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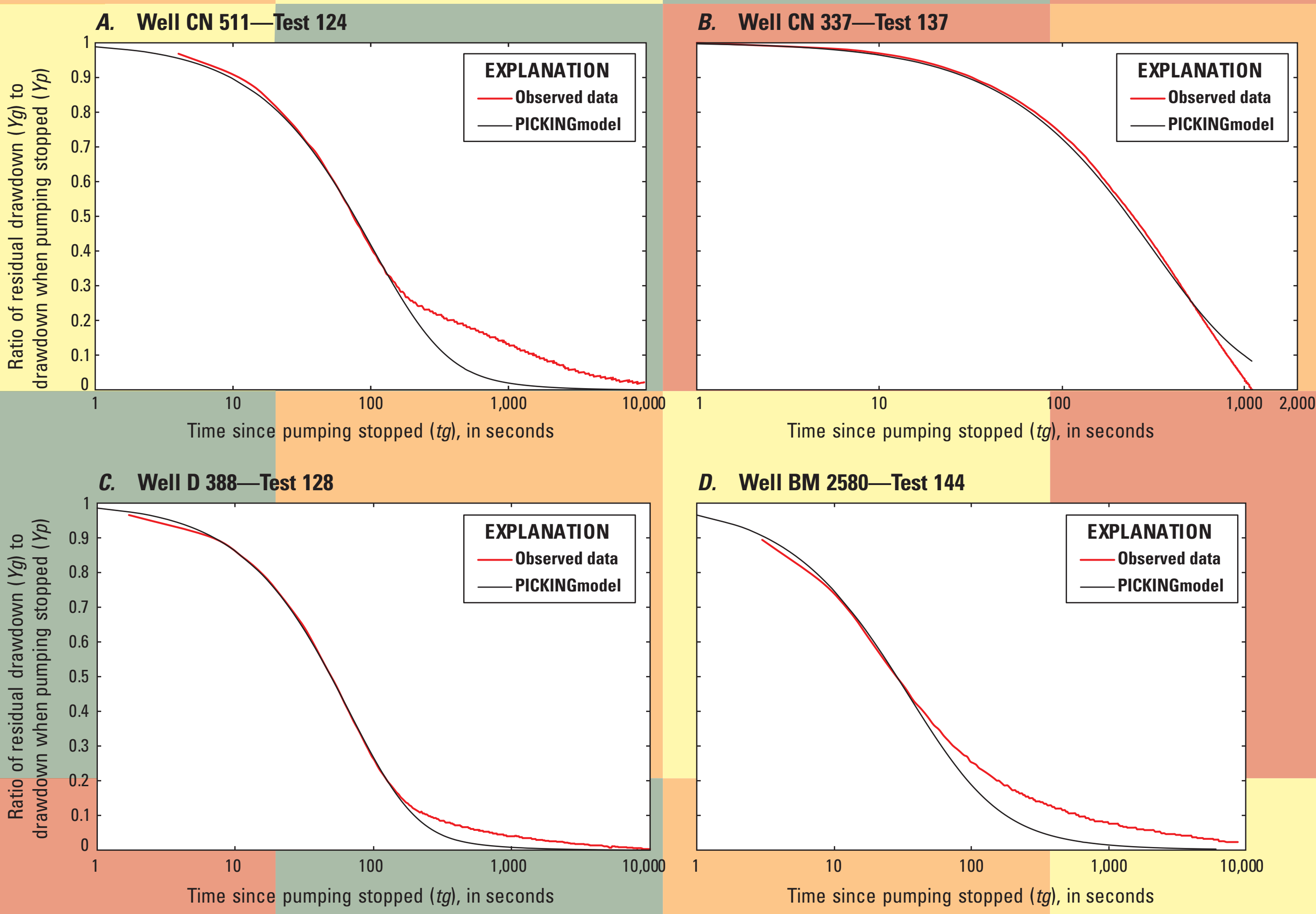
Transmissivity Estimated From Brief Aquifer Tests of Domestic Wells and Compared With Bedrock Lithofacies and Position on Hillsides in the Appalachian Plateau of New York



Scientific Investigations Report 2020–5087

U.S. Department of the Interior
U.S. Geological Survey

Cover. Observed water-level recovery compared to PICKINGmodel type curves for four tests of domestic wells in the Appalachian Plateau of New York. Figure 3 of this report.

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By Allan D. Randall and Andrew C. Mills

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per minute per foot (gal/min/ft)	12.42	liter per minute per meter (L/min/m)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
foot squared per second (ft^2/s)	0.09290	meter squared per second (m^2/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) except in figure 1, where the horizontal datum is the World Geodetic System 1984 datum.

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, feet squared per day (ft^2/d), is used for convenience. The computer program used to calculate transmissivity generates results in feet squared per second, so this unit also appears in the report.

Abbreviation

USGS	U.S. Geological Survey

Transmissivity Estimated From Brief Aquifer Tests of Domestic Wells and Compared With Bedrock Lithofacies and Position on Hillsides in the Appalachian Plateau of New York

By Allan D. Randall[1] and Andrew C. Mills[2]

Abstract

Procedures for undertaking and analyzing recovery from aquifer tests of 13 to 132 seconds (described in reports cited herein) were applied to 51 domestic drilled wells that penetrated bedrock outside major valleys in the part of the Appalachian Plateau of New York drained by the Susquehanna River. Transmissivities calculated from these tests ranged over three orders of magnitude in both the Catskill-Cattaraugus lithofacies (shales, mudstones, siltstones, medium to coarse sandstones, pebbly sandstones) and the Chemung-Hamilton lithofacies (shales, mudstones, siltstones, fine to medium sandstones). Median transmissivity values were 0.000425 foot squared per second (36.7 feet squared per day) in the Catskill-Cattaraugus lithofacies and 0.00055 foot squared per second (47.5 feet squared per day) in the Chemung-Hamilton lithofacies. The distributions of transmissivity values within the two lithofacies were likewise similar. The range and median values of transmissivity were also nearly the same on lower and midlevel hillsides and were only slightly greater on a few upper hillsides. Transmissivities estimated from such easily arranged and analyzed tests may be appropriate for estimating groundwater flux under the small gradients that prevail under natural conditions, but not under larger drawdowns and steeper gradients near clusters of domestic wells. Four of the 51 wells tested were also pumped for 10 to 32 minutes; analysis by the Theis recovery method yielded transmissivities consistent with the brief tests for 2 wells, but 7 to 9 times smaller for 2 wells.

Transmissivity values estimated by the PICKINGmodel were not significantly different from values estimated by an automated application of the Picking method (PPC-Recovery) at a probability of 95 percent. Transmissivities calculated by either method from data for time intervals of 120 seconds or less may be of limited practical value because they apply only to a small volume of bedrock close to the pumped well.

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Introduction

South-central and southwestern New York is an extensive upland, termed the Appalachian Plateau, that is composed of clastic sedimentary bedrock mantled by glacial till and is deeply incised by many valleys. Most of the region drains generally southward to the Delaware, Susquehanna, or Allegheny Rivers; the major valleys were widened and deepened by continental ice sheets and now contain a few hundred feet of sediments deposited by or in meltwater as the ice sheets retreated. The northern fringe of the Appalachian Plateau drains northward to Lake Ontario or the Mohawk River; major valleys here were even more deeply incised by ice and are now filled largely with till and fine-grained lacustrine sediments. Hydrogeological studies that compiled and analyzed records of many wells and test borings concluded that highly productive aquifers composed of sand and gravel are commonly but discontinuously present in the south-draining major valleys but are less abundant in the north-draining valleys (Randall, 2001).

The water-yielding potential of bedrock in the uplands between the major valleys in the Appalachian Plateau of New York has not been systematically appraised. Wetterhall (1959) reported that wells penetrating bedrock throughout Chemung County averaged 100 feet in depth and 8 gallons per minute in yield. Hollyday (1969) analyzed the yield distribution of 55 wells less than 400 feet deep that penetrated bedrock in the Susquehanna River Basin of New York. Most of these wells were in major valleys where bedrock is typically overlain by 100 feet or more of glacial sediments, including basal gravel aquifers in many places (MacNish and Randall, 1982) that could help sustain the yield of wells tapping bedrock. Hollyday (1969) reported that 6 of the 55 wells yielded less than 10 gallons per minute, and that half of the remaining 49 wells yielded 60 gallons per minute or more. No studies that attempted to calculate the variation in water-transmitting capacity of bedrock in this region, or the flux through bedrock into gravel aquifers in major valleys, were identified in the literature.

The objectives of the study that led to this report were to (1) delineate to the extent feasible from the geological literature the variation in lithology, particularly grain size, of the bedrock in the Appalachian Plateau within or bordering the Susquehanna River Basin; (2) select or devise a procedure suitable for undertaking and analyzing brief, minimally invasive aquifer tests of domestic wells that tap bedrock; (3) test a representative sample of domestic wells that tap bedrock in this region, and analyze the test results to estimate transmissivity of bedrock at each well site; and (4) ascertain whether transmissivity varies as a function of bedrock grain size or topographic setting. Objective 2 was fully addressed by Klusman (1999, 2004) and Randall and Klusman (2004) and is summarized in this report. Objectives 1, 3, and 4 are addressed as fully as feasible in this report, which first describes the three predominant lithofacies in the upper few hundred feet of bedrock in the Appalachian Plateau of New York and depicts their distribution, then explains the criteria used to select the wells that were tested during this investigation. The report goes on to describe the selection and refinement of the procedure that was used to analyze the data from these brief aquifer tests, and to compile and interpret test results. Finally, the distribution of transmissivity values is compared to bedrock lithofacies and to the position of wells on hillsides.

Lithofacies Distribution in the Devonian Bedrock of the Appalachian Plateau of New York

The Middle and Upper Devonian bedrock of the Appalachian Plateau comprises a huge clastic wedge, referred to as the "Catskill Delta." Sediment was transported northwestward across Pennsylvania and New York; both grain size and thickness of sediment decrease to the northwest (Sevon, 1985, p. 80–81). The principal lithofacies and corresponding depositional environments within the Middle and Upper Devonian bedrock of New York (Rickard, 1975) may be summarized as follows, from coarsest to finest:

1. Catskill-Cattaraugus lithofacies: Shales, mudstones, siltstones, medium to coarse quartz sandstones and subgraywackes, pebbly sandstones; piedmont and alluvial floodplain and peritidal environment.

2. Chemung-Hamilton lithofacies: Shales, mudstones, siltstones, fine to medium sandstones, coquinites; laminated and crossbedded, abundant marine shelly fauna; diverse subtidal shelf and nearshore environments.

3. Portage-Marcellus lithofacies: Shales, mudstones, siltstones, rare fine sandstones and argillaceous limestones; open shelf and anaerobic basin environments.

