Precision and Accuracy of Manual Water-Level Measurements Taken in the Yucca Mountain Area, Nye County, Nevada, 1988-90

by Michelle S. Boucher

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per foot (ft/ft)	1.000	meter per meter (m/m)
foot per (foot degree Fahrenheit) [ft/(ft • °F)]	1.80	meter per (meter degree Celsius) [m/(m • °C)]
foot per (foot pound) [ft/(ft • lb)]	2.205	meter per (meter kilogram) [m/(m • kg)]
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
inch (in.)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
pound (lb)	0.4536	kilogram (kg)
pound per foot (lb/ft)	1.488	kilogram per meter (kg/m)

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$°C = 5/9 (°F - 32).$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--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.

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Abstract

Water-level measurements have been made in deep boreholes in the Yucca Mountain area, Nye County, Nevada, since 1983 in support of the U.S. Department of Energy's Yucca Mountain Project, which is an evaluation of the area to determine its suitability as a potential storage area for high-level nuclear waste. Water-level measurements were taken either manually, using various water-level measuring equipment such as steel tapes, or they were taken continuously, using automated data recorders and pressure transducers. This report presents precision range and accuracy data established for manual water-level measurements taken in the Yucca Mountain area, 1988–90. Precision and accuracy ranges were determined for all phases of the water-level measuring process, and overall accuracy ranges are presented. Precision ranges were determined for three steel tapes using a total of 462 data points. Mean precision ranges of these three tapes ranged from 0.014 foot to 0.026 foot. A mean precision range of 0.093 foot was calculated for the multiconductor cable, using 72 data points. Mean accuracy values were calculated on the basis of calibrations of the steel tapes and the multiconductor cable against a reference steel tape. The mean accuracy values of the steel tapes ranged from 0.053 foot, based on three data points to 0.078, foot based on six data points. The mean accuracy of the multiconductor cable was 0.15 foot, based on six data points. Overall accuracy of the water-level measurements was calculated by taking the square root of the sum of the squares of the individual accuracy values. Overall accuracy was calculated to be 0.36 foot for water-level measurements taken with steel tapes, without accounting for the inaccuracy of borehole deviations from vertical. An overall accuracy of 0.36 foot for measurements made with steel tapes is considered satisfactory for this project.

INTRODUCTION

The Yucca Mountain area in Nye County, Nevada, located about 90 mi northwest of Las Vegas, adjacent to and within the Nevada Test Site, is being evaluated by the U.S. Department of Energy as a potential site for an underground, mined, high-level nuclear-waste repository. The U.S. Geological Survey, working in conjunction with the Department of Energy, is studying the physical properties of the area to determine if the site would be able to meet the design criteria for the repository. As a part of these investigations, scientists have been studying the ground-water flow system to ascertain its stability, characteristics, and possible trends. Since 1981, water levels have been measured in approximately 32 wells in the area. There are two primary methods for water-level data collection: periodic measurements and continuous measurements. Periodic measurements were taken by trained personnel who visited the well site approximately once per month (depending upon manpower, weather, and equipment) and manually measured the apparent depth to water using one of several water-level measuring devices, such as a steel tape or a multiconductor cable. The periodically measured well network included 15 wells at the end of 1990. The continuously measured well network included 12 wells at the end of 1990; these wells were instrumented with downhole pressure transducers connected at the land surface to automated data recorders which registered readings from all instruments connected to them at specified times (usually hourly) and were capable of storing over 2 months of data. Personnel visited continuously measured well network sites biweekly to transfer the data from the recorders to cassette tapes. Water-level data collected from both networks were later converted to true water-level altitudes which are to be used in the site characterization process (U.S. Department of Energy, 1988).

Owing to the unique nature of the water-level measurements taken in the vicinity of Yucca Mountain (where depths to water can approach 2,500 ft), and owing to the importance of the water-level data in the site characterization process, it is imperative to know the precision and accuracy ranges for all phases of the water-level measuring process. For example, a consistent change in water level of only 0.1 ft over 1 year could indicate a significant long-term trend; yet if the equipment were not sensitive enough to detect that trend, potentially valuable information would be lost. Therefore, before water-level data are used for site characterization, the precision and accuracy of the data should be determined.

This report establishes both the precision ranges and accuracy of the equipment used to make manual water-level measurements and the accuracy of the conversion to water-level altitude. The precision ranges and accuracy of equipment used in the continuous network is beyond the scope of this report.

PRECISION AND ACCURACY

The difference between precision and accuracy is important to understand. Precision is the degree of agreement among results obtained by repeated measurements under a given set of conditions (Harman, 1989, p. 159). Precision is synonymous with reproducibility and repeatability (Dunnicliff, 1988, p. 75). Accuracy is the closeness of approach of a measurement to the true value of the quantity that is being measured. Accuracy is synonymous with degree of correctness (Dunnicliff, 1988, p. 75). Precision can be determined when multiple measurements are taken using the same instrument, but accuracy generally can only be determined during calibrations. The difference between precision and accuracy is illustrated in figure 1.

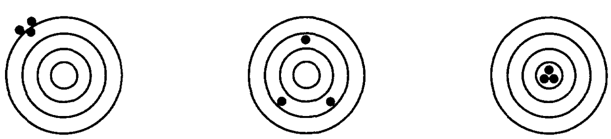

Figure 1. Precision versus accuracy (reprinted from Dunnicliff, 1988, p. 76, and published with permission from John Wiley and Sons, Inc.).

The difference between the measured value or the mean of consecutively measured values and the true value is termed an error. This type of error occurs during calibrations, when instruments are being compared against an absolute standard. Likewise, the difference between successive measurements of the same quantity (for example, water-level measurements) is termed an error in this report. This type of error is considered a precision error, as it is a determination of the precision of a type of measurement. There are four main types of errors that can influence the accuracy and precision of water-level measurements. These errors are gross error, environmental error, observational error, and random error.

Gross error occurs when personnel err in reading equipment, recording data, computing data, or installing or wiring equipment. These mistakes may be avoided by doublechecking all measurements and computations, and providing proper training for all personnel. All measurements and computations associated with water-level measurements are doublechecked. During 1988–90, all measurements were made by trained personnel with several years of experience. The gross error most likely to occur is a data-recording error. Robison and others (1988, p. 42) discuss a possible gross error in 1987 at well USW WT-10. Gross errors are thought to be rare in the data set analyzed here.

Environmental error is caused by the influence of factors such as heat, humidity, moisture, pressure, or vibrational shock. The effects of these factors may be counteracted by taking note of adverse conditions and correcting for them, and by choosing equipment that is suited for the area in which it will be used. Personnel making water-level measurements may record the temperature, barometric pressure, and weather at the time of the measurement, but the effects of weather on the water-level measurement process is considered negligible. The instruments used to make water-level measurements are sturdy and the weather does not influence their performance. However, water-level measurements are corrected for temperature in the well, as is discussed in the section Corrections and Adjustments.

Observational error occurs when multiple observers use different observational techniques. This error can be reduced through proper training in observational procedures, or by using automated data-collection systems. Generally, two people make the water-level measurement; usually both make the observations and compare results. Observational error is thought to be small because the personnel who made most of the measurements used in this report have worked together for several years.

Despite efforts to identify and correct for all types of error, there will still be error due to random factors such as equipment noise, friction and other environmental effects. Random error can be minimized by choosing the correct instrument for the task, by using multiple readings, and, if necessary, by statistically correcting for error. It is believed that the effects of random error are negligible in water-level measurements.

DATA-COLLECTION METHODS

Two different types of equipment, steel tapes and multiconductor-cable units, are used to make periodic, manual water-level measurements at Yucca Mountain. The equipment, its use, and the resulting precision and accuracy are different and must be analyzed separately. Three steel tapes, called the 2,800-ft reference steel tape, the 2,600-ft reeled steel tape, and chain #2, were used during 1988 to 1990. Only one multiconductor-cable unit was used during this period.

