 values were computed by ABB from hydrocone tests, as shown in September 1993 RFI report (appendix pages G-16 and G-17).

6 - KX values based on ABB slug test of sand pack in "model" well, as described in ABB letter to Navy dated September 13, 1993 (page 5).

7 - KX values based on mean of values obtained by ABB in analysis of sand pack by use of "Hazen method", as described in ABB letter to Navy dated May 24, 1993 (bottom of page 4), and in letter to Navy dated September 13,1993 (figure 2).

The pumping well fully penetrates the aquifer in the Neuman method of analysis, and means of correcting for a partially penetrating well are not given in the method. The thickness of the surficial aquifer in the area of site 11 is given as 90 feet in the ABB work plan (page 1-5). Considering depth to the water table is about 10 feet, saturated aquifer thickness is about 80 feet.

The exact depth of the planned pumping well (RW1) is not given in the work plan. The well depth will probably be about 70 feet, as estimated from figure 3-1 in the work plan, and so does not fully penetrate the aquifer. The well is evidently designed to intercept the VOC plume somewhat above the aquifer base. The saturated well length is about 60 feet. A 70-foot aquifer thickness was used to estimate pumping rates that are based on USGS-determined KX values. The 70-foot value is the mean of the 80-foot saturated aquifer thickness and 60-foot saturated well length, and is used (rather than the 80-foot aquifer thickness) to compensate for partial penetration of the pumping well.

The value used by ABB for saturated aquifer thickness in estimating pumping rate is unknown. The method ABB used to estimate pumping rate is not given in the work plan, nor a statement made as to how, or if, an adjustment was made for a partially penetrating well. Therefore, both the length of the saturated part of the well (60 feet) and the saturated thickness of the aquifer (80 feet) were used for estimating pumping rates based on ABB-determined KZ values (table 1).

The specific yield of the surficial aquifer at Kings Bay is unknown. Clean sand commonly has a specific yield of about 0.2. A range of 0.1 to 0.3 was used in this analysis, as applied to USGS-determined KX values. The mid-range (0.2) was used in this analysis, as applied to ABB-determined KX values.

The KZ at Kings Bay is unknown, so the KZ/KX ratio is unknown. Results of the planned aquifer tests may enable determination of this parameter. ABB described, in the September 1993 RFI report, strata of silty sand between strata of clean sand at Kings Bay. Therefore, KZ/KX ratio is probably not 1/1. A ratio of 1/2, or less, may be representative of the surficial aquifer at Kings Bay. For purposes of this analysis, a range of KZ/KX ratios from 1/1 to 1/3 was used for USGS-determined KX values, and for ABB-determined KX values from most slug tests of wells. The mid-range (1/2) was used for the remaining ABB-determined KX values.

Explanations of which KX values were used in estimating pumping rates are given in the footnotes of table 1. The USGS-determined KX values are based on analysis of later recovery data from ABB slug tests, as described in previous Navy-USGS correspondence (see table 1 footnotes). The results of the ABB tests on their "simulation" well (called "model" well here), as described in the September 13, 1993 letter from ABB to the Navy, indicate that even the later recovery data may be representative of the sand pack, rather than of the aquifer (see USGS letter to the Navy dated September 29, 1993). If this is the case, the USGS-determined KX values, and therefore the estimated pumping rates, are inaccurate. The USGS-determined KX values are considered to be the most reasonable to use at this time, however.

The KX values determined by ABB from hydrocone tests, as given in appendix G of the ABB September 1993 RFI report on site 11, are mostly less (by nearly an order of magnitude) than values given by ABB from slug tests of wells. No explanation for this difference is given in the ABB reports. Water-level recovery data and examples of the method of analysis from hydrocone tests were also not given in the ABB reports. Therefore, a comparison of the accuracy of slug tests at wells to the accuracy of the recovery tests in hydrocones cannot be made.