These lithofacies are referred to hereafter in this report as the Catskill, Chemung, and Portage lithofacies. They grade into one another, and their areal distribution varied with time of deposition. No map that delineates in detail the distribution of these lithofacies in New York was available to this study. However, Rickard (1975, plate 3) graphed their distribution in time (formation by formation) and in space (topographic quadrangle by quadrangle). Comparison of Rickard's plate 3 with the bedrock geologic map of New York (Fisher and others, 1970; Rickard and Fisher, 1970) allowed lithofacies distribution to be approximately delineated (fig. 1). Also, several reports (Pepper and de Witt, 1950, 1951; Pepper and others, 1956; Colton and de Witt, 1958; Sutton, 1960; Dugolinsky, 1967) describe variations in lithology west of 76 or 77 degrees longitude within the Canadaway, West Falls, and Sonyea Groups, each of whose surficial extent is delineated on the Finger Lakes sheet (Rickard and Fisher, 1970) and Hudson-Mohawk sheet (Fisher and others 1970) of the "Geologic Map of New York." Other reports (Grossman, 1944; Williams, 1951; de Witt and Colton, 1959, 1978) similarly describe the Genesee Group west of 75 degrees longitude. These reports do not include maps of lithofacies distribution but do include multiple correlated stratigraphic columns that represent exposures, from which the predominant lithofacies in particular localities can be inferred. The information in these reports allowed some lithofacies boundaries within the Upper Devonian (fig. 1) to be placed somewhat more precisely than could be inferred from Rickard's correlation chart (1975, plate 3).

Selection of Wells for Testing

After the boundaries of the Catskill, Chemung, and Portage lithofacies were approximately delineated on the bedrock geologic map of New York, those boundaries were sketched onto topographic quadrangle maps encompassing the Susquehanna River Basin. Domestic wells suitable for testing were selected during field visits in the late 1990s according to the following criteria:

1. Sites near lithofacies boundaries were avoided as these boundaries were approximately delineated. Sites less than 3 miles south of such a boundary were also avoided because bedrock dips southward at an average slope of 51 feet per mile in the central Susquehanna River Basin (Wright, 1973, plate 2), such that deep wells near the lithofacies boundary might penetrate into the underlying lithofacies. Substantial areas near Oneonta (north half of Oneonta and West Davenport 7.5-minute topographic quadrangles, east half of Otego quadrangle) were eliminated because the approximate lithofacies boundaries were closely spaced, with the Oneonta Formation (Catskill lithofacies) beneath hilltops and three formations apparently deemed Chemung lithofacies by Rickard (1975) on valley sides.

2. Sites on ridge crests or near the top of steep slopes were avoided. Water levels in these areas fluctuated below the bottom of the casing more commonly than elsewhere and resulted in unsteady rates of recovery after pumping as the water level rose past open fractures or irregularities in well diameter. (Static water levels were not measured until the date of the test because prior measurement would have required a second extended period of non-use by the homeowner. Therefore, 18 wells with water levels below the casing are included in the dataset.)

3. Sites were in uplands, where bedrock is mantled by till. Sites low on the sides of major valleys that contain outwash deposited by glacial meltwater were avoided because water-level recovery might be sustained by recharge from a nearby gravel aquifer atop bedrock. (The presence of postglacial alluvium beneath flood-plains of nearby upland streams, which is typically only a few feet thick, was deemed acceptable.)

4. Clusters of wells were avoided. Each well selected was at least 500 feet from any nearby wells whose intermittent pumping might cause water-level fluctuations in the tested well (unless the nearby residence was normally unoccupied during the day).

5. A record from the well driller listing well depth, casing length, tested yield, and other pertinent well properties, prepared at the time of well drilling, was available. (For several wells, this information was obtained during a subsequent visit to the driller.)

6. The well head was accessible, and the homeowner was willing to ensure that the pump would operate only once, when called for during the test, over a period as long as 6 hours. (Scheduling the test when no one was at home was most convenient for the homeowner and for the test.)

7. Sites tested were widely separated to ensure sampling many different segments of each lithofacies.

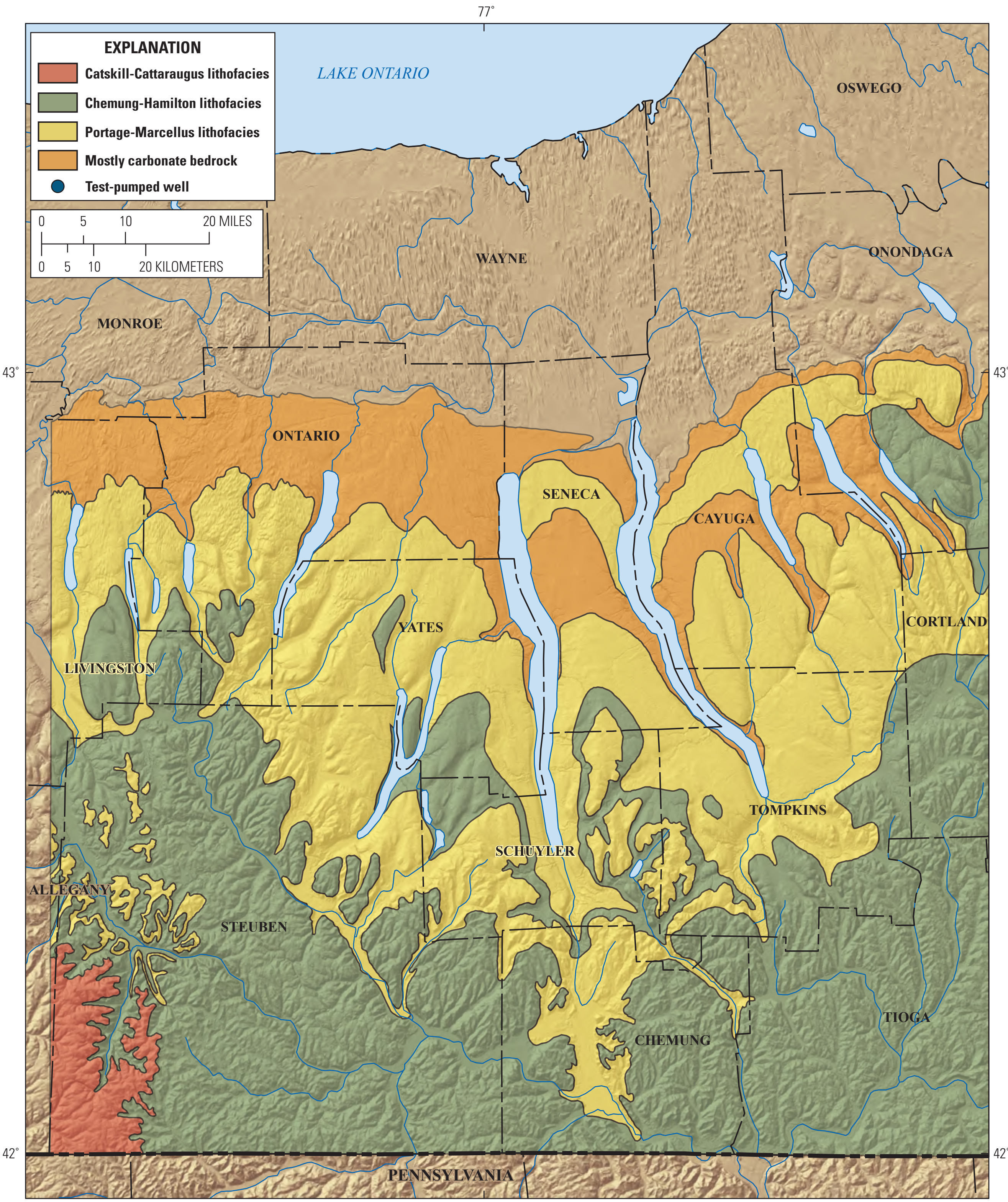
In Chenango County, most of the wells considered for testing were selected from well records published in U.S. Geological Survey (USGS) Water-Resources Investigations Report 91–4138 (McPherson, 1993). This report compiled records of many wells drilled in the late 1980s from well-completion reports submitted by drillers to the New York Department of Environmental Conservation. Most well locations (McPherson, 1993, plate 1) were determined by searching for the names of well owners on tax-parcel maps. Each potential well was visited during the present study before selection for testing. Several wells were determined to be mislocated by a few hundred feet to a few miles; the latitude, longitude, and elevation of each was corrected and entered in the USGS National Water Information System database (U.S. Geological Survey, 2019; https://waterdata.usgs.gov/nwis).

The original objectives of the present study included testing several wells that penetrated the Portage lithofacies in the northwestern part of the Susquehanna River Basin, but lack of time and resources prevented completion of this objective.

Selection of a Procedure for Analyzing Brief Aquifer Tests of Domestic Wells

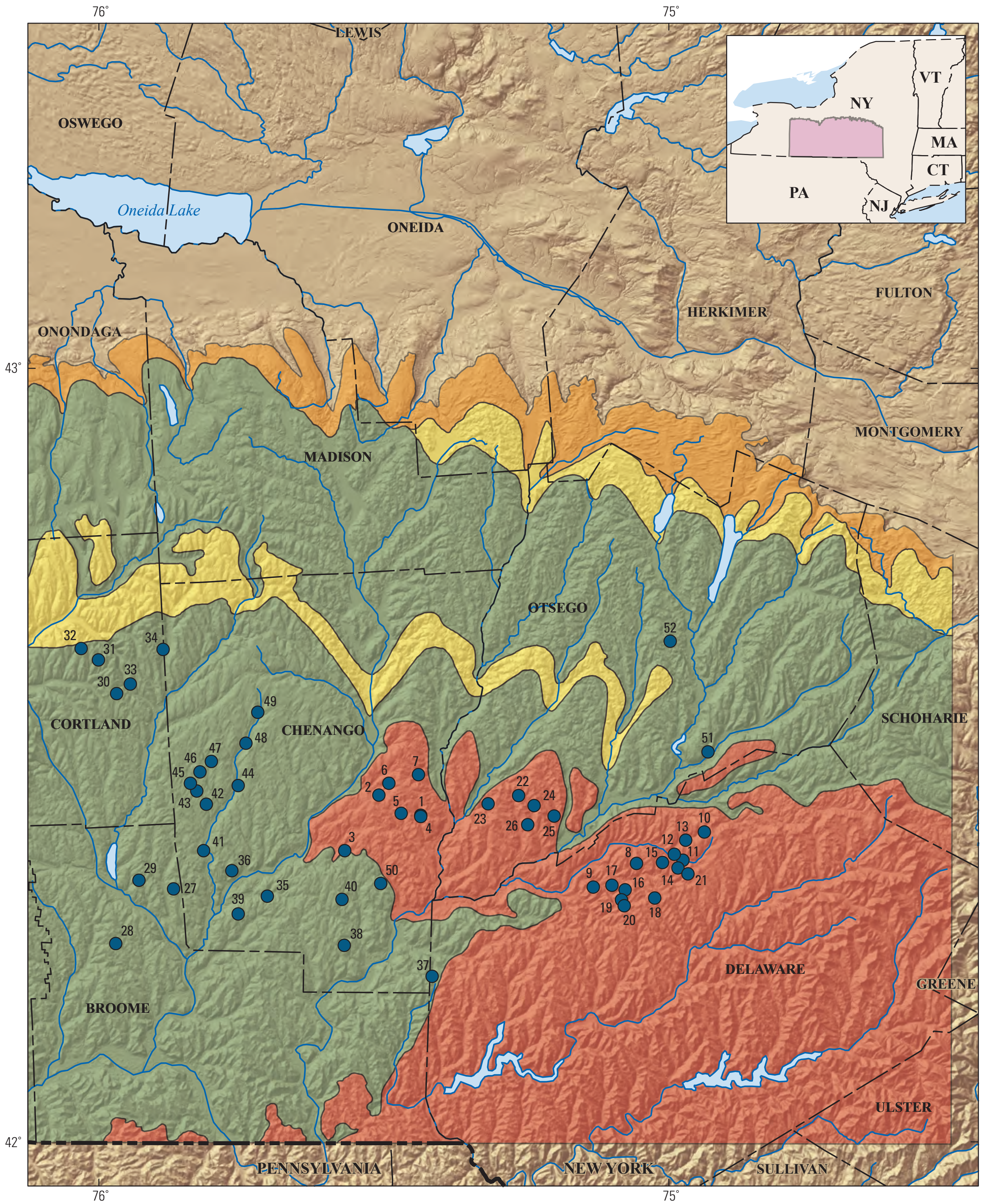
Numerous reports have implemented the method of Theis (1935) in analyzing transient drawdown around a pumped well to calculate aquifer transmissivity and storage, assuming well radius is small enough that storage in the well bore could be neglected. Papadopulos and Cooper (1967) developed an alternative equation that represents drawdown in the pumped well while accounting for storage in the well bore and published a lookup table of values of a term needed to solve that equation. Picking (1994) presented a procedure for estimating aquifer transmissivity and storage by analyzing water-level recovery in a pumped well following a brief period of pumping at an unknown constant rate; the only data required are the well radius, the times when pumping started and stopped, a series of water-level measurements at known times thereafter, and a value selected from the lookup table of Papadopulos and Cooper (1967). All the data required by Picking's procedure can be readily obtained from measurements during and following a brief episode of pumping of a domestic drilled well that taps bedrock.