Steel Tapes

The measurement of water levels in wells in the Yucca Mountain area is a mechanical process whereby a reeled steel tape is lowered into and retracted from wells using a power source connected to the tape reel. The procedure for making water-level measurements using a reeled steel tape is as follows: The bottom 6 ft of the tape is coated with a water-alterable material, such as double-stick tape and salt. A lead weight (about 1 lb) is attached to the end of the tape to facilitate lowering, and the tape is lowered to slightly below the estimated water level until a convenient foot mark on the tape is reached. This foot mark is held at a fixed point called the measuring point. The measuring point is generally the top of the access tubing used for making water-level measurements. This foot mark on the tape is known as the hold point. After the tape is retracted, the "water-cut" mark on the water-alterable material is identified, and the distance from zero on the tape to the water-cut mark is read to the nearest 0.01 ft. This distance is known as the cut point. The apparent depth to water below the measuring point is the non-wetted length of the tape between the measuring point and the water-cut mark and is calculated by subtracting the cut point from the hold point. The vertical distance between the measuring point and an arbitrary point of known altitude called the reference point is then subtracted from the apparent depth to water below the measuring point to obtain the apparent depth to water below the reference point. This procedure is repeated until the difference between consecutive water-level measurements is less than 0.1 ft (0.05 ft if the depth to water is less than 250 ft). Only two measurements are usually required to obtain the desired precision, but additional measurements may be made if the operator is not confident of one of the readings, or if the tape is being calibrated. The formula for calculating the apparent depth to water below the reference point is given in equation 1, and an example calculation is presented in example 1.

$$ADTW = HP - CP - MP, \qquad (1)$$

where,

ADTW is the apparent depth to water below the reference point,

HP is the hold point of the steel tape at the measuring point,

CP is the cut point at the end of the steel tape, and

MP is the height of the measuring point above the reference point.

Example 1. Using the data collected with chain #2 at well USW WT-10 on January 19, 1989, and substituting it into equation 1:

First Measurement		Second Measurement	
HP	1,144.00 ft	HP	1,145.00 ft
CP	3.18 ft	CP	4.17 ft
MP	1.03 ft	MP	1.03 ft
then, by substitution into equation 1:			
ADTW = HP - CP - MP		ADTW = HP - CP - MP	
ADTW = 1,144.00-3.18-1.03		ADTW = 1,145.00-4.17-1.03	
ADTW = 1,139.79 ft		ADTW = 1,139.80 ft	

Multiconductor Cable

The multiconductor cable is a four-conductor armored cable about 4,000 ft long, having an outside diameter of 0.186 in. and weighing approximately 60.0 lb per 1,000 ft. The conductors are used to transmit voltage to a water-level sensing device. The armor consists of two spiral wraps of steel wire going in opposite directions. The multiconductor cable is passed over a measuring wheel with an effective circumference of 2.34 ft. A counting device measures turns of the wheel and displays the apparent amount of cable passing over the wheel to the nearest 0.01 ft. The apparent amount of cable withdrawn from the well is used in the water-level measurement.

The first step in the procedure for making water-level measurements using a multiconductor cable is to select the probe that will detect water level. This probe may be either a pressure transducer or a float switch. A pressure transducer is a sensitive device which converts pressure due to submergence below the water to electrical voltage in uniform proportion. A float switch utilizes a dipolar-magnetic switch-equipped float, which responds to the water surface by opening or closing the switch. The opening or closing of the switch results in a large change in electrical resistance. Once the desired probe has been connected, the cable is lowered downhole until the transducer or float switch encounters the water. The encounter is detected at the land surface by a change either in voltage or resistance in the electrical circuit. The operators raise and lower the cable several times until they are confident that the device is at the exact location of the water surface. At this point, the reading on the counting device is recorded to the nearest 0.01 ft. This reading is the In-reading. When the cable is fully retracted from the well and the device is at the measuring point, the reading on the counting device is again recorded. This reading is the Out-reading. Sometimes when the cable is at the measuring point for the Out-reading, the counting device will be slightly less than zero, and the number indicated by the counting device will be slightly less than 100 ft. The difference between 100 ft and the indicated value (such as 99.63 ft) is a negative number (such as -0.37 ft), which is subsequently subtracted from the In-reading. The difference between the In-reading and the Out-reading, plus a correction for the probe length, is the apparent depth to water. The probe correction is the distance between the top of the probe that is placed at the measuring point and the point on the probe that reacts to the water surface. The measuring point is then subtracted to obtain the apparent depth to water below the reference point. This procedure is then repeated to obtain a second water-level measurement. As is the case with the steel tapes, usually only two measurements are needed to obtain the required level of precision, which for the multiconductor cable is 1 part in 1,000. The formula for calculating the apparent depth to water below the reference point is given in equation 2, and an example calculation is presented in example 2.

$$ADTW = IN - OUT + PROBE - MP, \quad (2)$$

where,

ADTW is the apparent depth to water below the reference point,

IN is the In-reading indicated on the counting device when water level is indicated by the probe being used,

OUT is the Out-reading indicated on the counting device when the top of the probe is retracted to the measuring point,

PROBE is the length of the water-level sensing device, and

MP is the height of the measuring point above the reference point.

Example 2. Using data collected with the multiconductor cable at well UE-25 WT #4 on January 9, 1989, and substituting it into equation 2:

First Measurement		Second Measurement	
IN	1,436.53 ft	IN	1,436.53 ft
OUT	-.37 ft	OUT	-.38 ft
PROBE	1.87 ft	PROBE	1.87 ft
MP	1.02 ft	MP	1.02 ft
then, by substitution into equation 2:			
ADTW = IN - OUT + PROBE - MP		ADTW = IN - OUT + PROBE - MP	
ADTW = 1,436.53 - (-.37) + 1.87 - 1.02		ADTW = 1,436.53 - (-.38) + 1.87 - 1.02	
ADTW = 1,437.75 ft		ADTW = 1,437.76 ft	

CORRECTIONS AND ADJUSTMENTS

After measurements are taken and recorded, corrections and adjustments are applied to obtain a true depth to water. The true depth to water below the reference point and the altitude of the reference point are used to calculate the altitude of the water level.

Measurements taken using the steel tapes were corrected for mechanical stretch and thermal expansion. Mechanical stretch is associated with the weight of the steel tape and the attached plumb bob. Thermal expansion of a steel tape occurs because of downhole changes in temperature. The thermal expansion correction is based on manufacturer's specifications for thermal-expansion coefficients and on temperature profiles in wells at Yucca Mountain (O'Brien, 1991, p. 11). An empirical calibration factor was applied to measurements taken with the multiconductor cable; this factor accounts for mechanical stretch, thermal expansion, and any inaccuracies in the counting device. Most measurements are also adjusted for deviation of the borehole from vertical.

2,800-ft Reference Steel Tape

The 2,800-ft reference steel tape is used as the standard against which the other water-level measuring devices are calibrated. It is a steel surveyor's chain that is 0.25 in. wide by 2,800 ft long. The tape is divided into 1.0-ft increments for most of its length, with the lower section divided into hundredths of feet. Mechanical-stretch and thermal-expansion coefficients are applied to correct the measurements to obtain the true depth to water below the reference point.

The correction for mechanical stretch of the tape is given by:

$$C = \frac{L^2WS}{2} + PLS - KLS, \qquad (3)$$

where,

C is the correction, in feet;
L is the apparent length of the tape, in feet;
W is the unit weight of the tape, in pounds per foot;
S is the stretch coefficient, in feet per (feet • pound);
P is the weight of the lead weight, in pounds; and
K is the reference tension during manufacture, in pounds.

(O'Brien, 1991, p. 11).

For the 2,800-ft reference steel tape,

W = 1.40×10^{-2} lb/ft;
S = 1.12×10^{-5} ft/(ft • lb); and
K = 20.0 lbs.

Correction for thermal expansion for the tape is determined by:

$$E = (D - R)\,TL, \qquad (4)$$

where,

E is the correction, in feet;
D is the mean air temperature in the well, in degrees Fahrenheit;
R is the reference temperature during manufacture, in degrees Fahrenheit;
T is the thermal expansion coefficient, in feet per (feet • °F); and
L is the apparent length of the tape, in feet.

(O'Brien, 1991, p. 13).

For the 2,800-ft reference steel tape,

R = 68.0 degrees Fahrenheit; and
T = 6.44×10^{-6} ft/(ft • °F).

The thermal characteristics of the tape and the reference tension during manufacture were provided by the manufacturer.

2,600-ft Reeled Steel Tape

The tape used to make routine water-level measurements until January of 1989 was the 2,600-ft reeled steel tape. The tape is a steel surveyor's chain that is 0.25 in. wide and 2,600 ft long. The tape is divided into 1.0-ft increments for most of its length, with the lower section divided into hundredths of feet.

For the 2,600-ft reeled steel tape,

W = 1.14×10^{-2} lb/ft;
S = 1.13×10^{-5} ft/(ft • lb);
K = 20.0 lb;
R = 68°F; and
T = 6.44×10^{-6} ft/(ft • °F).

The reference tension was provided by the manufacturer, and the unit weight was measured by U.S. Geological Survey personnel. The coefficient of mechanical stretch was directly measured by U.S. Geological Survey personnel by attaching increasingly heavy weights to the tape and measuring the stretch of the tape to the nearest 0.0014 ft. The correction for mechanical stretch of the tape is given by:

$$C = 6.44\times10^{-8}L^2 + 1.13\times10^{-5}PL - 2.26\times10^{-4}L, \qquad (5)$$

where the variables are the same as for equation 3.