Two KX values from hydrocone data are used in table 1. The first is from data given on page G-15 of appendix G of the ABB RFI report of September 1993. These data are evidently from hydrocones nearest site 11. The second is from data given on pages G-16 and G-17 of that report. These data are apparently from hydrocones both near site 11 and in the adjacent subdivision. The median is used in order to reduce effects of extremes (as illustrated in figures 1 and 2) in obtaining "average" KX values. No attempt was made to separate the hydrocone KX values by zones of depth.

Comparison of the values in table 1 to the enclosed copy of type curves shows that:

(1) values of W(UB,N), and estimated pumping rate, are less "sensitive" to changes in the KZ/KX ratio (value of N) at values of 1/UB greater than about 5 because the curves converge in this part of the plot. Errors in estimating SY may therefore be more important than errors in estimating the N ratio for the larger values of T.

(2) values of W(UB,N), and estimated pumping rate, are less "sensitive" to changes in SY at values of 1/UB less than about 5 because type curves separate more, and are flatter, in this part of the plot. Errors in estimating the N ratio may, therefore, be more important than errors in estimating SY for the smaller values of T.

The large pumping rates given at the bottom of table 1, ranging from 190 to 1100 gallons per minute (gal/min), would be necessary if the KX of the surficial aquifer and the KX of the sand pack in slug-tested wells at Kings Bay are about the same. The possibility of the aquifer and sand pack having the same KX is one of the ABB conclusions from tests of the "model" well, as stated at the bottom of page 9 in the ABB letter to the Navy dated September 13, 1993. The higher end of this pumping-rate range results from the KX values calculated by ABB when using the "Hazen" method of analysis, as given in the September 13, 1993 letter.

The estimated pumping rates given in the upper part of table 1, which are based on USGS-determined KX values and ABB-determined KX values from slug tests of wells, are about 2 to 4 times greater than the 7 to 15 gal/min anticipated pumping rates given in the middle of page 4-3 of the ABB work plan. The maximum-capacity pump intended for use in the aquifer test, as described on page 3-3 of the work plan, has a capacity of 20 gal/min, and all estimated pumping rates given in table 1 that are based on slug tests of wells exceed this rate. Only the values in table 1 that are based on hydrocone tests fall within the anticipated range of pumping rates given in the work plan. As explained previously, information is insufficient to evaluate the hydrocone data.

Equation 8.14, as shown on the enclosed copy of the page from the Freeze and Cherry (1979) textbook, can be used to solve for the expected drawdown s (which is equal to the h0-h in the equation) for a given pumping rate, T, and W(UB,N) value. Table 2 shows the estimated drawdowns for the range of anticipated pumping rates cited in the ABB work plan, and for the 20 gal/min maximum-capacity pump to be used. Table 2 is organized similarly to table 1, and the reasons for using the KX values are the same as shown in table 1.

The range of estimated drawdowns which are based on the KX determined from slug-tests at wells is from about 0.2 foot at 7 gal/min to about 0.8 foot at 20 gal/min (table 2). The drawdowns are nearly undetectable, even at 20 gal/min, if the KX of the aquifer is about the same as the KX of the sand packs in the slug-tested wells. Drawdowns exceed about 0.8 foot only for KX values that were determined by hydrocone tests.

Table 2. Assumed aquifer parameters and estimated drawdown in an observation well located 50 feet from a pumping well after 1 day of pumping at rates of 7, 15, and 20 gal/min.