In conjunction with the present investigation, Klusman (1999) wrote a computer program in Fortran, termed PICKINGmodel, that replicates Picking's procedure, except that instead of interpolating between values in a lookup table, it directly calculates the values needed, thereby eliminating a significant source of error. Klusman (1999) applied that program to tests of 14 domestic wells that tap bedrock in the Susquehanna River Basin of New York. Klusman (2004) described the theoretical basis, application, and limitations of the program. Randall and Klusman (2004) explained the procedure used for data collection and the advantages of this minimally disruptive method of testing domestic wells. They also reported values of transmissivity and storage coefficient generated by analyzing 26 brief aquifer tests with PICKINGmodel and showed that similar values were obtained by the slug-test procedure of Cooper and others (1967) and the discrete-kernel procedure of Mishra and Chachadi (1985), after minor modifications to accommodate the data from the brief aquifer tests. As pointed out by Randall and Klusman (2004), permission from homeowners to undertake these minimally disruptive tests of domestic wells is relatively easy to obtain because no water is poured into the well (as commonly done in slug tests), and the stress on the well is no more than occurs many times each day due to normal operation of the homeowner's pump. Also, the period of data collection, during which the homeowner can use only water already stored in the pressure tank or in buckets, can be as short as 2 hours (1 hour



Base from U.S. Geological Survey digital data, 2018
Web Mercator Auxiliary Sphere projection, World Geodetic System 1984 datum

Figure 1. Distribution of three lithofacies within the Middle and Upper Devonian bedrock of the Appalachian Plateau, and locations of domestic wells that were tested during this investigation.



Base from U.S. Geological Survey digital data, 2018
Web Mercator Auxiliary Sphere projection, World Geodetic System 1984 datum

Figure 1. Distribution of three lithofacies within the Middle and Upper Devonian bedrock of the Appalachian Plateau, and locations of domestic wells that were tested during this investigation.—Continued

to document the pre-test water-level trend and 1 hour to pump briefly and measure recovery). The current report presents tabulated values of aquifer transmissivity and storage coefficient estimated by applying PICKINGmodel to tests of 51 wells penetrating bedrock in the uplands of the Appalachian Plateau of New York and provides evaluations of the correlation of test results with bedrock lithofacies and position on hillsides.

To apply PICKINGmodel, the user estimates a trial value of transmissivity and several trial values of alpha (storage coefficient), from which the program calculates an array of type curves (one for each alpha value). Each type curve represents theoretical values of residual drawdown at multiple times since pumping stopped, each divided by drawdown at the moment pumping stopped (*Yg*/*Yp*), that would be expected from an aquifer with the postulated value of transmissivity and one of the postulated values of storage coefficient. The user must also plot a data curve in which each measured residual drawdown during recovery (*Yg)* is divided by drawdown at the moment pumping stopped *(Yp)* and plotted at the time since pumping stopped *(tg)*. The type curves and the data curve must be plotted on the same graph by using a suitable graphics package; the user can then estimate new trial values of transmissivity and alpha to generate new type curves until a satisfactory match to the data curve is obtained.

One objective of the selected protocol for brief aquifer tests is to generate values of transmissivity that could be applied (individually or averaged among multiple wells) to estimate groundwater flux under natural hydraulic gradients. Also, if a well is tested, then the test could easily be replicated in the future to ascertain whether nearby construction or excavation has affected the yield of that well. These test results should not be extrapolated to estimate maximum sustained well yield because prolonged or higher-rate pumping would likely result in dewatering of shallow fractures and (or) more turbulent flow in fractures, which would alter the ratio of drawdown to pumping rate.

Analysis of 51 Brief Aquifer Tests

A total of 51 domestic wells penetrating bedrock in the Appalachian Plateau, all within or immediately adjacent to the Susquehanna River Basin, were test-pumped between 1996 and 1999 for periods ranging from 13 to 132 seconds, following field procedures described by Randall and Klusman (2004). For each well tested, the observed record of water-level recovery after pump shutdown, expressed as residual drawdown divided by drawdown at the time of shutdown, was plotted against time in seconds since shutdown and compared with several type curves generated by PICKINGmodel (Klusman, 2004) that were based on trial values of transmissivity and storage coefficient. The trial values for the type curve that most closely matched the observed data are recorded in table 1. An additional well in table 1 (well CN 467, test 140) was test-pumped only for 10 minutes; that test was analyzed by methods described in Kruseman and deRidder (1990). Well dimensions are also summarized in table 1. Well locations are shown in figure 1. The input template for PICKINGmodel calls for pumping time (*tp*) and recovery time (*tg*) in seconds and trial transmissivity values in feet squared per second, which is appropriate for these brief tests. Table 1 reports best-fit transmissivity results in feet squared per second and in feet squared per day.

Drawdown and residual drawdown, based on measurements of water level every few seconds during most tests by a transducer and data logger and corrected for minor logger drift based on periodic taped measurements, are depicted in a companion USGS data release (Randall, 2020). Multiple spreadsheets and graphs that document which among several trial runs of PICKINGmodel best match the observed data are also included in the data release.

Table 1 indicates that in 23 of the 51 wells tested, the measured water-level recovery closely matched one of the trial type curves calculated by PICKINGmodel over the entire period of data collection, which was typically 3,500 to 10,000 seconds (58 to 167 minutes), as illustrated for two tests in figure 2. In another 23 wells, however, the measured values of residual drawdown matched a type curve for only the initial 15 to 1,000 seconds. Thereafter, the residual drawdown values decreased more gradually than the type curve and generally remained above the type curve to the end of the period of data collection, as illustrated for tests 124, 128, and 144 in figure 3. This behavior might be attributed to the cone of depression having expanded into a zone of lesser transmissivity due to decreased aperture or pinch-out of fractures at greater distances from the well. One well (OG 382, test 119) exhibited behavior like both groups, with drawdown matching the type curve for the first 110 seconds then flattening beyond 1,500 seconds. In four wells, by contrast, the late measured values of residual drawdown decreased *more* rapidly than the type curve fitted to the early values and generally reached zero residual drawdown 1,000 to 3,000 seconds after shutdown, as illustrated for test 137 in figure 3. This behavior could be attributed to the cone of depression having expanded into a zone of greater transmissivity at greater distances from the well. It should be possible to simulate, with an aquifer model or with image-well analysis, spatial and temporal variations in drawdown around a pumped well resulting from unknown variable extent and aperture of fractures, but water-level measurements at multiple sites would be needed for calibration. If some mathematical computation has been or could be developed to estimate change in effective transmissivity up to at least 10,000 seconds (167 minutes) from tests in which change in the rate of water-level recovery in the pumped well causes the data curve to flatten or steepen over time relative to PICKINGmodel type curves, that would enhance the applicability of test results.

As pointed out by Randall and Klusman (2004), these brief aquifer tests are easily arranged, undertaken, and analyzed by PICKINGmodel. If replicated at some later date, the tests could verify precisely whether any change in well

Table 1. Well properties and pumping test data for 52 domestic wells penetrating bedrock in or adjacent to the Susquehanna River Basin in the Appalachian Plateau of New York.

[USGS, U.S. Geological Survey; no., number; ID, identifier; ft, foot; gal/min, gallon per minute; gal/min/ft, gallon per minute per foot; s, second; ft²/s, foot squared per second; ft²/d, foot squared per day]