The correction for thermal expansion of the tape is given by:

$$E = (D - 68.0) \times (6.44 \times 10^{-6})L \qquad (6)$$

where the variables are the same as for equation 4.

The thermal characteristics of the tape were provided by the manufacturer.

Chain #2

Beginning January 18, 1989, chain #2 became the steel tape used to make routine water-level measurements. Chain #2 is a steel surveyor's tape that is 0.31 in. wide and 2,600 ft long. The tape is divided into 1.0-ft increments for most of its length, with the lower section divided into hundredths of feet. On the basis of calibrations performed by personnel on January 11–13, 1989, measurements made using chain #2 were corrected for mechanical stretch and thermal expansion using equations 3 and 4 outlined previously. The characteristics of the tape were provided by the manufacturer, and the stretch coefficient was measured directly by U.S. Geological Survey personnel. The coefficients used in the equation are:

W = 1.74×10^{-2} lb/ft;
S = 7.53×10^{-6} ft/(ft • lb);
K = 20 lb;
R = 68 °F; and
T = 6.44×10^{-6} ft/(ft • °F).

Multiconductor Cable

The multiconductor cable was calibrated against the 2,800-ft reference steel tape. The calibration was done in three wells where depths to water spanned the range of water levels found at Yucca Mountain. During calibrations, sequential measurements were made using both the steel tape and the multiconductor cable. At least two measurements were made using each device, and tape measurements bracketed the cable measurements. If the water level appeared to be changing over the calibration period, more measurements were made and the trend was defined.

The measurements taken using the 2,800-ft reference steel tape were corrected as previously discussed to determine the true depth to water. The true depth to water was compared to the apparent depth indicated by the multiconductor cable. The difference between the two depths, divided by the reference tape depth, was the correction factor applied to that set of measurements.

On the basis of calibrations against the reference steel tape performed during January 1989 and December 1989, an average correction factor was calculated. The average correction factor was determined to be +0.00162 ft/ft for both sets of calibrations; this factor was applied to all measurements taken using the multiconductor cable from 1988 through 1990.

Borehole Deviation

In order to obtain values of true depth to water below land surface, corrections must be made not only for the physical properties of the measuring devices, but also for borehole deviations from vertical. As a borehole deviates from vertical, the borehole length is longer for a given depth than a vertical borehole. Gyroscopic surveys were made of all wells (except wells J-11, J-12, and J-13) to determine borehole deviation from vertical and the difference between borehole-measured depth and true vertical depth. The difference between true vertical depth and measured depth results in the borehole correction factor. Corrections for most wells are -0.67 ft or less, but they range from -0.04 to -5.58 ft (table 1). Corrections generally increase with increasing well depth (O'Brien, 1991, p. 14).

Table 1. Borehole-deviation correction factors for wells in the Yucca Mountain area

Well name (superscript is the number or size of the access tube)	Borehole deviation correction factor (feet)
USW WT-1	-1.07
USW WT-2	-1.75
UE-25 WT #3	-0.89
UE-25 WT #4	-1.49
UE-25 WT #6	-0.67
USW WT-7	-0.11
USW WT-10	-0.10
USW WT-11	-0.38
UE-25 WT #12	-0.60
UE-25 WT #13	-0.04
UE-25 WT #14	-0.28
UE-25 WT #15	-0.62
UE-25 WT #16	-0.21
UE-25 WT #17	-1.58
UE-25 WT #18	-0.51
UE-25a #1	-5.58
UE-25b #1	-0.80
UE-25c #1	-0.21
UE-25c #2	-0.19
UE-25c #3	-0.32
UE-25p #1	-0.07
USW G-3	-1.85
USW G-4	-5.02
USW H-1[1]	-0.47
USW H-1[2,3,4]	-0.59
USW H-3 [1 3/4"]	-0.26
USW H-3 [2 7/8"]	-0.19
USW H-4	-0.21
USW H-5	-0.26
USW H-6	-0.17
USW VH-1	-0.16
Well J-11	------[a]
Well J-12	------[a]
Well J-13	------[a]

[a]Gyroscopic surveys were not available for wells J-11, J-12, and J-13, so no correction is made for borehole deviation.

PRECISION OF WATER-LEVEL MEASUREMENTS

In order to determine the precision of equipment used to make manual water-level measurements, all measurements for the period 1988 to 1990 from both networks made using each piece of equipment were examined. For the purpose of the precision determination only, some terms have been redefined to facilitate the explanation of how the precision data were calculated. A water-level measurement is defined to be a set of uncorrected water-level measurements made at a well on a certain day. Each individual measurement is referred to as a run. Therefore, if the tape was lowered into and retracted from a borehole twice on a certain day, that was considered to be two runs. Those two runs equal one water-level measurement. The difference between runs determines the precision range of the water-level measurement. The use of range in place of standard deviation is justified for limited sets of data where n is less than or equal to 10 because range is approximately as efficient as standard deviation (Harman, 1989, p. 165). In this report, n is only 2 or 3 for precision range.

In order to determine precision range, the runs for each measurement were compared. This comparison was done after subtracting either the cut point from the hold point for steel tape runs or the Out-reading from the In-reading for multiconductor cable runs, but before applying any corrections. Example 3 shows how precision ranges were calculated for measurements taken using steel tapes, and example 4 shows how precision ranges were calculated for measurements taken using the multiconductor cable.

Example 3. Using data collected with the 2,600-ft reeled steel tape at well USW WT-10 on January 19, 1989:

Run 1		Run 2	
Hold point	1,144.00 ft	Hold point	1,145.00 ft
Cut point	3.18 ft	Cut point	4.17 ft
Difference	1,140.82 ft	Difference	1,140.83 ft
	= 1,140.83 - 1,140.82		
	Precision range = 0.01 ft		

As previously mentioned, usually only two runs were made per measurement, but occasionally, three runs were made. In most instances, a third run was made during a calibration. In such cases, the three runs were compared and two precision-range data points were generated. Occasionally, however, a third run was made because one of the previous runs produced a clearly questionable reading. For instance, residual drilling fluid in a well may cause the water-cut mark to appear diffuse and difficult to read, producing a reading that is clearly inconsistent with previous readings. In such a case, a third run is made to verify the suspicion that the reading was questionable. In cases where three runs were made, and it was clearly indicated in the logbook that there was a reason for the questionable reading (for example, the tape came out oily and the water-cut mark could not be read), and the third run was outside the required 0.10-ft precision-range limit, the questionable run was not used to calculate a precision-range data point, as it is not an indication of the precision of the tape. In such instances, only one precision-range data point was generated. If, however, a third run was made because one of the previous runs produced a questionable reading, but no reason for the questionable reading was given in the logbook, then all three runs were compared and two precision-range data points were generated. For the period 1988–90, there were no instances when a precision data point from a third run was not used because the logbook indicated a valid reason for discarding the run. Therefore, all runs made during 1988–90 were considered in this report. Example 5 illustrates an instance where all three runs were made during a calibration, and all three runs were compared to generate two precision-range data points. Example 6 illustrates an instance when three runs were made because one of the runs was suspect, and two precision-range data points were generated because there was no reason given in the logbook to justify the questionable reading.

Example 4. Using data collected with the multiconductor cable at well USW H-4 on January 14, 1988:

Run 1		Run 2	
In-reading	1,691.37 ft	In-reading	1,691.27 ft
Out-reading	-.59 ft	Out-reading	-.65 ft
Difference	1,691.96 ft	Difference	1,691.92 ft
	= 1,691.96 - 1,691.92		
	Precision range = 0.04 ft		

Example 5. Using data collected with the 2,800-ft reference steel tape at well UE-5N on December 15, 1989:

Run 1		Run 2	Run 3
Hold point	714.00 ft	714.50 ft	712.00 ft
Cut point	5.96 ft	6.49 ft	4.00 ft
Difference	708.04 ft	708.01 ft	708.00 ft
= 708.04 - 708.01		= 708.01 - 708.00	
Precision range = 0.03 ft		Precision range = 0.01 ft	

Example 6. Using data collected with the 2,800-ft reference steel tape at well Test Well B on January 11, 1989:

Run 1		Run 2	Run 3
Hold point	1,509.00 ft	1,510.00 ft	1,511.00 ft
Cut point	3.96 ft	4.80 ft	5.80 ft
Difference	1,505.04 ft	1,505.20 ft	1,505.20 ft
= 1,505.20 - 1,505.04		= 1,505.20 - 1,505.20	
Precision range = 0.16 ft		Precision range = 0.00 ft	

Precision Range Percentages

Precision range percentages were calculated for each water-level measuring device during 1988, 1989, and 1990. The percentages were calculated by dividing the total number of measurements having a certain precision range, such as 0.01 ft, by the total number of measurements made with that piece of equipment for the specified annual time block or the cumulative time block. For example, during 1988, 82 measurements were taken using the 2,600-ft reeled steel tape, of which 37 had a precision range of 0.01 ft. Therefore, 45 percent of the 82 measurements taken using the 2,600-ft reeled steel tape in 1988 had a precision range of 0.01 ft. The results of the precision range analyses are presented in the next sections.