KZ/KX	SY	W(UB,B)	TRANSMISSIVITY KX*b (FT-squared/DAY)	s AT PUMPING RATE 7 GPM (FT)	s AT PUMPING RATE 15 GPM (FT)	s AT PUMPING RATE 20 GPM (FT)
1/1	0.1	2.1	(12)*(70)=840	0.27	0.57	0.77
1/2	" "	2.1	" "	0.27	0.57	0.77
1/3	" "	2.1	" "	0.27	0.57	0.77
1/1	0.2	1.6	" "	0.20	0.44	0.58
1/2	" "	1.7	" "	0.22	0.47	0.62
1/3	" "	1.8	" "	0.23	0.49	0.66
1/1	0.3	1.3	" "	0.17	0.36	0.47
1/2	" "	1.5	" "	0.19	0.41	0.55
1/3	" "	1.7	" "	0.22	0.47	0.62
1/1	0.2	1.5	(9)*(80)=720	0.22	0.48	0.64
1/2	" "	1.7	" "	0.25	0.54	0.72
1/3	" "	1.8	" "	0.27	0.57	0.77
1/1	" "	1.2	(9)*(60)=540	0.24	0.51	0.68
1/2	" "	1.4	" "	0.28	0.60	0.79
1/3	" "	1.6	" "	0.32	0.68	0.91
1/2	" "	1.2	(1.2)*(80)=96	1.34	2.87	3.83
1/2	" "	0.85	(1.2)*(60)=72	1.27	2.71	3.62
1/2	" "	1.3	(2.7)*(80)=220	0.63	1.36	1.81
1/2	" "	0.95	(2.7)*(60)=160	0.64	1.36	1.82
1/2	" "	4.2	(190)*(80)=15200	0.03	0.06	0.08
1/2	" "	3.9	(190)*(60)=11400	0.04	0.08	0.10
1/2	" "	5.4	(1100)*(80)=88000	0.01	0.01	0.02
1/2	" "	5.3	(1100)*(60)=66000	0.01	0.02	0.02

FT is feet and GPM is gallons per minute. KZ is hydraulic conductivity (in feet per day) in the vertical and KX is hydraulic conductivity in the horizontal. SY is specific yield (dimensionless). Transmissivity (T) is the product of KX*b. s is drawdown. W(UB,B) is a function of T, pumping rate (Q), and drawdown; it is obtained from theoretical type curves.

REFERENCES

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, N.J.

Kruseman, G.P., and de Ridder, N.A., 1991, Analysis and evaluation of pumping test data: International Institute for Land Reclamation and Improvement/ILRI, Wageningen, The Netherlands.

Neuman, S.P., Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response: Water Resources Research, V. 11, pp. 329-342.

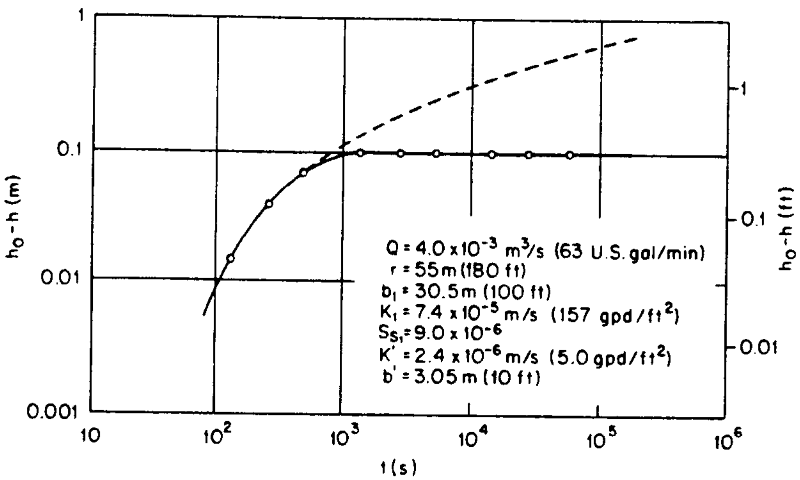

Figure 8.10 Calculated curve of $h_0 - h$ versus t for a leaky aquifer, based on Hantush-Jacob theory.

leaky aquifers, as there is now an additional source of water over and above that which can be supplied by the aquifer itself. Predictions based on the Theis equation therefore provide a conservative estimate for leaky systems; that is, they overpredict the drawdown, or, put another way, actual drawdowns are unlikely to reach the values predicted by the Theis equation for a given pumping scheme in a multiaquifer system.