Map no. (fig. 1)	Lithofacies	USGS well no.	National Water Information System site ID[a]	Pumping test no.	From driller's report: Depth (ft)	Casing length (ft)	Yield (gal/min)	Test data: Specific capacity[b] (gal/min/ft)	Depth to water at: Start[c]	Shut-down	Pumping duration (s)	Analysis by PICKINGmodel: Transmissivity (ft^2/s)	Transmissivity (ft^2/d)	Data match to type curve (s)[d]	Storage coefficient	Topographic position on hillside
1	Catskill	CN 139	422527075263601	125	132	16	18	1.65	52.8	56.7	45	0.00045	38.88	F 3–250	0.03	Middle
2	Catskill	CN 357	422703075310101	141	200	30	--	0.078	[e]70.2	76	51	0.0002	17.28	P 1–200	0.0000001	Middle
3	Catskill	CN 474	422255075344201	117	149	21	7.5	0.0019	8.8	12.1	40	0.00036	31.104	C 5–8,000	0.001	--
4	Catskill	CN 511	422525075263301	124	100	22	4	0.92	44.2	46.1	25	0.0012	103.68	F 20–150	0.001	Upper
5	Catskill	CN 516	422539075283801	118	198	23	6	0.2	56.9	61.2	53	0.00032	27.648	C 5–3,500	0.0001	Middle
6	Catskill	CN 557	422751075300401	120	148	31	12+	0.8	21.2	25.2	41	0.00045	38.88	C 3–10,000	0.1	Lower
7	Catskill	CN 577	422850075340801	121	143	115	7	0.097	74	83.2	99	0.00007	6.048	F 70–1,500	0.1	Middle
8	Catskill	D 349	422148075035301	102	170	30	20	1	68.9	71.7	84	0.0008	69.12	F 6–20	0.1	Middle
9	Catskill	D 350	421956075082401	101	165	72	10	0.24	21.7	29.2	84	0.00029	25.056	C 6–10,000	0.001	Upper
10	Catskill	D 354	422415074564301	110b	90	60	10	1	30.9	33.2	36	0.0004	34.56	F 6–70	0.1	Middle
11	Catskill	D 355	422202074585901	113	255	15	3.5	0.3	90	92.3	110	0.0003	25.92	F 15–55[fg]	0.1	Lower
12	Catskill	D 357	422230074595401	105	298	53	8	0.8	41.3	44.7	66	0.00184	158.976	C 6–>2,000	0.00001	Lower
13	Catskill	D 358	422336074584301	103	173	50	180	3.1	12.9	13.9	66	0.005	432	F 5–40	0.1	Lower
14	Catskill	D 359	422127074293101	106	115	107	15	0.9	55.3	59.7	66	0.00172	148.608	F 6–200	0.0001	Middle
15	Catskill	D 366	422152075010801	107b	135	85	--	0.9	8.7	12.5	95	0.00167	144.288	C 5–>2,400	0.0001	Lower
16	Catskill	D 367	421945075050401	109b	213	106	--	1.3	45.7	49.2	68	0.0007	60.48	F 4–60	0.2	Middle
17	Catskill	D 375	422006075062601	112	165	125	10	0.32	43.6	51.2	132	0.00028	24.192	C 6–800,>3,000	0.01	Middle
18	Catskill	D 376	421905075015701	111	198	20	3	0.28	39.6	44.6	104	0.00008	6.912	C 1–10,000	0.0001	Middle
19	Catskill	D 385	421858075052801	122	225	180	9	0.0004	11.8	18.7	74	0.00084	72.576	F 2–950	0.000003	Middle
20	Catskill	D 388	421830075051001	128	185	10	8	1.2	67.8	71	90	0.0038	328.32	F 7–150	0.000001	Lower
21	Catskill	D 390	422059074582601	108	180	10	8	0.32	75.9	80.9	54	0.00067	57.888	C 6–>5,400	0.00001	Middle
22	Catskill	OG 378	422702075161801	116	175	95	5	0.22	9.5	11.7	30	0.0002	17.28	C 6–>7,800	0.001	Lower
23	Catskill	OG 379	422623075193101	127b	127	87	--	3.5	8.6	9.9	57	0.0025	216	C 5–3,500	[h]0.5	Middle
24	Catskill	OG 380	422617075143901	302b	175	20	--	0.33	26.3	30.5	58	0.0002	17.28	F 1–150	0.15	Middle
25	Catskill	OG 381	422528075123301	115	189	61	6	0.4	49.8	51.8	72	0.000205	17.712	C 6–>7,400	0.1	Lower
26	Catskill	OG 382	422446075151901	119	440	25	--	0.032	51.4	55.3	[i]64	0.00001 0.00001	0.864 0.864	F 1–110 C 1,500–8,000	0.1 0.01	Lower
27	Chemung	BM2578	421943075523501	145	100	15	5	0.47	12.2	17.2	42	0.0007	60.48	C 1–5,573	0.0001	Lower

Table 1. Well properties and pumping test data for 52 domestic wells penetrating bedrock in or adjacent to the Susquehanna River Basin in the Appalachian Plateau of New York.—Continued

[USGS, U.S. Geological Survey; no., number; ID, identifier; ft, foot; gal/min, gallon per minute; gal/min/ft, gallon per minute per foot; s, second; ft^2/s, foot squared per second; ft^2/d, foot squared per day]

Map no. (fig. 1)	Lithofacies	USGS well no.	National Water Information System site ID [a]	Pumping test no.	From driller's report: Depth (ft)	Casing length (ft)	Yield (gal/min)	Test data: Specific capacity[b] (gal/min/ft)	Depth to water at: Start[c]	Shutdown	Pumping duration (s)	Transmissivity (ft^2/s)	Analysis by PICKINGmodel: Transmissivity (ft^2/d)	Data match to type curve (s)[d]	Storage coefficient	Topographic position on hillside
28	Chemung	BM2579	421529075584101	146	93	29	20	6.7	7.8	10.5	55	0.002	172.8	F 1–25	0.1	Middle
29	Chemung	BM2580	422023075560501	144	125	40	--	2	12.1	14.2	24	0.002	172.8	F 2–43	0.05	Middle
30	Chemung	C 466	423455075584101	147	197	19	5.5	0.265	35.4	39.9	60	0.0004	34.56	C 1–2,000	0.0001	Middle
31	Chemung	C 484	423721076003901	150	104	47	6	0.73	17.2	22.5	99	0.0003	25.92	F 1–70	0.15	Middle
32	Chemung	C 504	423822076022801	149	162	20	6	0.46	20.2	23.1	33	0.00035	30.24	C 2–8,000	0.01	Middle
33	Chemung	C 536	423537075571601	151	248	55	30	0.64	94.6	97.3	41	0.0004	34.56	F 20–350	0.03	Lower
34	Chemung	C 541	423817075540801	148	180	20	7	0.47	62.8	68.2	62	0.00013	11.232	C 1–10,000	0.25	Middle
35	Chemung	CN 158	421911075424401	123	198	85	--	1.16	69.3	74.1	105	0.0018	155.52	F 5–140	0.001	Upper
36	Chemung	CN 23	422109075462901	153	190	12	6	0.11	34.8	42.1	107	0.000035	3.024	C 1–5,000	0.05	Lower
37	Chemung	CN 331	421259075252101	129	185	93	5	0.4	83.2	91.1	60	0.00025	21.6	C 160–1,800[f]	0.01	Middle
38	Chemung	CN 337	421522075343801	137	223	43	10	0.33	0	5.7	48	0.0005	43.2	P 1–600	0.0001	Lower
39	Chemung	CN 352	421713075454101	143	117	24	5	0.13	14.2	19.2	118	0.0001	8.64	C 3–10,000	0.01	Upper
40	Chemung	CN 399	421910075323401	126	247	31	3.5	0.23	43	47.8	58	0.00075	64.8	F 3–1,000	0.0000001	Upper
41	Chemung	CN 467	422242075492601	140	188	59	10	0.045	17.1	22.9	125	0.00005	4.29	j	0.2	Middle
42	Chemung	CN 525	422620075491501	134	173	49	5	0.15	46.9	53.9	80	0.000082	7.0848	F 1–900	0.01	Upper
43	Chemung	CN 547	422720075501701	133	150	67	20	12	50.1	51.6	59	0.0335	2894.4	F 3–15	0.00001	Middle
44	Chemung	CN 556	422749075454501	139	198	123	17.5	0.6	79.1	83.2	74	0.0006	51.84	F 1–200	0.01	Middle
45	Chemung	CN 560	422759075505401	136	175	93	20	4.8	37.7	39.6	43	0.009	777.6	F 1–56	0.001	Upper
46	Chemung	CN 578	422850075495001	135	200	170	15	2.5	9	11.7	59	0.008	691.2	C 2–3,300	0.000001	Middle
47	Chemung	CN 606	423043075514701	142	116	44.3	10	0.45	41.4	41.9	[k]13	0.00127	109.728	C 3–1,000	0.002	Middle
48	Chemung	CN 612	423108075445701	132	124	32	8	4.7	16.8	[l]17.8	80	0.008	691.2	C 1–600	0.1	Lower
49	Chemung	CN 641	423328075433301	130	197	65	20	2.1	41	44.1	91	0.0034	293.76	C 3–3,500	0.01	Upper
50	Chemung	CN 69	422011075304701	131	160	68	10+	0.7	37.2	42.3	71	0.0008	69.12	F 2.5–85	0.01	Middle
51	Chemung	OG 376	423029074562201	200	169	13	--	0.28	0.2	2.8	70	0.000098	8.4672	P 10–1,500	0.1	Middle
52	Chemung	OG 377	423903075002201	100	112	10	--	0.49	0	3.7	52	0.00043	37.152	P 5–400	0.01	Middle

Table 1. Well properties and pumping test data for 52 domestic wells penetrating bedrock in or adjacent to the Susquehanna River Basin in the Appalachian Plateau of New York.—Continued

[USGS, U.S. Geological Survey; no., number; ID, identifier; ft, foot; gal/min, gallon per minute; gal/min/ft, gallon per minute per foot; s, second; ft^2/s, foot squared per second; ft^2/d, foot squared per day]

Map no. (fig. 1)	Lithofacies	USGS well no.	National Water Information System site ID[a]	Pumping test no.	From driller's report			Test data				Analysis by PICKINGmodel				Topographic position on hillside
					Depth (ft)	Casing length (ft)	Yield (gal/min)	Specific capacity[b] (gal/min/ft)	Depth to water at Start[c]	Depth to water at Shut-down	Pumping duration (s)	Transmissivity (ft^2/s)	Transmissivity (ft^2/d)	Data match to type curve (s)[d]	Storage coefficient	

[a]Site ID consists of degrees, minutes, and seconds of latitude (6 digits) followed by degrees, minutes, and seconds of longitude (7 digits) followed by a serial number to distinguish multiple wells at the same location (01 for each well in this table).

[b]Water-level recovery between first 2 or 3 measurements after shutdown, extrapolated to rate in 1 minute, times 1.5 gallons per foot (in 6-inch casing), divided by distance from prepumping water level to midpoint of recovery interval.

[c]In most tests, water level at start of pumping was rising slowly in response to earlier pumping in that well or wells nearby. Water levels are reported to the nearest 0.1 ft below land surface.

[d]Data match to type curve: C, complete match throughout measured range of recovery data; F, data curve flattens (slopes more gently than type curve) beyond range listed; P, data curve plunges (slopes much more steeply than type curve) beyond range listed.

[e]Depth to water measured July 31, 1998, immediately before test. On May 14, 1998, depth to water was 64.0 feet, and a small amount of water entered at about 53 feet.

[f]No data logger; water level measured manually with electric tape.

[g]Poor match to PICKINGmodel type curve.

[h]A storage coefficient of 0.5 is implausible for fractured bedrock, but other analytical methods also indicate large storage. Perhaps a sand lens atop bedrock sustains well yield?

[i]Drawdown and recovery were briefly slowed by draining and refilling of a cavity between 53.8 and 54.1 depth. Pumping time was reduced by 20 seconds and segments of the recovery hydrograph before and after the cavity were merged to allow PICKINGmodel analysis.

[j]PICKINGmodel not used. Transmissivity and storage coefficient are from analysis of subsequent 10-minute test. Sediment 4 to 6 feet thick on bottom of well may have restricted yield from a near-basal fracture.

[k]Actual duration of pumping was 56 seconds. However, an apparent cavity at or slightly below the end of the casing slowed drawdown and recovery in this depth interval. Therefore, analysis was limited to the first 13 seconds of drawdown merged with the (much later) recovery within the casing.

[l]Depth to water was stable for 20 seconds immediately before shutdown due to smaller pumping rate as pressure tank filled.