2,800-ft Reference Steel Tape

Since 1986, the 2,800-ft reference steel tape has been considered the reference, and all other water-level measuring devices have been calibrated against it. Because it is the calibration standard, this tape was not routinely used to make water-level measurements to prevent undue wear and stretch. In 1988, 9 measurements were made; in 1989, 16 measurements were made; and in 1990, 6 measurements were made using this tape. Most of these measurements were made while performing calibrations of other equipment; but, on occasion, the reference steel tape was used when other pieces of equipment were unavailable.

In 1988, 89 percent (eight) of the nine measurements taken were precise to within 0.05 ft or less. The remaining 11 percent, or one measurement, was precise to 0.10 ft. Therefore 100 percent of the measurements taken in 1988 fell within the required precision range of 0.10 ft or less (fig. 2).

In 1989, 88 percent (14) of the 16 measurements taken using this tape were precise to within a range of 0.05 ft or less. The remaining 12 percent was evenly divided between a measurement with a precision range of 0.10 ft and a measurement with a precision range of 0.16 ft. The measurement that resulted in a precision range of 0.16 ft was considered to be an outlier (an extreme observation); however, it is depicted in figure 3, and was counted when calculating percentage values (fig. 3).

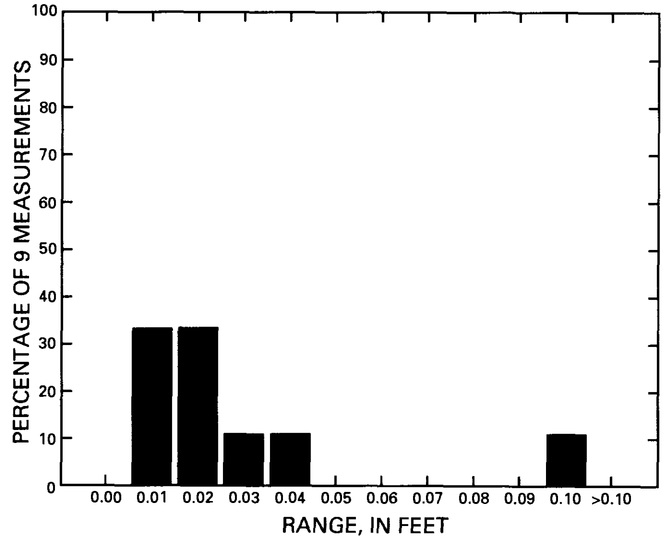

Figure 2. Precision ranges for nine water-level measurements made using the 2,800-ft reference steel tape in 1988.

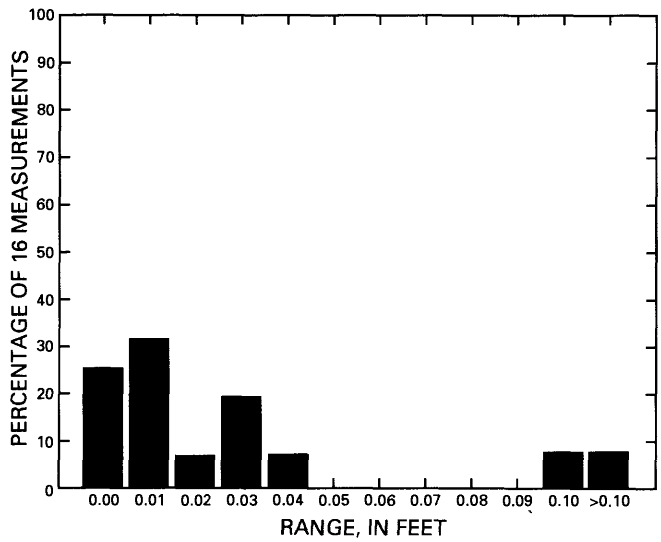

Figure 3. Precision ranges for 16 water-level measurements made using the 2,800-ft reference steel tape in 1989.

In 1990, 83 percent (five) of the six measurements taken were precise to within a range of 0.05 ft or less. The remaining 17 percent, representing one measurement, was within the required precision range of 0.10 ft or less (fig. 4).

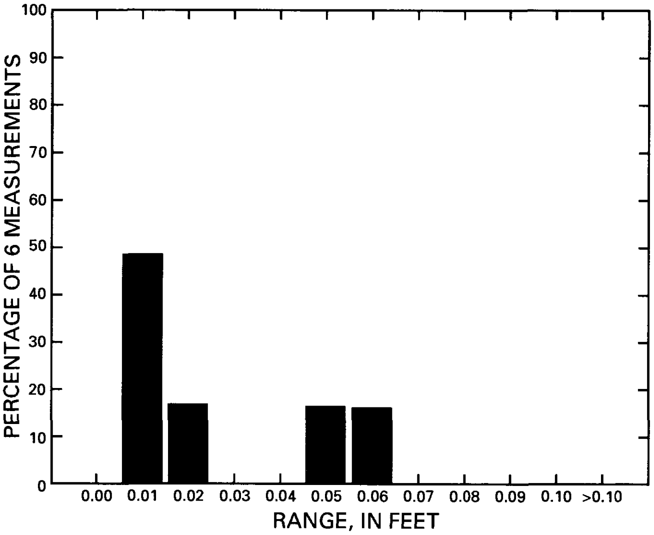

Figure 4. Precision ranges for six water-level measurements made using the 2,800-ft reference steel tape in 1990.

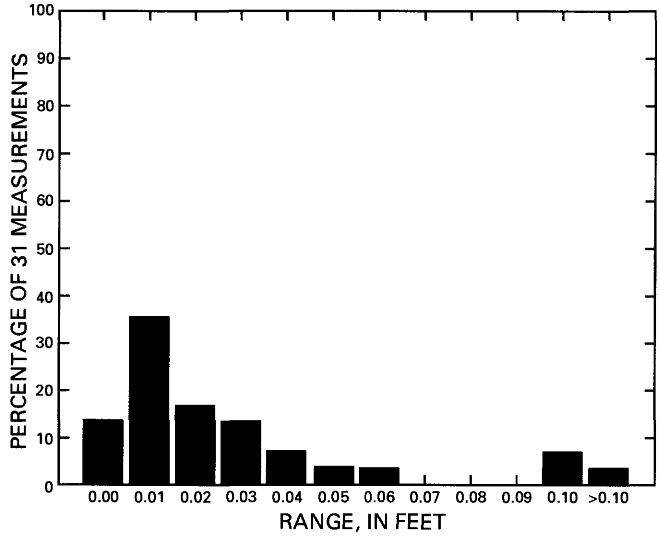

Figure 5. Precision ranges for all 31 water-level measurements made using the 2,800-ft reference steel tape, 1988–90.

Cumulatively during 1988 to 1990, 86 percent of all measurements taken using this tape were precise to within a range of 0.05 ft or less. In all, 95 percent of the measurements were precise to within a range of 0.10 ft or less. The data for the cumulative percentages are shown in table 2 and in figure 5.

Table 2. Precision range data for the 2,800-ft reference steel tape, 1988–90

Precision range (feet)	Number of measurements	Percentage of total 31 measurements
0.00	4	13
0.01	11	35
0.02	5	16
0.03	4	13
0.04	2	6
0.05	1	3
0.06	1	3
0.07	0	0
0.08	0	0
0.09	0	0
0.10	2	6
0.16	1	3
TOTAL:	31	[1]100

[1]Rounding percentage values to whole numbers causes the total percentage to be less than 100 percent.

2,600-ft Reeled Steel Tape

The 2,600-ft reeled steel tape was the primary water-level measuring device used in 1988, when 82 measurements were taken using this tape. In January 1989, the tape was replaced by chain #2, and consequently only eight measurements were taken using this tape that year.

In 1988, 99 percent (81) of the 82 measurements were precise to within a range of 0.05 ft or less. The remaining 1 percent, representing one measurement, was precise to within a range of 0.06 ft. In 1989, 50 percent of the eight measurements were precise to within a range of 0.01 ft, and the other 50 percent were precise to within a range of 0.02 ft (figs. 6 and 7).

Cumulatively, during the period from 1988 to 1989, 98 percent of all measurements were precise to within a range of 0.05 ft or less, and 100 percent of the measurements fell within the 0.10 ft precision range required by operating procedures. The data for the cumulative percentages are presented in table 3 and in figure 8.