Unconfined Aquifers

When water is pumped from a confined aquifer, the pumpage induces hydraulic gradients toward the well that create drawdowns in the potentiometric surface. The water produced by the well arises from two mechanisms: expansion of the water in the aquifer under reduced fluid pressures, and compaction of the aquifer under increased effective stresses (Section 2.10). There is no dewatering of the geologic system. The flow system in the aquifer during pumping involves only horizontal gradients toward the well; there are no vertical components of flow. When water is pumped from an unconfined aquifer, on the other hand, the hydraulic gradients that are induced by the pumpage create a drawdown cone in the water table itself and there are vertical components of flow (Figure 8.11). The water produced by the well arises from the two mechanisms responsible for confined delivery *plus* the actual dewatering of the unconfined aquifer.

There are essentially three approaches that can be used to predict the growth of unconfined drawdown cones in time and space. The first, which might be termed the complete analysis, recognizes that the unconfined well-hydraulics problem (Figure 8.11) involves a saturated-unsaturated flow system in which

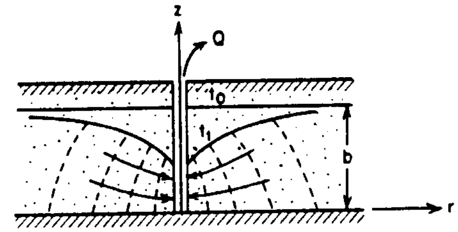

Figure 8.11 Radial flow to a well in an unconfined aquifer.

water-table drawdowns are accompanied by changes in the unsaturated moisture contents above the water table (such as those shown in Figure 2.23). The complete analysis requires the solution of a boundary-value problem that includes both the saturated and unsaturated zones. An analytical solution for this complete case was presented by Kroszynski and Dagan (1975) and several numerical mathematical models have been prepared (Taylor and Luthin, 1969; Cooley, 1971; Brutsaert et al., 1971). The general conclusion of these studies is that the position of the water table during pumpage is not substantially affected by the nature of the unsaturated flow above the water table. In other words, while it is conceptually more appealing to carry out a complete saturated-unsaturated analysis, there is little practical advantage to be gained, and since unsaturated soil properties are extremely difficult to measure *in situ*, the complete analysis is seldom used.

The second approach, which is by far the simplest, is to use the same equation as for a confined aquifer [Eq. (8.7)] but with the argument of the well function [Eq. (8.6)] defined in terms of the specific yield S_y rather than the storativity S. The transmissivity T must be defined as $T = Kb$, where b is the *initial* saturated thickness. Jacob (1950) has shown that this approach leads to predicted drawdowns that are very nearly correct as long as the drawdown is small in comparison with the saturated thickness. The method in effect relies on the Dupuit assumptions (Section 5.5) and fails when vertical gradients become significant.

The third approach, and the one most widely used in practice, is based on the concept of delayed water-table response. This approach was pioneered by Boulton (1954, 1955, 1963) and has been significantly advanced by Neuman (1972, 1973b, 1975a). It can be observed that water-level drawdowns in piezometers adjacent to pumping wells in unconfined aquifers tend to decline at a slower rate than that predicted by the Theis solution. In fact, there are three distinct segments that can be recognized in time-drawdown curves under water-table conditions. During the first segment, which covers only a short period after the start of pumping, an unconfined aquifer reacts in the same way as does a confined aquifer. Water is released instantaneously from storage by the compaction of the aquifer and by the expansion of the water. During the second segment, the effects of gravity drainage are felt. There is a decrease in the slope of the time-drawdown curve relative to the Theis curve because the water delivered to the well by the dewatering that accompanies the falling water table is greater than that which would be delivered by an equal decline in a confined potentiometric surface. In the third segment, which occurs at later times, time-drawdown data once again tend to conform to a Theis-type curve.

Boulton (1963) produced a semiempirical mathematical solution that reproduces all three segments of the time-drawdown curve in an unconfined aquifer. His solution, although useful in practice, required the definition of an empirical *delay index* that was not related clearly to any physical phenomenon. In recent years there has been a considerable amount of research (Neuman, 1972; Streltsova, 1972; Gambolati, 1976) directed at uncovering the physical processes responsible for delayed response in unconfined aquifers. It is now clear that the delay index is not an aquifer constant, as Boulton had originally assumed. It is related to the vertical components of flow that are induced in the flow system and it is apparently a function of the radius r and perhaps the time t.