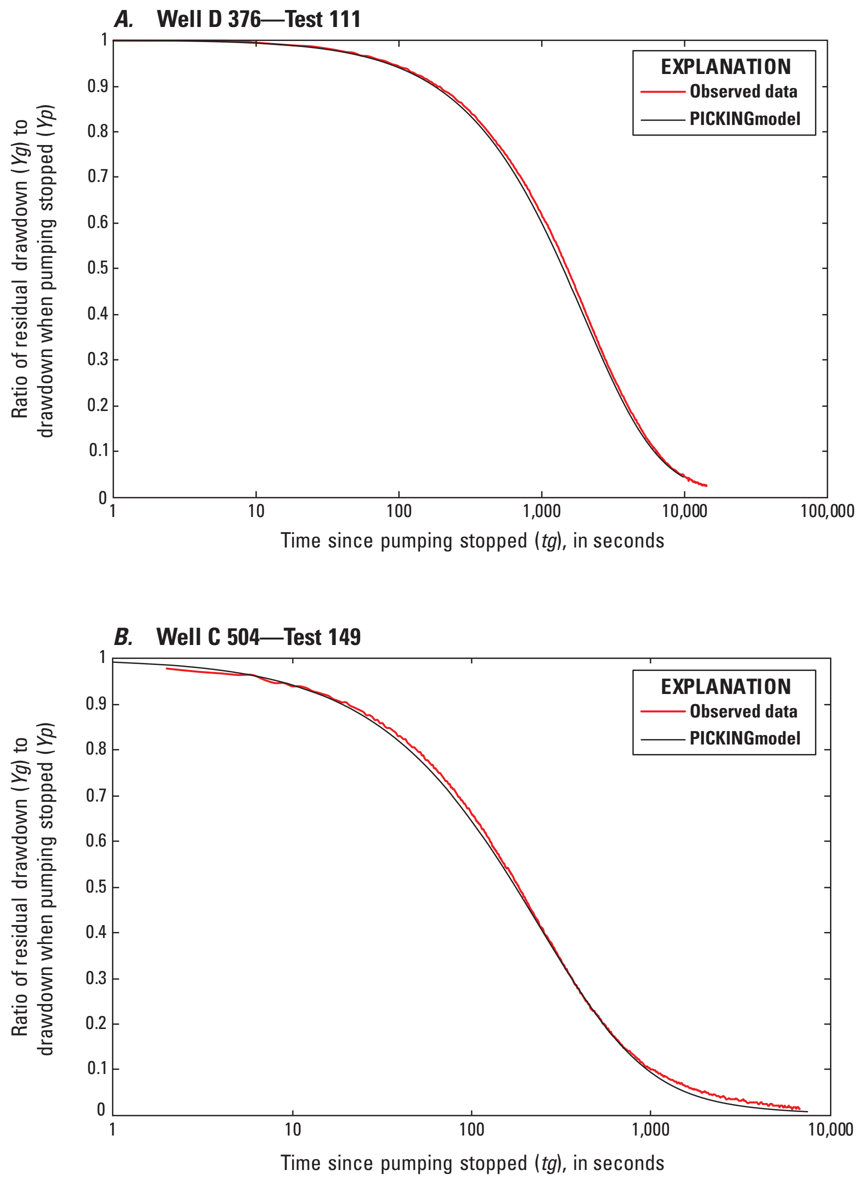


Figure 2. Observed water-level recovery compared to PICKINGmodel type curves for tests 111 and 149 of two domestic wells in the Appalachian Plateau of New York. Test data fit type curves over the entire range of data collection.

performance has occurred. Transmissivity values computed from these tests may be suitable for estimating flow under natural gradients, including flow through bedrock to valley-fill aquifers. They would not be suitable for estimating maximum sustainable yield to individual wells or well clusters because about half the tests in this study documented reductions in recovery rate and transmissivity within a few minutes of the start of stress, presumably due to constrictions in water-yielding fractures several feet or more from the pumped well. Prolonged pumping stress from individual wells or overlapping stresses within well clusters could be expected to intersect more flow boundaries and to dewater some shallow fractures.

Longer Aquifer Tests of Five Wells

Four of the 51 wells that were pumped briefly for analysis by PICKINGmodel and one additional well (CH 467, test 140) were pumped for longer periods of 10 to 32 minutes, shortly before or after a brief test analyzed by PICKINGmodel. These longer tests were analyzed by the Theis recovery method (Kruseman and deRidder, 1990, p. 194–195). Transmissivities calculated from the longer tests, as well as the data timespans from which the transmissivities were calculated, are compared with results from PICKINGmodel in table 2.

Transmissivities calculated from the brief test and the longer test of well 143 are nearly identical, and for wells 132 and 133 the brief tests and the longer tests seem reasonably consistent (albeit for different reasons). The measured water-level recovery from brief test 132 fits a PICKINGmodel type curve closely throughout the timespan of measured recovery, as shown in figure 4. (During brief test 132, the logger was set to record water levels only at 5-second intervals, but manual graphing of the data allowed estimation of the shutdown time to the nearest second, also values of *tg* and *Yg*/*Yp* at four times during the first 10 seconds of

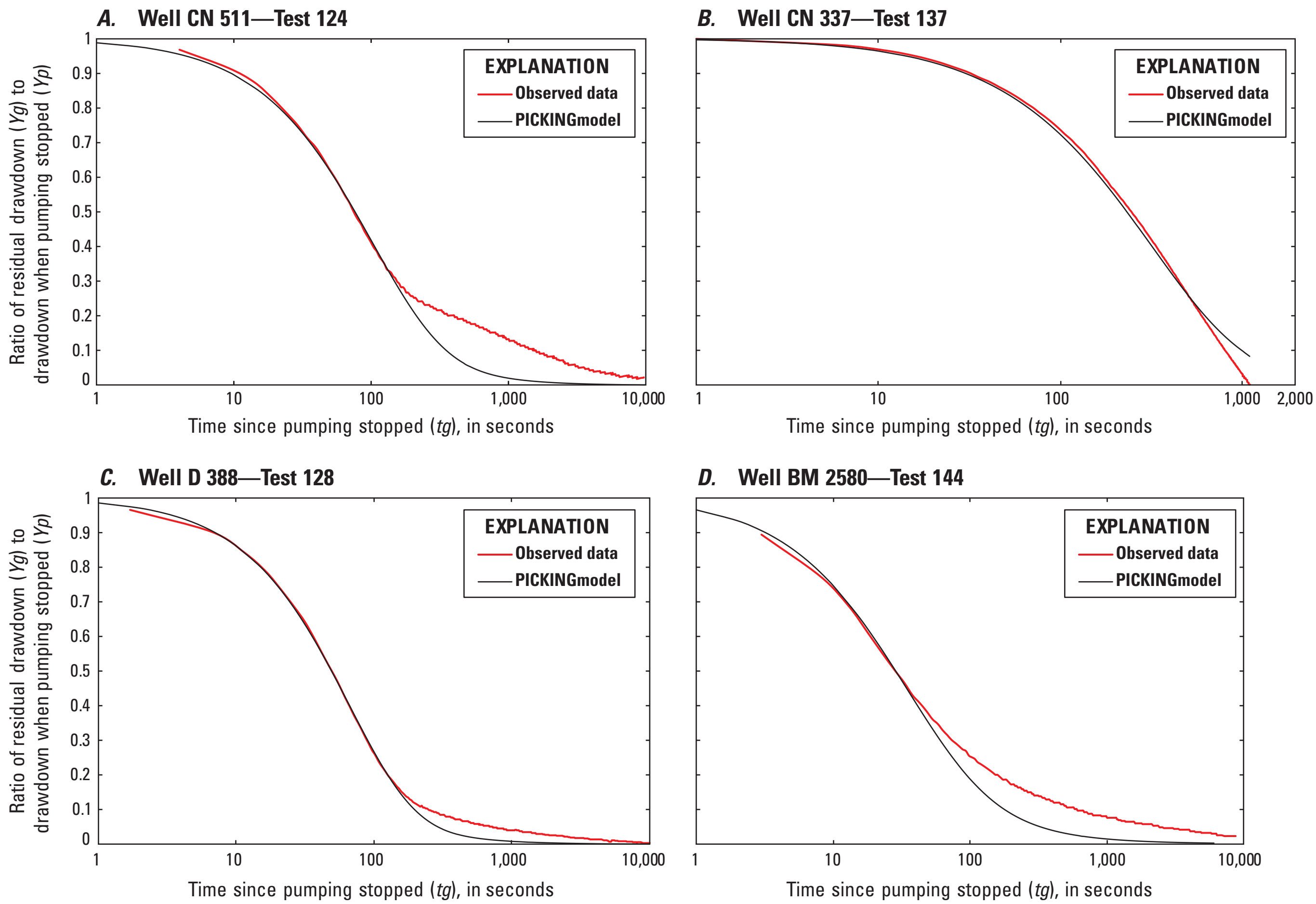


Figure 3. Observed water-level recovery compared to PICKINGmodel type curves for tests 124, 128, 137, and 144 of domestic wells in the Appalachian Plateau of New York. Early test data fit type curves, but later test data slope more gently (tests 124, 128, and 144) or more steeply (test 137) than the type curve matched to the early data.

Table 2. Comparison of analyses of brief pumping tests by PICKINGmodel with analyses of longer tests by Theis recovery method for four domestic wells penetrating bedrock in the Appalachian Plateau of New York.

[ft^2/s, foot squared per second; α, alpha; t/t', time since start of pumping divided by time since start of recovery]

Parameters measured	Test 132	Test 133	Test 135	Test 143
PICKINGmodel				
Duration of pumping (seconds)	80	59	59	125
Duration of measured recovery (seconds)	2,480	3,780	3,800	10,000
Transmissivity (ft^2/s)	0.008	0.0335	0.008	0.0001
Storage coefficient (α)	0.1	0.00001	0.000001	0.01
Duration of data fit to type curve (seconds)	1–600 and more	3–18 (above curve 18 to 1,000 and beyond)	2 to 3,300	3 to 10,000
Theis recovery method				
Duration of pumping (seconds)	780	615	638	1,920
Duration of measured recovery (seconds)	7,970	18,285	3,760	12,045
Transmissivity (ft^2/s)	0.0061	0.0115	0.00093	0.00014
Timespan of straight-line portion of graph of residual drawdown versus t/t' whose slope defines transmissivity (seconds)	30–7,970	20–165 (steeper curved line 165–1,125)	22–72	1,486–6,048