Chain #2

Chain #2 was the device routinely used to take manual water-level measurements from January 1989 through 1990. In 1989, 128 measurements were taken using this tape; and in 1990, 213 measurements were taken.

In 1989, 96 percent (123) of the 128 measurements made were precise to within a range of 0.05 ft or less. Of the remaining 4 percent, one measurement, or

1 percent, had a precision range greater than 0.10 ft. This last data point was considered to be an outlier, but it was depicted in figure 9 and was counted when the percentage values were calculated.

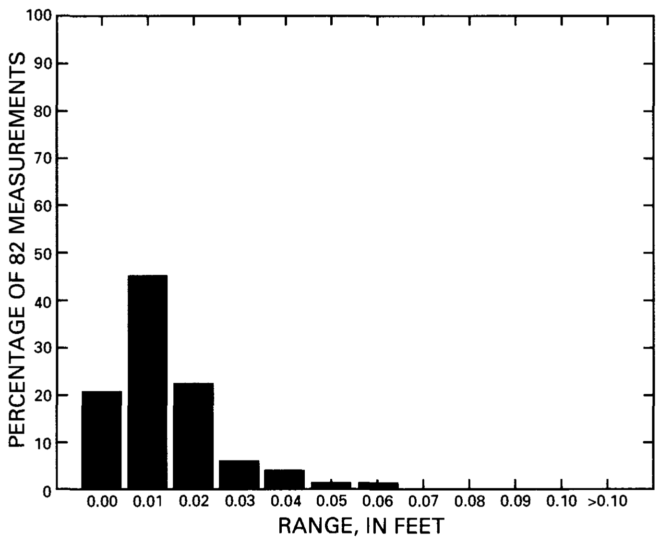

Figure 6. Precision ranges for 82 water-level measurements made using the 2,600-ft reeled steel tape in 1988.

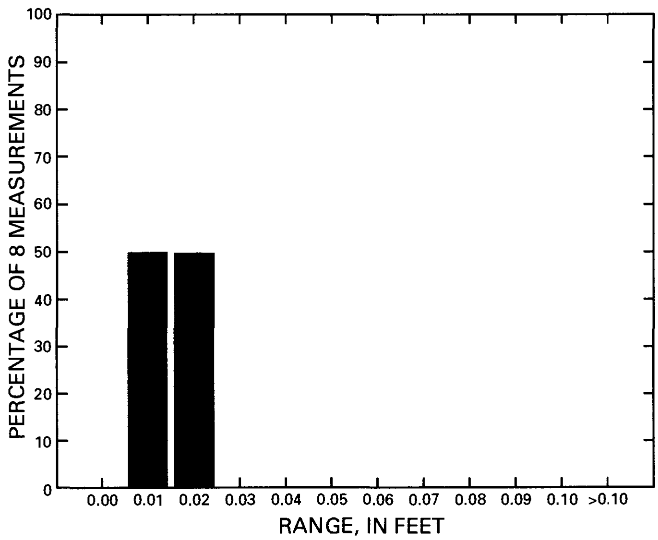

Figure 7. Precision ranges for eight water-level measurements made using the 2,600-ft reeled steel tape in 1989.

In 1990, 99 percent (210) of the 213 measurements taken fell within a precision range of 0.05 ft or less. The remaining 1 percent represents three measurements, one precise to 0.06 ft, one precise to 0.07 ft, and the last precise to 0.11 ft. The measurement that resulted in a 0.11-ft precision range was considered to be an outlier, but it was depicted in figure 10 and was counted when percentage values were calculated.

Table 3. Precision range data for the 2,600-ft reeled steel tape, 1988–89

Precision range (feet)	Number of measurements	Percentage of total 90 measurements
0.00	17	19
0.01	41	45
0.02	22	24
0.03	5	6
0.04	3	3
0.05	1	1
0.06	1	1
0.07	0	0
0.08	0	0
0.09	0	0
0.10	0	0
TOTAL:	90	[1]100

[1]Rounding percentage values to whole numbers causes the total percentage to be less than 100 percent.

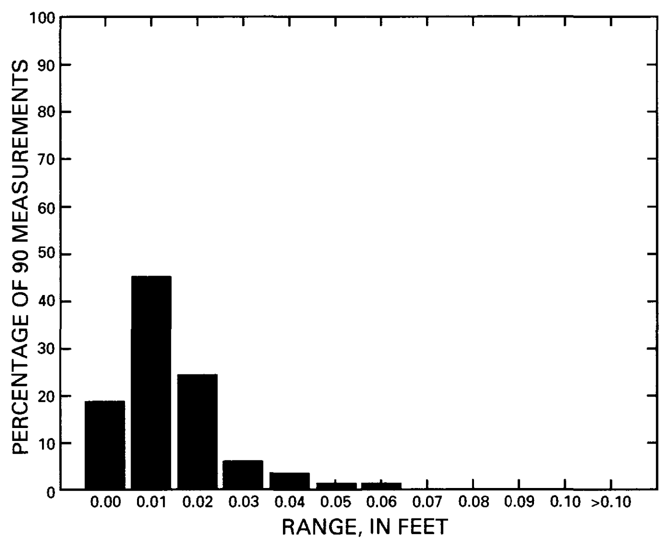

Figure 8. Precision ranges for all 90 water-level measurements made using the 2,600-ft reeled steel tape, 1988–89.

Cumulatively during the period from 1989 to 1990, 98 percent of all measurements fell within a precision range of 0.05 ft or less, and 99 percent fell within the required precision range of 0.10 ft or less. The data for the cumulative percentages are presented in table 4 and in figure 11.

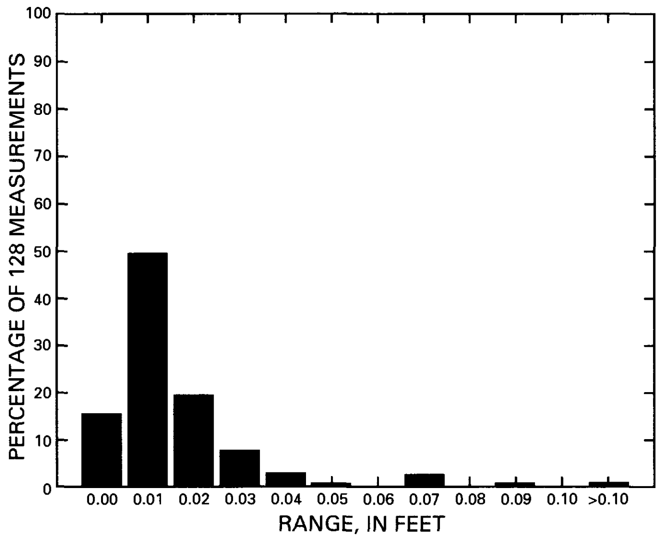

Figure 9. Precision ranges for 128 water-level measurements made using chain #2 in 1989.

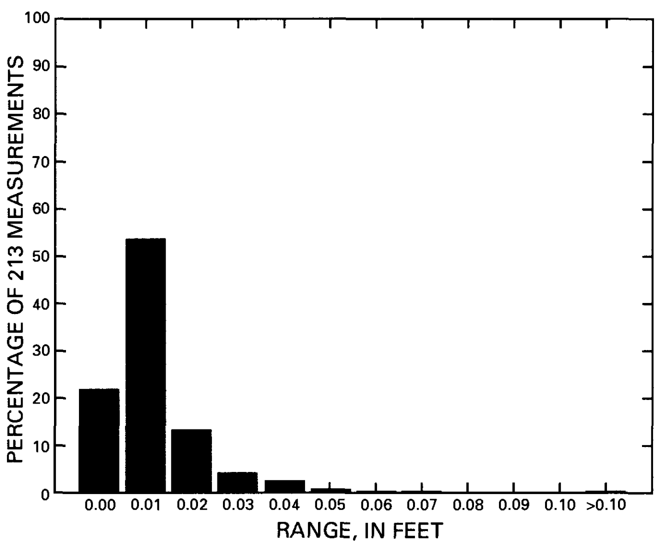

Figure 10. Precision ranges for 213 water-level measurements made using chain #2 in 1990.

Multiconductor Cable

The multiconductor cable is used when operators are unable to insert a steel tape into a well, owing either to excessive friction between the tape and the well casing, or owing to the vertical irregularity of the borehole, which prevents the tape from traveling smoothly downhole. Over the past few years, the multiconductor cable has not been used frequently because mechanical counting-device problems cause the error in measurements made using this equipment to be greater than that associated with the steel tapes. Additionally, as methods for measuring water levels using steel tapes have been refined and improved over the years, the need to use the multiconductor cable has decreased. In 1988, 53 measurements were taken using this cable; in 1989, 14 measurements were taken; and, in 1990, only 5 measurements were taken using this cable.