The solution of Neuman (1972, 1973b, 1975a) also reproduces all three segments of the time-drawdown curve and it does not require the definition of any empirical constants. Neuman's method recognizes the existence of vertical flow components, and the general solution for the drawdown, $h_0 - h$, is a function of both r and z, as defined in Figure 8.11. His general solution can be reduced to one that is a function of r alone if an *average drawdown* is considered. His complex analytical solution can be represented in simplified form as

$$h_0 - h = \frac{Q}{4\pi T} W(u_A, u_B, \eta) \tag{8.12}$$

where $W(u_A, u_B, \eta)$ is known as the *unconfined well function* and $\eta = r^2/b^2$. Figure 8.12 is a plot of this function for various values of η. The type A curves that grow out of the left-hand Theis curve of Figure 8.12, and that are followed at early time, are given by

$$h_0 - h = \frac{Q}{4\pi T} W(u_A, \eta) \tag{8.13}$$

where

$$u_A = \frac{r^2 S}{4Tt}$$

and S is the elastic storativity responsible for the instantaneous release of water to the well. The type B curves that are asymptotic to the right-hand Theis curve of Figure 8.12, and that are followed at later time, are given by

$$h_0 - h = \frac{Q}{4\pi T} W(u_B, \eta) \tag{8.14}$$

where

$$u_B = \frac{r^2 S_y}{4Tt}$$

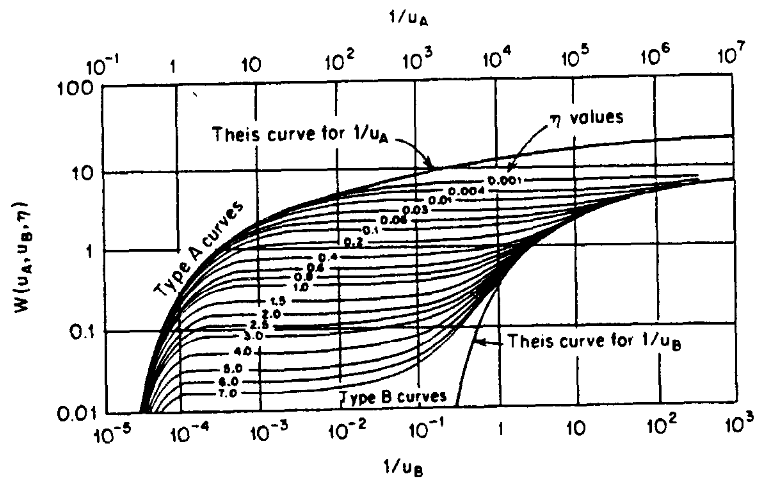

Figure 8.12 Theoretical curves of $W(u_A, u_B, \eta)$ versus $1/u_A$ and $1/u_B$ for an unconfined aquifer (after Neuman, 1975a).

and S_y is the specific yield that is responsible for the delayed release of water to the well.

For an anisotropic aquifer with horizontal hydraulic conductivity K_r and vertical hydraulic conductivity K_z, the parameter η is given by

$$\eta = \frac{r^2 K_z}{b^2 K_r} \tag{8.15}$$

If the aquifer is isotropic, $K_z = K_r$, and $\eta = r^2/b^2$. The transmissivity T is defined as $T = K_r b$. Equations (8.12) through (8.15) are only valid if $S_y \gg S$ and $h_0 - h \ll b$.

The prediction of the average drawdown at any radial distance r from a pumping well at any time t can be obtained from Eqs. (8.13) through (8.15) given Q, S, S_y, K_r, K_z, and b.

Multiple-Well Systems, Stepped Pumping Rates, Well Recovery, and Partial Penetration

The drawdown in hydraulic head at any point in a confined aquifer in which more than one well is pumping is equal to the sum of the drawdowns that would arise from each of the wells independently. Figure 8.13 schematically displays the drawdown $h_0 - h$ at a point B situated between two pumping wells with pumping rates $Q_1 = Q_2$. If $Q_1 \neq Q_2$, the symmetry of the diagram about the plane $A - A'$ would be lost but the principles remain the same.