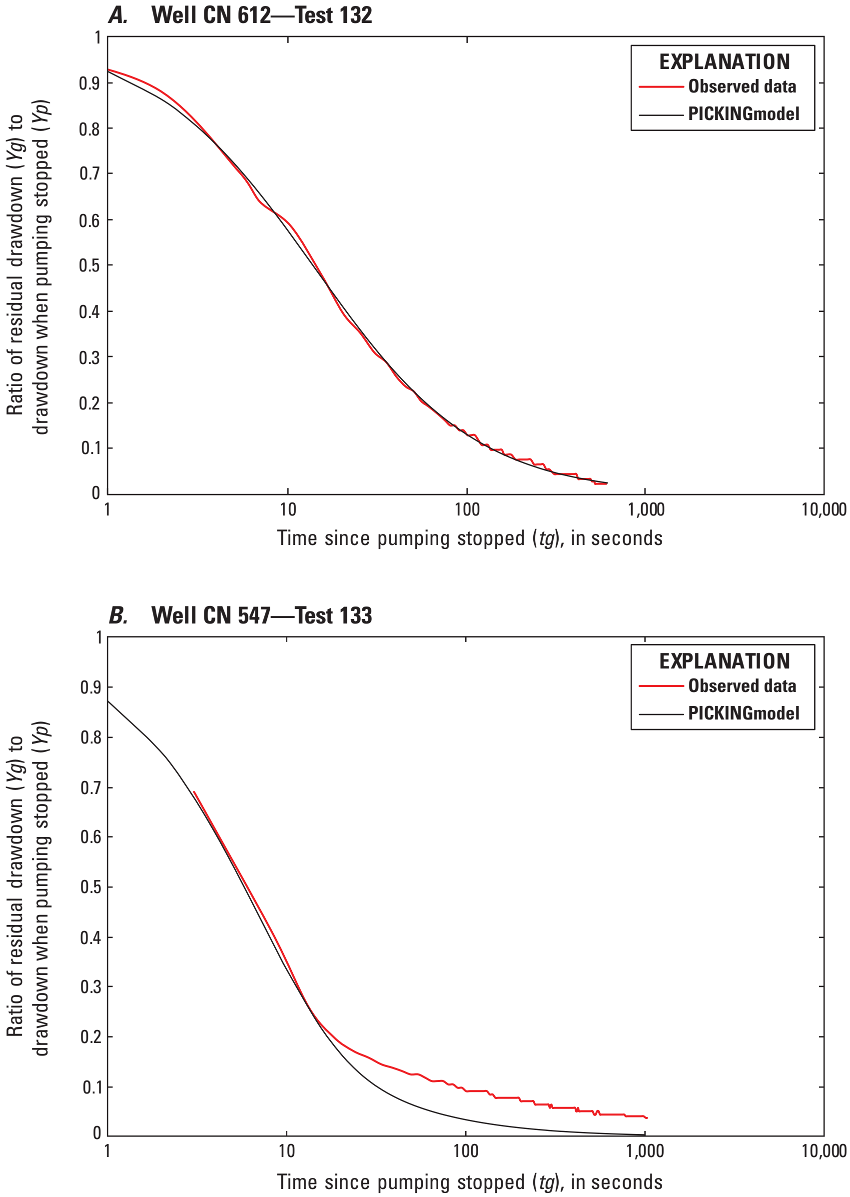


Figure 4. Water-level recovery compared to PICKINGmodel type curves for brief tests 132 and 133 of wells CN 612 and CN 547, respectively, in the Appalachian Plateau of New York. These wells were later test-pumped for 10 to 13 minutes.

recovery.) Transmissivity estimated by PICKINGmodel from brief test 132 differs by only a factor of 1.3 from transmissivity calculated from recovery measurements over the entire timespan of data collection during the longer test (table 2). PICKINGmodel accounts for storage of water in the well bore (Klusman, 2004), which may allow a more accurate interpretation of water-level rise measured in the pumped well during the first several seconds of recovery than allowed by the Theis recovery method, which assumes the diameter of the well to be infinitely small (Kruseman and deRidder, 1990, p. 56).

The measured recovery from brief test 133 matched a PICKINGmodel type curve for only the first 18 seconds of recovery, then gradually departed from that type curve and remained above it throughout the remainder of the period of data collection (fig. 4). This behavior might be attributed to a transition to smaller transmissivity values a short distance outward from the well, caused by narrowing or pinch-out of one or more water-yielding fractures—and, indeed, the transmissivity estimated from data for 20 to 165 seconds of recovery in the longer test is about one-third of the transmissivity estimated by PICKINGmodel from data for 3–17 seconds of recovery.

Transmissivity estimated by PICKINGmodel from brief test 135 is 8.6 times the transmissivity estimated from a 10.6-minute test of the same well by the Theis recovery method (table 2). Brief tests of other wells were not supplemented by 10 to 30-minute tests, chiefly because nearly all the wells tested were used for domestic water supply; minimizing the interruption of service was often helpful in obtaining permission from the homeowner to test.

Comparison of PICKINGmodel to PPC-Recovery

Mills (2010, 2019) devised a computer program, termed PPC-Recovery, which is also based on the procedure of Picking (1994) and can be used to analyze brief recovery tests. PPC-Recovery also requires the user to estimate several transmissivity and alpha values and to supply an array of *tg* and *Yg*/*Yp* data values; then the program automatically compares the type curve defined by each pair of transmissivity and alpha values with the array of data values and calculates the sum of the residuals squared for each such match. This method eliminates the subjective judgement inherent in visual curve-matching and evaluates multiple alternative transmissivity and alpha options in less time than a single set of type curves can be calculated by PICKINGmodel, graphed, and evaluated. As part of this study, however, half of the brief aquifer tests conducted had already been evaluated (Randall and Klusman, 2004) using PICKINGmodel. Also, visual displacement of the latter part of some type curves from PICKINGmodel data curves, discussed in the report section "Analysis of 51 Brief Aquifer Tests," provided some insight into the potential factors influencing the drawdown curve that would not be obvious from the test results (sum of residuals squared) provided by PPC-Recovery. Accordingly, PICKINGmodel was used to analyze all aquifer tests in this report.

Subsequently, as a verification check, field measurements for most tests were analyzed with the PPC-Recovery program; transmissivities calculated by PICKINGmodel and PPC-Recovery for the tests in table 3 differed by 0 to 58 percent, with a median percentage difference of 8 percent and a mean of 14 percent. The pairs of transmissivities differed by less than 20 percent for 36 of the 50 tests. Application of the sign test (Gilbert, 1987) to all of these tests indicated that the transmissivity estimates by PICKINGmodel were not significantly different from estimates by PPC-Recovery at a probability of 95 percent.

As explained in the section "Analysis of 51 Brief Aquifer Tests," for 23 of the wells test-pumped for this study, PICKINGmodel generated type curves that fit the entire range of water-level recovery measurements, over as many as 10,000 seconds. These tests are identified by the letter C in the column "Range of data, in seconds, that fit a type curve" in table 3. Transmissivities calculated by PICKINGmodel and PPC-Recovery differed by less than 20 percent for 16 of these 23 tests. PICKINGmodel estimates were higher than PPC-Recovery estimates for 9 tests, lower for 12 tests, and equal for 2 tests. For another 23 tests, identified by the letter "F" in table 3, only the first 18 to 1,500 seconds of data fit a PICKINGmodel type curve; thereafter, the data curve sloped more gently than the type curve. For these 23 tests, PICKINGmodel estimates of transmissivity were higher than PPC-Recovery estimates for 10 tests, lower for 12 tests, and equal for 1 test; estimates differed by less than 20 percent for 20 of these 23 tests. Application of the sign test (Gilbert, 1987) individually to the "C" and "F" subsets indicated that transmissivity estimates by PICKINGmodel were not significantly different from estimates by PPC-Recovery, at a probability of 95 percent. For each of the tests in table 3, PPC-Recovery was constrained to analyze data from the same time interval that was analyzed by PICKINGmodel. The closely comparable results demonstrate that the two methods are mathematically consistent. However, transmissivities calculated by either method from data for time intervals of 120 seconds or less may be of limited practical value because they apply only to a small volume of bedrock close to the pumped well.

The data for 10 of the 23 "F" type tests, in which only the first 18 to 204 seconds fit a PICKINGmodel type curve, were further analyzed by applying the PPC-Recovery method to 5 or 6 alternative time intervals during recovery. For each well tested, at least 10 data points were analyzed, and the data in table 4 are listed in order of increasing length of time analyzed. For each of these wells, as the analyzed time interval lengthened, the calculated transmissivity decreased somewhat, while the sum of residuals squared per data point increased, which indicates a progressively slightly poorer fit of the longer arrays of data to the best-fit PPC-Recovery type curves. These results are interpreted to indicate that (1) the cone of depression had expanded into a zone of lower transmissivity, in agreement with the interpretation of PICKINGmodel results in the text, and (2) as longer timespans encompassed a greater proportion of low-transmissivity bedrock, type curves computed from single transmissivity values became less able to fit both early and late recovery data, so the sums of squared residuals per data point increased.

Results demonstrate that when PPC-Recovery is applied to the same data interval as PICKINGmodel, the resulting estimates of transmissivity and storage are generally quite similar. This similarity indicates that the two procedures are computationally consistent and provides independent verification that PICKINGmodel is a mathematically sound adaptation of the procedure devised by Picking (1994).

Test Results Compared With Bedrock Lithofacies

Of the 52 wells tested, 26 penetrated bedrock assigned to the Catskill lithofacies, while 26 penetrated the Chemung lithofacies. The distributions of transmissivity values calculated for wells in these two lithofacies are shown in figure 5. Both distributions are similar, although 15 percent of the transmissivity values in the Chemung lithofacies exceeded 0.005 foot squared per second, which was the largest value in the Catskill lithofacies. The median value among all wells tested was 0.000425 foot squared per second in the Catskill lithofacies and 0.00055 foot squared per second in the Chemung lithofacies. Application of the Wilcoxon rank sum test (U.S. Environmental Protection Agency, 2006) indicated that at a probability of 95 percent these two median values

Table 3. Comparison of recovery test results using two methods, for wells penetrating bedrock in the Appalachian Plateau of New York.