Table 4. Precision range data for chain #2, 1989–90

Precision range (feet)	Number of measurements	Percentage of total 341 measurements
0.00	67	20
0.01	177	52
0.02	55	16
0.03	20	6
0.04	10	3
0.05	4	1
0.06	1	0.3
0.07	4	1
0.08	0	0
0.09	1	0.3
0.10	0	0
0.11	1	0.3
0.21	1	0.3
TOTAL:	341	[1]100

[1]Rounding percentage values to whole numbers causes the total percentage to be more than 100 percent.

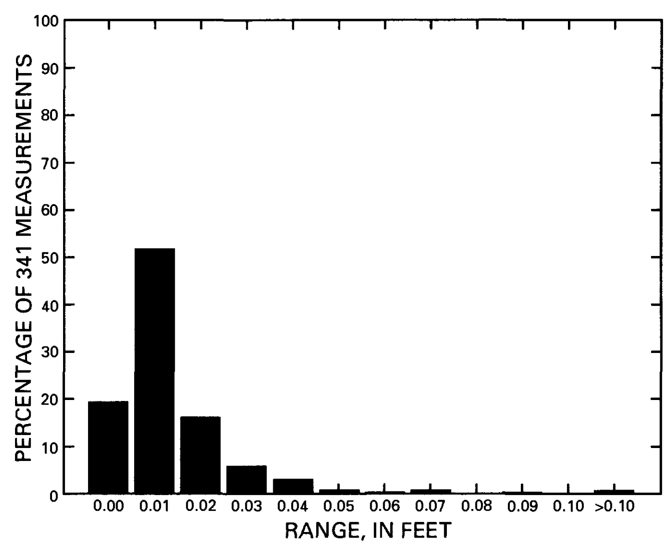

Figure 11. Precision ranges for all 341 water-level measurements made using chain #2, 1989–90.

Because of the inherent error associated with this technique, the precision required by the operating procedures is one part in 1,000, or 1 ft for every 1,000 ft. Although 100 percent of the measurements made during 1988 to 1990 fell within this range, only 78 percent (56) of the measurements were precise to less than or equal to the 0.10 ft that is attainable with the steel tapes, with some precision-range data points as high as 0.92 ft. Because of the low precision of the multiconductor cable when compared to the precision of steel tapes, personnel use steel tapes whenever possible. The precision-range data for the years 1988, 1989, and 1990 are shown in figures 12 to 14. The cumulative precision-range data are listed in table 5 and shown in figure 15.

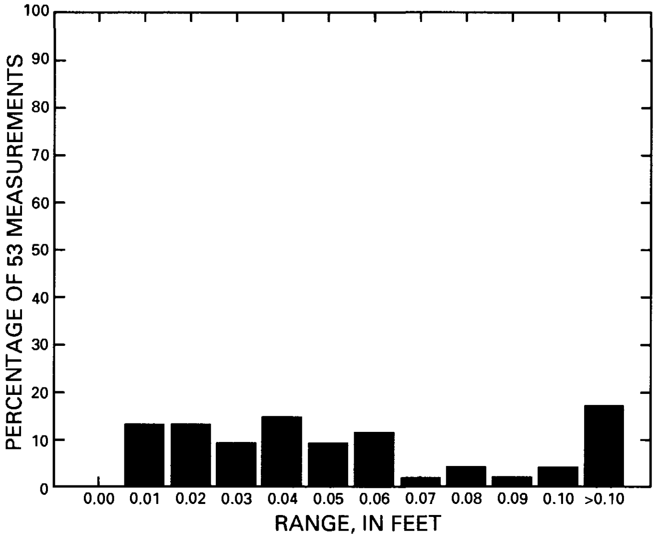

Figure 12. Precision ranges for the 53 water-level measurements made using the multiconductor cable in 1988.

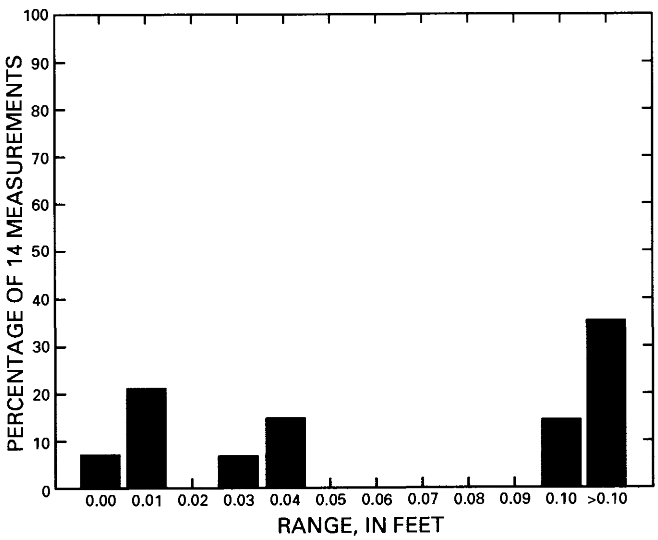

Figure 13. Precision ranges for the 14 water-level measurements made using the multiconductor cable in 1989.

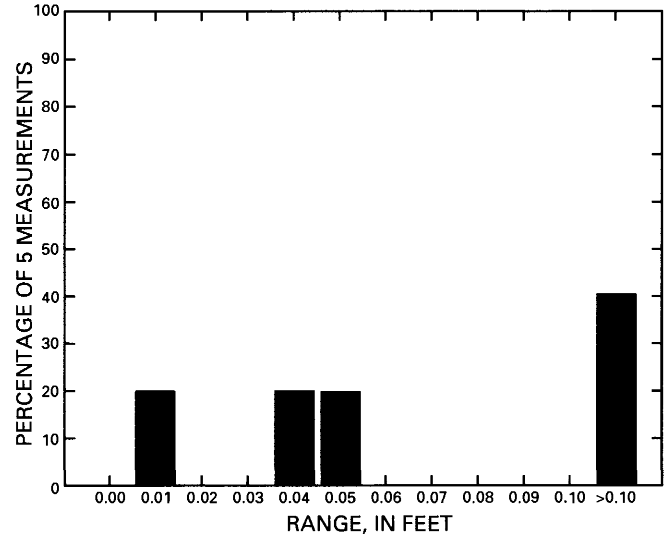

Figure 14. Precision ranges for the five water-level measurements made using the multiconductor cable in 1990.

Table 5. Precision range data for the multiconductor cable, 1988–90

Precision range (feet)	Number of measurements	Percentage of total 72 measurements
0.00	1	1
0.01	11	15
0.02	7	10
0.03	6	8
0.04	11	15
0.05	6	8
0.06	6	8
0.07	1	1
0.08	2	3
0.09	1	1
0.10	4	5
0.11	1	1
0.12	1	1
0.13	1	1
0.14	2	3
0.15	1	1
0.20	1	1
0.22	1	1
0.24	1	1
0.25	1	1
0.26	1	1
0.27	1	1
0.37	1	1
0.45	1	1
0.49	1	1

Table 5. Precision range data for the multiconductor cable, 1988–90 --Continued

Precision range (feet)	Number of measurements	Percentage of total 72 measurements
0.92	1	1
TOTAL:	72	[1]100

[1]Rounding percentage values to whole numbers causes the total percentage to be less than 100 percent.

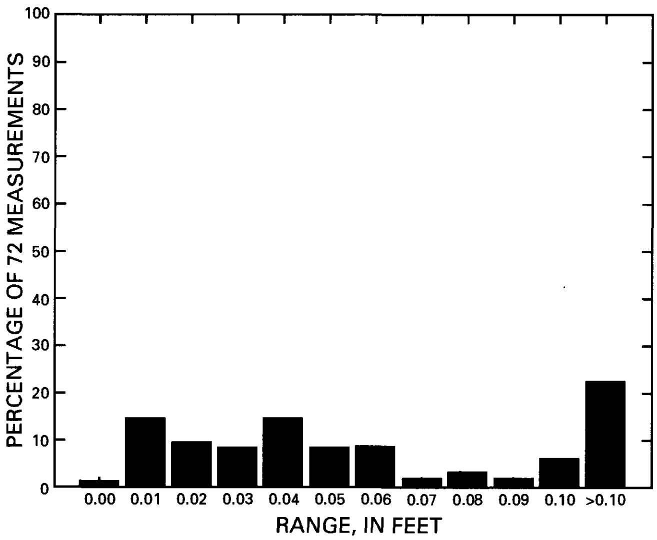

Figure 15. Precision ranges for all 72 water-level measurements made using the multiconductor cable, 1988–90.

Conclusions

On the basis of the cumulative precision-range data presented in tables 2–5, both a mean and a standard deviation were calculated for each water-level measuring device using common statistical equations. These calculations are presented in table 6.