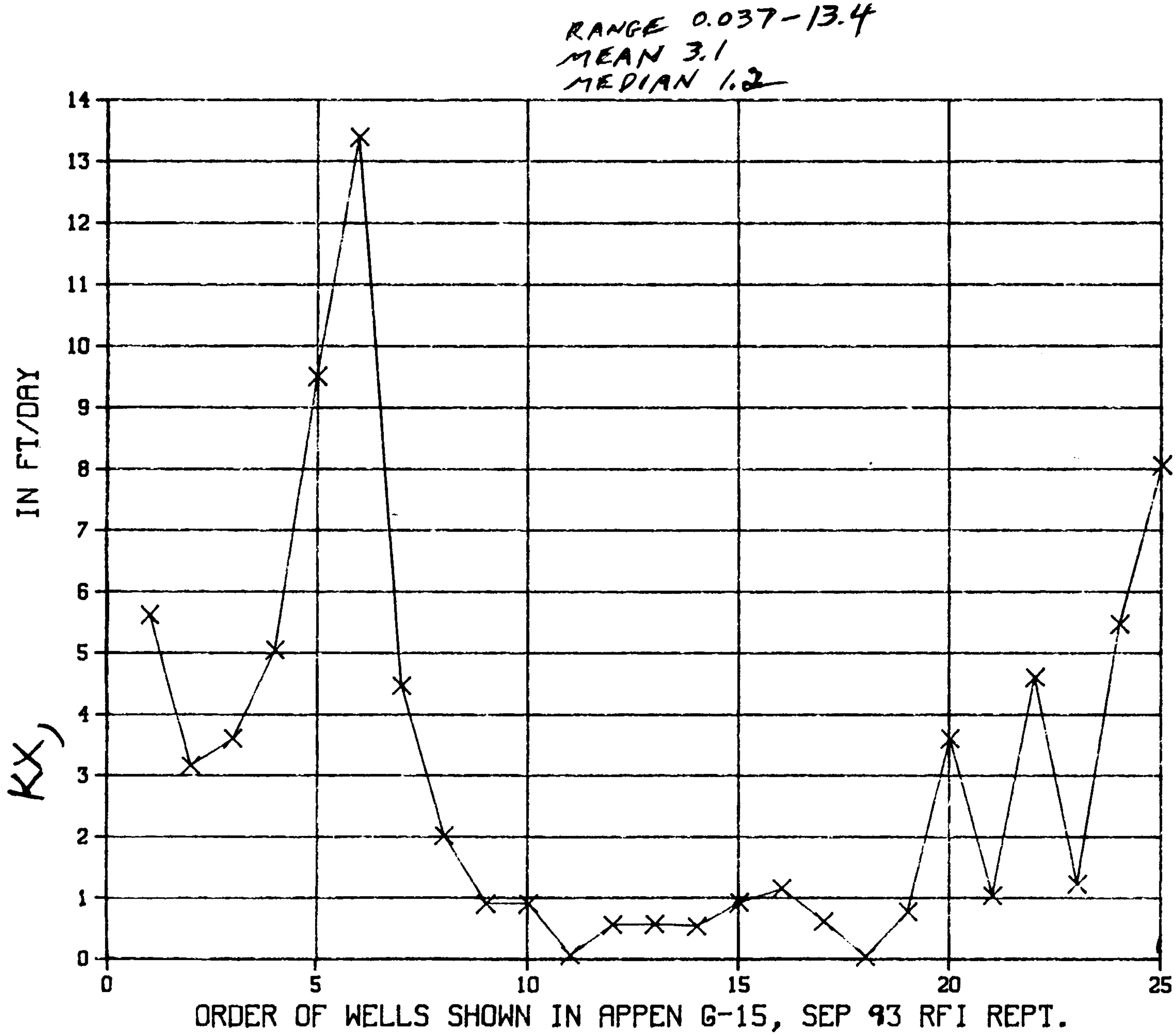

FIGURE 1. Values of KX from ABB RFI report, page G-15.