[ft, foot; ft^2/s, foot squared per second]

U.S. Geological Survey well number	Pumping test number	Well depth (ft)	Analysis by PICKINGmodel			Analysis by PPC-Recovery[b]			Percent difference in transmissivity between two methods
			Transmis-sivity (ft^2/s)	Storage coefficient	Range of data, in seconds, that fit a type curve[a]	Transmis-sivity (ft^2/s)	Storage coefficient	Sum of residuals squared per data point	
OG 377	TEST 100	112	0.000430	0.01	P 5–400	0.00044	0.01	0.000030	2.3
D 350	TEST 101	165	0.000290	0.001	C 6–9,700	0.00027	0.002	0.000051	6.9
D 349	TEST 102	170	0.0008	0.1	F 6–24	0.00079	0.1	0.000080	1.3
D 358	TEST 103	173	0.005	0.1	F 6–42	0.0050	0.008	0.00015	0.0
D 357	TEST 105	298	0.00184	0.00001	C 6–>2,000[c]	0.0029	0.00000001	0.0000017	58
D 359	TEST 106	115	0.00172	0.0001	F 6–200	0.0016	0.0002	0.0000076	7.0
D 366	TEST 107b	135	0.00167	0.0001	C 5–>2,400[c]	0.0019	0.00002	0.000012	14
D 390	TEST 108	180	0.00067	0.00001	C 6–>5,400	0.00064	0.00002	0.0000024	4.5
D 367	TEST 109b	213	0.0007	0.2	F 4–64	0.00081	0.1	0.000047	16
D 354	TEST 110b	90	0.0004	0.1	F 6–70	0.00041	0.1	0.000058	2.5
D 376	TEST 111	198	0.00008	0.0001	C 1–10,000	0.000075	0.0001	0.000011	6.3
D 375	TEST 112	165	0.00028	0.01	C 6–800	0.00028	0.01	0.000013	0.0
OG 381	TEST 115	189	0.000205	0.1	C 6–>7,400[c]	0.000208	0.01	0.000015	1.5
OG 378	TEST 116	175	0.0002	0.001	C 6–>7,800[c]	0.00016	0.004	0.000013	20
CN 474	TEST 117	149	0.00036	0.001	C 5–8,000	0.00036	0.001	0.000007	0.0
CN 516	TEST 118	198	0.00032	0.0001	C 5–3,500	0.00036	0.00002	0.000011	13
OG 382	TEST 119	440	0.00001	0.1	F 4–110	0.000012	0.08	0.000023	20
CN 557	TEST 120	148	0.00045	0.1	C 3–9,400	0.00047	0.1	0.000047	4.4
CN 577	TEST 121	143	0.00007	0.1	F 70–1,500	0.000069	0.1	0.000045	1.4
D 385	TEST 122	225	0.00084	0.000003	F 2–950	0.0011	0.00000006	0.000046	31.0
CN 158	TEST 123	198	0.0018	0.001	F 5–140	0.0015	0.01	0.000073	17
CN 511	TEST 124	100	0.0012	0.001	F 20–150	0.0013	0.0008	0.000037	8.3
CN 139	TEST 125	132	0.00045	0.03	F 3–250	0.00041	0.06	0.000023	8.9
CN 399	TEST 126	247	0.00075	0.0000001	F 4–1,000	0.0010	0.0000000004	0.000079	33
OG 379	TEST 127b	127	0.0025	0.2	C 5–3,500	0.0027	0.1	0.00011	8.0
D 388	TEST 128	185	0.0038	0.000001	F 7–150	0.0041	0.0000004	0.000015	7.9
CN 331	TEST 129	185	0.00025	0.01	C 160–1,800	0.00027	0.008	0.0000080	8.0
CN 641	TEST 130	197	0.0034	0.01	C 3–3,500	0.0032	0.02	0.0000034	5.9
CN 69	TEST 131	160	0.0008	0.01	F 2.5–86	0.00069	0.02	0.0000034	14
CN 612	TEST 132	124	0.008	0.1	C 1–600	0.0082	0.1	0.000036	2.5
CN 547	TEST 133	150	0.0335	0.00001	F 3–18	0.032	0.00001	0.000040	4.5
CN 525	TEST 134	173	0.000082	0.01	F 3–900	0.000087	0.008	0.000021	6.1
CN 578	TEST 135	200	0.008	0.000001	C 2–3,300	0.010	0.00000001	0.000083	25
CN 560	TEST 136	175	0.009	0.001	F 1–70	0.0091	0.002	0.00029	1.1
CN 337	TEST 137	223	0.0005	0.0001	P 1–600	0.00076	0.0000002	0.000022	52
CN 556	TEST 139	198	0.0006	0.01	F 3–200	0.00053	0.02	0.0000088	12

Table 3. Comparison of recovery test results using two methods, for wells penetrating bedrock in the Appalachian Plateau of New York.—Continued

[ft, foot; ft²/s, foot squared per second]

U. S. Geological Survey well number	Pumping test number	Well depth (ft)	Analysis by PICKINGmodel			Analysis by PPC-Recovery[b]			Percent difference in transmissivity between two methods
			Transmis-sivity (ft^2/s)	Storage coefficient	Range of data, in seconds, that fit a type curve[a]	Transmis-sivity (ft^2/s)	Storage coefficient	Sum of residuals squared per data point	
CN 357	TEST 141	200	0.0002	0.0000001	P 4–200[d]	0.00028	0.0000000001	0.0000035	40
CN 606	TEST 142	116	0.00127	0.002	C 3–1,000	0.0012	0.004	0.000078	5.5
CN 352	TEST 143	117	0.0001	0.01	C 3–9,800	0.000095	0.01	0.000013	5.0
BM2580	TEST 144	125	0.002	0.05	F 3–43	0.0017	0.1	0.000042	15
BM2578	TEST 145	100	0.0007	0.0001	C 1–5,600	0.00086	0.000008	0.000011	23
BM2579	TEST 146	93	0.002	0.1	F 1–25	0.0030	0.08	0.000046	50
C 466	TEST 147	197	0.0004	0.0001	C 1–2,000	0.00048	0.00002	0.000027	20
C 541	TEST 148	180	0.00013	0.25	C 1–10,000	0.00017	0.1	0.00034	31
C 504	TEST 149	162	0.00035	0.01	C 2–7,600	0.00034	0.01	0.000063	2.9
C 484	TEST 150	104	0.0003	0.15	F 1–70	0.00034	0.1	0.000020	13
C 536	TEST 151	248	0.0004	0.03	F 20–370	0.00037	0.06	0.000084	7.5
CN 23	TEST 153	190	0.000035	0.05	C 1–5,000	0.000027	0.1	0.000012	23
OG 376	TEST 200	169	0.000098	0.1	P 10–1,500	0.000093	0.1	0.000053	5.1
OG 380	TEST 302b	175	0.0002	0.15	F 3–150	0.00024	0.08	0.000032	20
								Median:	8.0
								Mean:	14

[a]C = Data curve fits type curve over entire data range. F = Data curve flattened (sloped more gently than type curve) beyond listed range.

P = Data curve plunged (sloped more steeply than type curve) beyond listed range.

[b]PPC-Recovery was applied to the same data range as was reported for the analysis by PICKINGmodel.

[c]Recovery nearly complete at end of range.

[d]Data curve plunged during time period 220–2,000 seconds, then flattened during the time period 2,000–10,000 seconds.

Table 4. Effect of including data beyond early fit to type curve on estimation of aquifer properties by PPC-Recovery for wells penetrating bedrock in the Appalachian Plateau of New York.

[ft^2/s, foot squared per second, -- fit of data to PICKINGmodel type curves not optimal over this time range]

Pumping test number and analysis number	Analysis by PICKINGmodel		Analysis by PPC-Recovery					
	Transmissivity (ft^2/s)	Storage coefficient	Transmissivity (ft^2/s)	Storage coefficient	Time range, in seconds	Number of points	Sum of residuals squared	Sum of residuals squared per data point
TEST 102-1	0.0008	0.1	0.00079	0.1	6–24	4	0.000320	0.0000800
TEST 102-2	--	--	0.00045	0.08	6–216	36	0.041350	0.0011486
TEST 102-5	--	--	0.00045	0.1	6–228	38	0.045400	0.0011900
TEST 102-6	--	--	0.00037	0.1	6–669[a]	77	0.167900	0.0022000
TEST 102-3	--	--	0.00036	0.1	6–1,014	90	0.230750	0.0025639
TEST 102-4	--	--	0.00034	0.1	6–6,204	179	0.439150	0.0024534
TEST 103-1	0.005	0.1	0.0050	0.008	6–42	7	0.001020	0.0001457
TEST 103-5	--	--	0.0044	0.04	6–60	10	0.002000	0.0002000
TEST 103-6	--	--	0.0041	0.08	6–84[a]	14	0.003300	0.0002300
TEST 103-2	--	--	0.0041	0.1	6–102	17	0.005230	0.0003076
TEST 103-3	--	--	0.0035	0.1	6–624	49	0.073400	0.0014980
TEST 103-4	--	--	0.0033	0.1	6–1,674	66	0.100800	0.0015273
TEST 106-5	--	--	0.0021	0.00001	6–96	16	0.000032	0.0000020
TEST 106-6	--	--	0.0016	0.0002	6–198[a]	33	0.000240	0.0000100
TEST 106-1	0.00172	0.0001	0.0016	0.0002	6–204	34	0.000260	0.0000076
TEST 106-2	--	--	0.0012	0.0040	6–702	89	0.007180	0.0000807
TEST 106-3	--	--	0.0011	0.0100	6–1,812	141	0.016730	0.0001187
TEST 106-4	--	--	0.0011	0.0100	6–6,552	202	0.024210	0.0001199
TEST 109b-1	0.0007	0.2	0.00081	0.1	4–64	11	0.000520	0.0000473
TEST 109b-5	--	--	0.00063	0.1	4–202	34	0.039700	0.0011700
TEST 109b-2	--	--	0.00057	0.1	4–310	47	0.091630	0.0019496
TEST 109b-6	--	--	0.00050	0.1	4–610[a]	67	0.241800	0.0036090
TEST 109b-3	--	--	0.00044	0.1	4–1,030	95	0.471320	0.0049613
TEST 109b-4	--	--	0.00039	0.1	4–8,170	216	1.067270	0.0049411
TEST 110b-1	0.0004	0.1	0.00041	0.1	6–72	12	0.000690	0.0000575
TEST 110b-5	--	--	0.00034	0.1	6–222	37	0.016100	0.0004300
TEST 110b-2	--	--	0.00031	0.1	6–384	51	0.040670	0.0007975
TEST 110b-6	--	--	0.00028	0.1	6–729[a]	74	0.126400	0.0017000
TEST 110b-3	--	--	0.00027	0.1	6–1,014	92	0.203630	0.0022134
TEST 110b-4	--	--	0.00026	0.1	6–1,514	175	0.469730	0.0026842
TEST 123-5	--	--	0.00180	0.002	5–110	22	0.001200	0.0000530
TEST 123-1	0.0018	0.001	0.0015	0.01	5–140	26	0.002040	0.0000785
TEST 123-6	--	--	0.0013	0.04	5–220[a]	44	0.006500	0.0001500
TEST 123-2	--	--	0.0011	0.1	5–895	125	0.098450	0.0007876
TEST 123-3	--	--	0.0010	0.1	5–2,940	241	0.294580	0.0012223
TEST 123-4	--	--	0.0010	0.1	5–16,695	456	0.462730	0.0010148

Table 4. Effect of including data beyond early fit to type curve on estimation of aquifer properties by PPC-Recovery for wells penetrating bedrock in the Appalachian Plateau of New York.—Continued

[ft^2/s, foot squared per second, -- fit of data to PICKINGmodel type curves not optimal over this time range]