On the basis of the 31 measurements taken using the 2,800-ft reference steel tape in 1988–90, the mean precision range was 0.026 ft, with a standard deviation of 0.033 ft. Eighty-nine percent of the measurements were precise to within a range of 0.05 ft, and 98 percent of all measurements were precise to within a range of 0.10 ft.

On the basis of the 90 measurements taken using the 2,600-ft reeled steel tape in 1988–89, the mean precision range was 0.014 ft, with a standard deviation of 0.011 ft. Ninety-four percent of the measurements were precise to within a range of 0.03 ft, and 98 percent of the measurements were precise to within a range of 0.05 ft.

On the basis of the 341 measurements taken using chain #2 in 1989–90, the mean precision range was 0.014 ft, with a standard deviation of 0.017 ft. Ninety-eight percent of the measurements were precise to within a range of 0.05 ft. Then, on the basis of the steel tapes, namely the 2,800-ft reference steel tape, the 2,600-ft reeled steel tape, and chain #2, 97 percent of all 462 measurements were precise to within a range of 0.05 ft.

On the basis of the 72 measurements taken using the multiconductor cable in 1988–90, the mean precision range was 0.093 ft, with a standard deviation of 0.14 ft. Ninety-eight percent of the measurements were precise to within a range of 0.50 ft.

On the basis of the means and standard deviations presented in table 6, the three steel tapes appear to be similarly precise. Moreover, the 2,600-ft reeled steel tape is apparently more precise than the other two steel tapes. Therefore, the three steel tapes are regarded as similar in precision, but the multiconductor cable is less precise than the steel tapes.

Table 6. Precision range data, means and standard deviations

Measuring device	Mean (feet)	Standard deviation (feet)	Number of measurements
2,800-ft reference steel tape	0.026	0.033	31
2,600-ft reeled steel tape	0.014	0.011	90
Chain #2	0.014	0.017	341
Multiconductor cable	0.093	0.14	72

ACCURACY OF WATER-LEVEL MEASUREMENTS

Accuracy is defined as the closeness of approach of a measurement to the true value of the quantity being measured. Accuracy differences are determined by calibration against a standard. As has been indicated, the 2,800-ft reference steel tape is the standard against which the other water-level measuring devices are calibrated. The 2,800-ft reference steel tape itself has never been calibrated against a national standard, but this does not present a problem, as absolute values are not needed. Water levels are measured over several years to show relative changes in both a well over time or between wells over time. Therefore, relative changes are as useful as absolute changes, as long as the standard is consistent.

Calibrations of water-level measuring equipment against the 2,800-ft reference steel tape were done generally every 3 years for the steel tapes and yearly for the multiconductor cable. The calibrations were performed at three different wells whose depths to water span the range of water levels normally measured in the Yucca Mountain area. Consecutive water-level measurements were made using the two water-level measuring devices, and at least two measurements were made at each well. The results of these calibrations are discussed below.

2,600-ft Reeled Steel Tape

On January 10 to 13, 1989, the 2,600-ft reeled steel tape was calibrated against the reference steel tape. The depths to water in the three wells used for the calibration were approximately 708 ft, 1,505 ft, and 2,467 ft. After the corrections for thermal expansion and mechanical stretch were applied, the differences between the two sets of measurements ranged from 0.00 to 0.09 ft (table 7).

Chain #2

On January 11 to 13, 1989, chain #2 was calibrated against the 2,800-ft reference steel tape. The depths to water of the three wells used for the calibration were approximately 708 ft, 1,505 ft, and 2,467 ft. After the corrections for thermal expansion and mechanical stretch were applied, the differences between chain #2 and the reference steel tape ranged from 0.03 to 0.15 ft (table 8).

Table 7. Summary of calibration of 2,600-ft reeled steel tape, January 10 to 13, 1989

Well name	Depth to water, in feet below the measuring point				Difference between corrected values (feet)
	Uncorrected		Corrected		
	Reference steel tape	2,600-ft reeled steel tape	Reference steel tape	2,600-ft reeled steel tape	
UE-5n	708.01	708.08	707.89	707.96	0.07
USGS Test Well B	1,504.97	1,505.01	1,504.84	1,504.84	0.00
USW H-3 (upper interval)	2,466.67	2,466.85	2,466.80	2,466.89	0.09

Table 8. Summary of calibration of chain #2, January 11 to 13, 1989, and December 12, 1989

Well name	Depth to water, in feet below the measuring point				Difference between corrected values (feet)
	Uncorrected		Corrected		
	Reference steel tape	Chain #2	Reference steel tape	Chain #2	
	Calibration during January 11 to 13, 1989				
UE-5n	708.20	708.18	708.08	708.11	0.03
USGS Test Well B	1,505.24	1,505.32	1,505.11	1,505.26	0.15
USW H-3 (upper interval)	2,466.70	2,466.70	2,466.82	2,466.92	0.10
	Calibration during December 12, 1989				
UE-5n	708.02	708.00	707.90	707.93	0.03
USGS Test Well B	1,505.01	1,505.03	1,504.88	1,504.97	0.09
USW H-5 (upper interval)	2,307.94	2,307.92	2,307.71	2,307.78	0.07

On December 12, 1989, chain #2 was again calibrated against the 2,800-ft reference steel tape. The three wells used for the calibrations had depths to water of approximately 708 ft, 1,505 ft, and 2,308 ft. After all the appropriate corrections were applied, the differences between chain #2 and the 2,800-ft reference steel tape ranged from 0.03 to 0.09 ft (table 8).

Multiconductor Cable

The multiconductor cable was calibrated on January 10 to 11, 1989, against the 2,800-ft reference steel tape. The depths to water in the wells where the calibrations were performed were approximately 708 feet, 1,505 feet, and 2,467 feet. On December 12 to 15, 1989, the multiconductor cable was again calibrated against the reference steel tape in three wells whose depths to water were approximately 708 feet, 1,505 feet, and 2,308 feet. The measurements taken using the 2,800-ft reference steel tape were corrected for mechanical stretch and thermal expansion and were compared to the measurements taken using the cable to define the differences between the two sets of measurements. Using the calculated differences in water-level measurements for the three wells, an average correction factor was computed for the multiconductor cable. On the basis of the calibrations performed in January and December of 1989, a correction factor of +0.00162 ft/ft was used to correct all water-level measurements taken using the multiconductor cable in 1988 to 1990 (table 9) (O'Brien, 1991, p. 11).

Conclusions

On the basis of the calibration data presented in tables 7 to 9, a mean difference of corrected values was calculated for each water-level measuring device. Because of the paucity of calibration data points, it was not logical to calculate standard deviations. The 2,600-ft reeled steel tape and chain #2 are apparently very accurate, and the multiconductor cable is nearly as accurate as the 2,600-ft reeled steel tape and chain #2 (table 10).

The difference in corrected values for the 2,600-ft reeled steel tape ranged from 0.00 to 0.09 ft, and the mean was 0.053 ft. The difference in corrected values for chain #2 ranged from 0.03 to 0.15 ft, and the mean was 0.078 ft. The difference in corrected values for the multiconductor cable ranged from -0.20 to 0.46 ft, and the mean was 0.07 ft, after corrections were applied using the average correction factor of +0.00162 ft/ft.

Table 10. Means of accuracy data

Measuring device	Mean (feet)	Number of points
2,600-ft reeled steel tape	0.053	3
Chain #2	0.078	6
Multiconductor cable	0.065	6

Table 9. Summary of calibration of the multiconductor cable, January 10 to 11, 1989, and December 12 to 15, 1989

Well name	Depth to water, in feet below the measuring point: Uncorrected — Reference steel tape	Uncorrected — Multiconductor cable	Corrected — Reference steel tape	Corrected — Multiconductor cable	Difference between corrected values (feet)
Calibration during January 10 to 11, 1989					
UE-5n	708.01	706.70	707.89	707.84	-0.05
USGS Test Well B	1,504.95	1,502.39	1,504.82	1,504.82	0.00
USW H-3 (upper interval)	2,466.54	2,462.78	2,466.66	2,466.77	0.11
Calibration during December 12 to 15, 1989					
UE-5n	708.02	706.56	707.90	707.70	-0.20
USGS Test Well B	1,505.01	1,502.52	1,504.88	1,504.95	0.07
USW H-5 (upper interval)	2,307.94	2,304.44	2,307.71	2,308.17	0.46

ACCURACY OF REFERENCE POINTS

In 1984, altitudes above sea level of reference points were determined at 32 wells from the U.S. Geological Survey's unadjusted 1983 second-order, class 1 level line that crosses Yucca Mountain. The altitudes were established at the top of a 0.25-in. -thick metal tag 7 in. by 1.5 in. that is welded to the well casing. At the top of the tag, a hole was marked to indicate the exact location of the altitude. This mark is referred to as the reference point. Altitudes of wells located close to the 1983 level line were established by short-fly level lines, using a Zeiss level. The majority of well altitudes were established by Topcon GTS 2 traverses (guppy), using the T-2 at the prism end to record simultaneous reciprocal angles (P. Ibarra, U.S. Geological Survey, written commun., 1984).