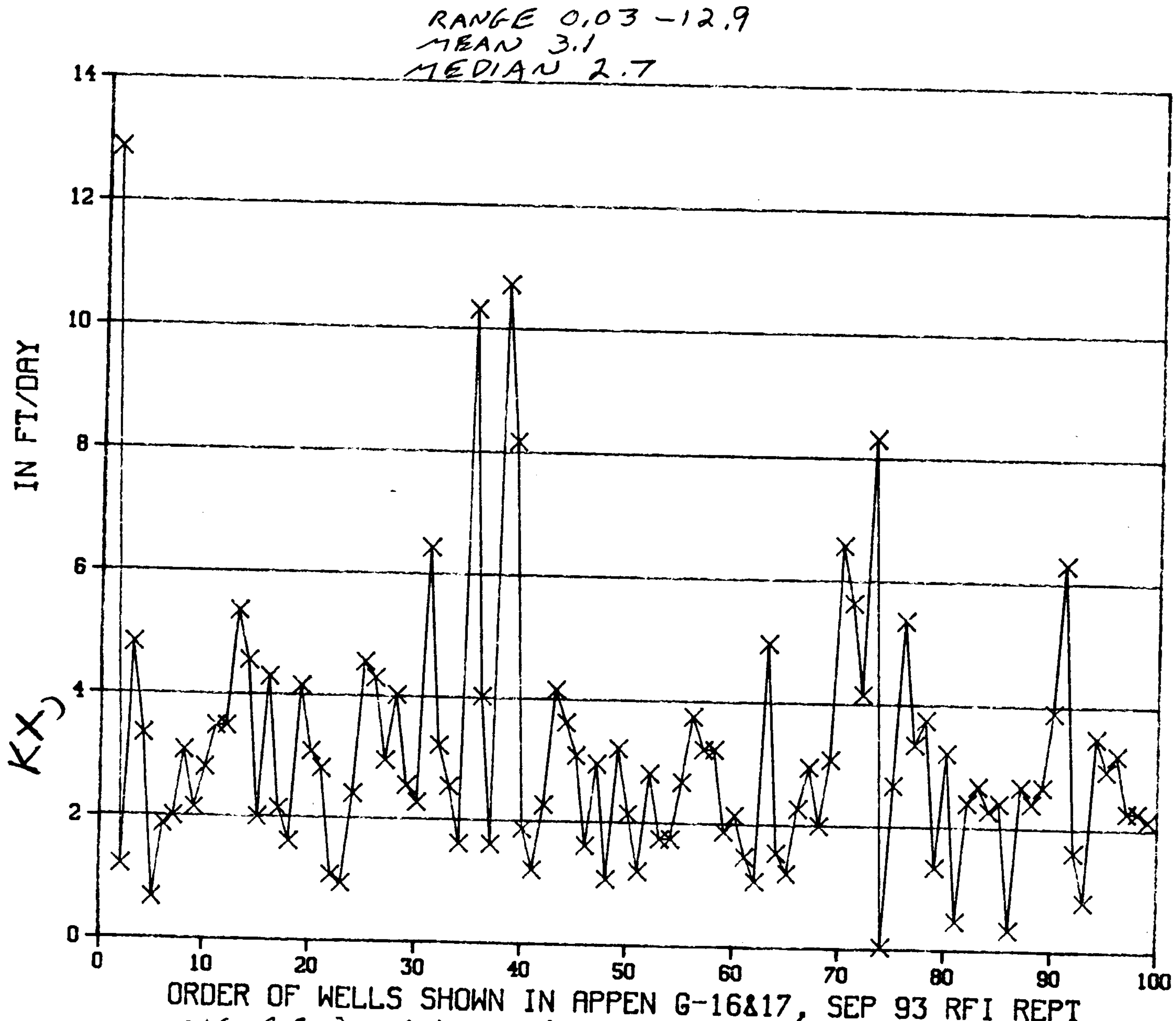

FIGURE 2. Values of KX from ABB RFI report, pages G-16 and G-17.