The closure lines for each well are shown in table 11. Wells VH-1 and J-11 are not represented because reference points have not been surveyed. The closure lines range from -0.127 to +0.137 ft. However, due to inaccuracies in the surveying method, closure lines are considered to be accurate to within 0.33 ft for this report.

Table 11. Line closures at wells in the Yucca Mountain area

Well number	Line number [1]	Line closures (feet)
USW G-3	2	-0.077
USW G-4	3	-0.022
USW H-1	3	-0.022
USW H-3	2	-0.077
USW H-4	3	-0.022
USW H-5	Level line #3	+0.110
USW H-6	6	-0.047
USW WT-1	5	+0.026
USW WT-2	3	-0.022
USW WT-7	Level line #6	+0.110
USW WT-10	8	+0.006
USW WT-11	7	+0.137
UE-25a #1	Level line #4	+0.030
UE-25b #1	Level line #4	+0.030
UE-25c #1	Level line #5	-0.010
UE-25c #2	Level line #5	-0.010
UE-25c #3	4	-0.102
UE-25p #1	4	-0.102
UE-25 WT #3	Level line #1	-0.090
UE-25 WT #4	3	-0.022
UE-25 WT #6	3	-0.022
UE-25 WT #12	1	-0.127
UE-25 WT #13	3	-0.022
UE-25 WT #14	4	-0.102
UE-25 WT #15	3	-0.022
UE-25 WT #16	3	-0.022
UE-25 WT #17	Level line #2	+0.010
UE-25 WT #18	3	-0.022
Well J-12	1	-0.127
Well J-13	1	-0.127

[1]Line number, unless otherwise noted, refers to Topcon GTS-2 traverse.

ACCURACY OF MEASURING POINTS

The measuring point is a convenient mark, usually the top of the water-level access tube, that the operators use as a reference from which to measure when taking water-level measurements. The vertical distance between the measuring point and the reference point that has a known altitude was measured manually using a standard commercial-grade steel engineer's tape which was divided into 0.01-ft increments. When the measuring points were established, a carpenter's level was used in conjunction with the engineer's tape in order to ensure maximum possible accuracy. Therefore, the heights of the measuring points above the reference points are considered accurate to within 0.01 ft. Measuring-point values differ for each well, and they range from 0.11 to 2.08 ft above the reference point.

ACCURACY OF BOREHOLE DEVIATION

The wells in the water-level network are not perfectly vertical but deviate from true vertical to some degree. This borehole deviation from vertical results in an apparent depth to water that is greater than the true depth to water. Water-level measurements are corrected for this borehole deviation. As noted previously, this correction ranges from -0.04 to -5.58 ft for wells used in this report.

Borehole deviations were determined using gyroscopic surveys (Robison and others, 1988, p. 14). The surveys were done by a contractor to the U.S. Department of Energy at the Nevada Test Site. The survey report lists the type of survey as gyro multi-shot, and says that the method used was the radius of curvature method. Readings were taken every 50 ft down and up the boreholes. Angles were recorded to the nearest 0.25 degrees, and distances were recorded to the nearest 0.01 ft. However, the accuracy of the methods used is not known. The uncertainty involved with the borehole correction factors has a large impact when trying to determine overall accuracy of the water-level measurements. If the accuracy of the borehole-deviation correction is high compared to the less-accurate components, the effect of borehole deviation on overall accuracy would be small. On the other hand, if the accuracy of the borehole-deviation correction is low, it could be a dominant factor in determining overall accuracy. In order to more accurately measure water levels, all the wells in the Yucca Mountain area that are used for water-level data collection should be resurveyed using procedures with known accuracies.

CALCULATION OF OVERALL ACCURACY

In order to compare water levels between wells and to calculate the gradient of the water table, water-level measurements should be as accurate as possible, and this accuracy should be known. To make comparisons of water levels between wells, all water-level measurements are adjusted to altitude above sea level. The accuracy of the computed water-level altitude is a function of the accuracy of the: (1) Manual water-level measurement (device dependent), (2) borehole-deviation correction, (3) height of the measuring point, and (4) altitude of the reference point. The precision of the 2,800-ft reference steel tape is also a factor, as it determines the accuracy of the other water-level measuring devices.

The overall accuracy of manual water-level measurements cannot be determined by simply adding the accuracy values together because of possible compensating errors. A more appropriate way to estimate overall accuracy is to take the square root of the sum of the squares of the individual accuracy values. Neglecting the accuracy of the borehole-deviation correction because it is indeterminate, the overall accuracy for manual water-level measurements is estimated to be:

$$A = \sqrt{(X_1)^2 + (X_2)^2 + (X_3)^2 + (X_4)^2} \qquad (7)$$

where,

A is the overall accuracy value, in feet;

X_1 is the precision value for the 2,800-ft reference steel tape, in feet;

X_2 is the largest inaccuracy in the calibration of the water-level measuring device, in feet;

X_3 is the accuracy of the altitude of the reference points, in feet; and

X_4 is the accuracy of the measuring points, in feet.

Then, by substitution into equation 7, the overall accuracy of water-level measurements made with steel tapes is estimated to be:

$$A = \sqrt{(0.03)^2 + (0.15)^2 + (0.33)^2 + (0.01)^2}$$

or 0.36 ft, without accounting for the inaccuracy of the borehole-deviation correction. If the accuracy values were simply added, the overall accuracy value, neglecting borehole deviation, would be 0.52 ft.

By substitution into equation 7, the overall accuracy of water-level measurements made with the multiconductor cable, again neglecting to include the accuracy of the borehole-deviation correction, is estimated to be:

$$A = \sqrt{(0.03)^2 + (0.46)^2 + (0.33)^2 + (0.01)^2}$$

or 0.57 ft. If the accuracy values were simply added, the overall accuracy, neglecting borehole deviation, would be 0.83 ft.

SUMMARY AND CONCLUSIONS

The precision of water-level measurements at Yucca Mountain was determined from the precision range between successive measurements taken in the same well on the same day with the same equipment. Precision is important in order to be able to detect changes in water level over time in the same well. Precision ranges were determined for three different steel tapes using a total of 462 data points. Mean precision ranges were 0.026 ft (based on 31 points) for the 2,800-ft reference steel tape, and 0.014 ft for both the 2,600-ft reeled steel tape and chain #2 (based on 90 and 341 points, respectively). Ninety-seven percent of all measurements taken with the steel tapes were precise to within 0.05 ft. Precision ranges were also determined for the multiconductor cable. Ninety-eight percent of the 72 multiconductor cable measurements were precise to within 0.50 ft, and the mean precision range was 0.093 ft.

Accuracy is important in order to compare water levels between wells and to calculate the gradient of the water table. To make such comparisons, all water levels are adjusted to altitude above sea level. The accuracy of the computed water-level altitude is shown to be a function of the accuracy of the: (1) Water-level measurement (device dependent), (2) borehole-deviation correction, (3) height of the measuring point, (4) altitude of the reference point, and (5) the precision of the 2,800-ft reference steel tape.

The standard for water-level measurements at Yucca Mountain was the 2,800-ft reference steel tape; its precision was approximately 0.03 ft. On the basis of 9 points, the differences between the reference steel tape and the other 2 steel tapes ranged from 0.00 to 0.15 ft. On the basis of 6 points, the differences between the multiconductor cable and the reference steel tape ranged from 0.00 to 0.46 ft. The accuracy of the reference point altitudes is about 0.33 ft. The height of the measuring points was accurate to within 0.01 ft. The accuracy of the borehole-deviation correction factors is indeterminate and poses a problem when calculating overall accuracy values. If the accuracy of the corrections is high, the effect of the borehole deviation on overall accuracy would be small. On the other hand, if the accuracy of the corrections is low, it could be the dominant factor in determining overall accuracy. The borehole-deviation surveys should be redone using methods with known accuracy values.

The overall accuracy of manual water-level measurements at Yucca Mountain is estimated by taking the square root of the sum of the squares of the individual accuracy values. The overall accuracy of manual water-level measurements taken with steel tapes is estimated to be 0.36 ft, neglecting the accuracy of the borehole-deviation correction factors. The overall accuracy of manual water-level measurements taken with the multiconductor cable is estimated to be 0.57 ft, neglecting the accuracy of the borehole-deviation correction factors.

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