Pumping test number and analysis number	Analysis by PICKINGmodel		Analysis by PPC-Recovery					
	Transmissivity (ft^2/s)	Storage coefficient	Transmissivity (ft^2/s)	Storage coefficient	Time range, in seconds	Number of points	Sum of residuals squared	Sum of residuals squared per data point
TEST 133-1	0.0335	0.00001	0.033	0.00001	3–18	4	0.000160	0.0000400
TEST 133-5	--	--	0.026	0.002	3–48[b]	10	0.003700	0.0003700
TEST 133-2	--	--	0.026	0.02	3–103	21	0.013865	0.0006602
TEST 133-3	--	--	0.032	0.1	3–303	57	0.051956	0.0009115
TEST 133-4	--	--	0.032	0.1	3–1,003	111	0.101334	0.0009129
TEST 136-5	--	--	0.012	0.00006	1–46[b]	10	0.001700	0.0001700
TEST 136-1	0.009	0.001	0.0099	0.0006	1–61	13	0.002720	0.0002092
TEST 136-2	--	--	0.0094	0.04	1–506	76	0.053450	0.0007033
TEST 136-3	--	--	0.0070	0.1	1–1,416	136	0.079950	0.0005879
TEST 136-4	--	--	0.0075	0.1	1–7,726	307	0.111164	0.0003621
TEST 146-1	0.002	0.1	0.0030	0.08	1–25	25	0.001140	0.0000456
TEST 146-5	--	--	0.0027	0.1	1–28	28	0.001600	0.0000570
TEST 146-2	--	--	0.0025	0.1	1–101	49	0.020680	0.0004220
TEST 146-6	--	--	0.0025	0.1	1–131[a]	55	0.032000	0.0005800
TEST 146-3	--	--	0.0022	0.1	1–981	150	0.150846	0.0010056
TEST 146-4	--	--	0.0022	0.1	1–6,581	314	0.207292	0.0006602
TEST 150-1	0.0003	0.15	0.00033	0.1	1–70	70	0.001380	0.0000197
TEST 150-2	--	--	0.00027	0.1	1–200	187	0.060505	0.0003236
TEST 150-5	--	--	0.00027	0.1	1–226	208	0.084900	0.0004100
TEST 150-3	--	--	0.00023	0.1	1–804	381	0.415778	0.0010913
TEST 150-6	--	--	0.00022	0.1	1–984[a]	415	0.509400	0.0012000
TEST 150-4	--	--	0.00021	0.1	1–2,549	529	0.822220	0.0015543

[a]Time in seconds to achieve 80-percent recovery.

[b]Utilizing at least 10 points; exceeds 80-percent recovery.

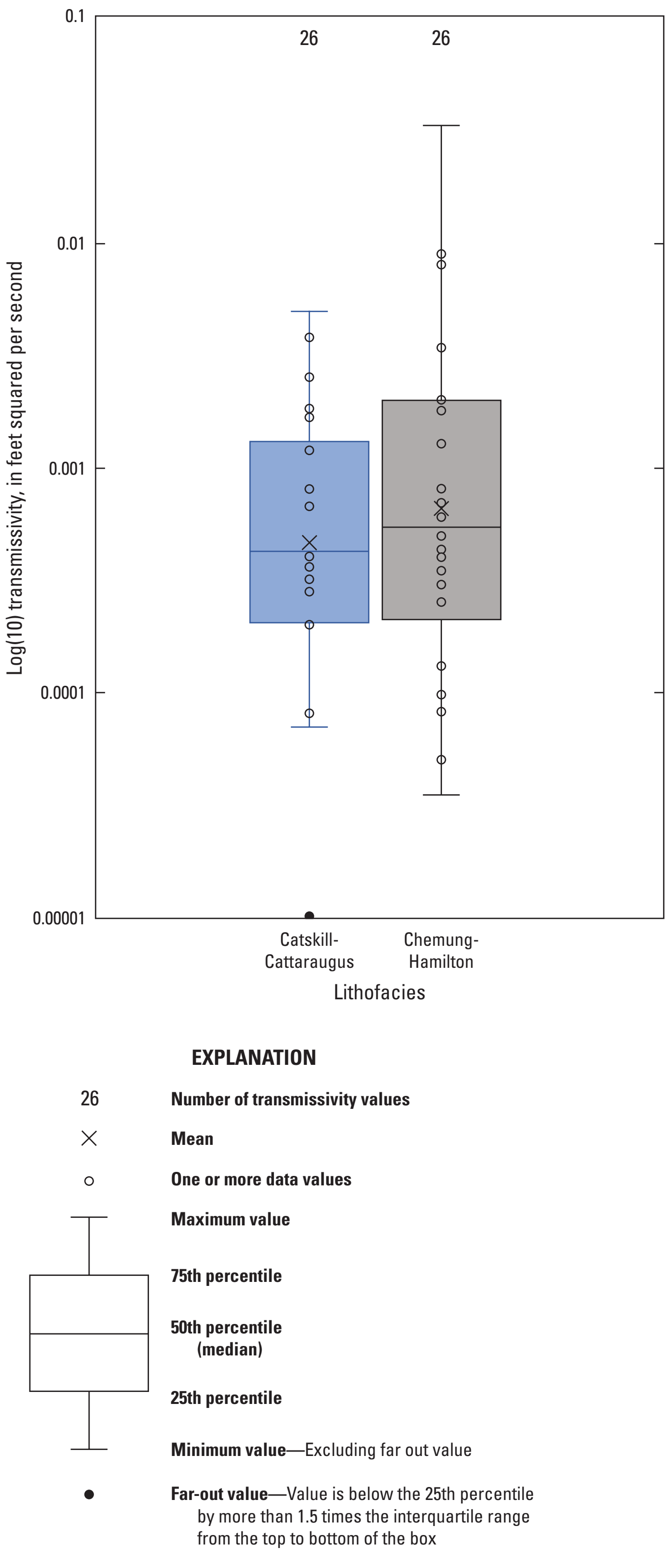


Figure 5. Distribution of transmissivity values for wells penetrating bedrock in the Catskill-Cattaraugus and Chemung-Hamilton lithofacies in the Appalachian Plateau of New York.

are statistically the same. In each lithofacies, the median transmissivity calculated for wells where only early recovery data match a PICKINGmodel type curve exceeds the median transmissivity calculated for wells where the entire data array matches a type curve (table 5).

The values of transmissivity calculated from these tests are not based on measurements of dimensions or flow rates in water-yielding fractures; instead, these values describe a uniform granular porous aquifer that would transmit the same amount of water that is able to flow to the pumped wells through scattered bedrock fractures. Also, the static water level in a well that penetrates more than one water-yielding fracture will be a dynamic function of the heads and dimensions of these fractures and may differ from the water table prior to well construction.

Test Results Compared With Position on Hillsides

The Appalachian Plateau of New York is a region of substantial relief, where ridge crests are commonly about 1,000 feet above the floors of major valleys. To evaluate the possibility that topographic position may correlate with well yield, the 52 tests analyzed during this investigation were classified into three categories by examination of topographic maps.

1. Upper hillsides, where elevation of the well site is much closer to the elevation of nearby ridge crests or hilltops than to the elevation of the nearest reach of the upland stream that drains several square miles including the site. (The selection of wells for testing excluded sites on ridge crests or at the top of steep valley walls, so that water-level fluctuations during the test would generally be within the casing, hence rates of recovery would not be subject to irregularities due to variations in borehole diameter or fractures in the bedrock within the interval of fluctuation.)

2. Lower hillsides, where the well site is much closer in elevation to the channel of a nearby tributary stream that drains several square miles than to nearby ridge crests. The deeper parts of these wells are generally below stream grade. Some nearby tributaries have alluvial floodplains 100 to 300 feet wide, but none of the wells tested bordered major valleys that contain outwash gravels deposited by glacial meltwater.

3. Middle hillsides, where elevation of the well site is intermediate between categories 1 and 2. Many of these middle hillsides are slightly incised by tiny headwater streams that lack alluvial floodplains recognizable on topographic or soils maps.

Table 5. Transmissivity as a function of data fit to PICKINGmodel type curves for wells in two bedrock lithofacies in the Appalachian Plateau of New York.

[ft^2/s, foot squared per second; ft^2/d, foot squared per day]

Lithofacies	Category of data fit to PICKINGmodel type curve	Number of wells	Median transmissivity value for type curves fitted to datasets	
			ft^2/s	ft^2/d
Catskill-Cattaraugus	A. All wells tested	26	0.000425	36.17
	B. Wells where all residual drawdown data values match a type curve (fig. 2)	12	0.00034	29.4
	C. Wells where only early residual drawdown values match a type curve, while later values decrease more slowly with time	13	0.0007	60.5
	D. Wells where later data values decrease more rapidly than type curve	1	0.0002	17.3
Chemung-Hamilton	A. All wells tested	26	0.00055	47.5
	B. Wells where all residual drawdown data values match a type curve (fig. 2)	11	0.0004	34.6
	C. Wells where only early residual drawdown values match a type curve, while later values decrease more slowly with time	11	0.008	691.2
	D. Wells where later data values decrease more rapidly than type curve	3	0.00043	37.2

The median transmissivity for each of these categories is presented in table 6, which indicates that water-transmitting fractures in bedrock are slightly more abundant, or more open, on the upper hillsides than on the middle and lower hillsides. However, results of individual well tests range far above and below the median values in each hillside category, and only eight test sites were classified as "upper hillsides." A Kruskal-Wallis statistical test (U.S. Environmental Protection Agency, 2009) concluded that median transmissivity values for the three hillside categories are statistically indistinguishable at a probability of 95 percent. The median transmissivity value in each of the three topographic categories was compared with medians of the other two categories by a Wilcoxon rank sum test; the three medians were statistically equal at a probability of 95 percent. These tests demonstrate that hillside position does not have a strong influence on water-transmitting properties of the uppermost few hundred feet of bedrock in this region.

Table 6. Variation in transmissivity of bedrock as a function of well position on hillsides in the Appalachian Plateau of New York.

[ft^2/s, foot squared per second; ft^2/d, foot squared per day]

Position on hillside	Number of tests	Transmissivity			
		Range (ft^2/s)	Median (ft^2/s)	Range (ft^2/d)	Median (ft^2/d)
Upper hillside	8	0.00008 to 0.009	0.001	6.91 to 777	86.4
Middle hillside	29	0.00005 to 0.0335	0.00055	4.32 to 2,894	47.5
Lower hillside	14	0.000035 to 0.008	0.0006	3.02 to 691	51.8

Summary

Water-level recoveries from brief (13–132 seconds) episodes of pumping 51 domestic drilled wells that penetrate till-mantled bedrock in the Appalachian Plateau of south-central New York were analyzed by applying a computer program termed PICKINGmodel. In each well tested, water levels were recorded frequently from the moment of pump shutdown until the water level approached the extrapolated pre-test trend. A data curve of time since shutdown in relation to residual drawdown (expressed as a ratio to drawdown at shutdown) was plotted and compared to a series of type curves, each calculated by PICKINGmodel from trial values of transmissivity and storage. For 23 of the tests, a type curve was selected that matched the observed data exactly or nearly so throughout the range of data collection. For 23 other tests, however, the selected type curve matched only the early data (as little as 15 to as much as 1,000 seconds), after which the observed residual drawdown decreased more slowly than the type curve, which indicates that the cone of depression may have expanded into a region of lesser transmissivity. In four tests, the late residual drawdown data values decreased more quickly than the type curve that matched the early data, which indicates that the cone of depression may have expanded into a region of greater transmissivity. Analysis of longer aquifer tests (10 to 32 minutes) of four of these wells by the Theis recovery method yielded transmissivity estimates 0.12 to 1.4 times the transmissivity estimates from PICKINGmodel analysis of these wells.

Transmissivity estimated by PICKINGmodel from these tests ranged over three orders of magnitude in both the Catskill-Cattaraugus lithofacies (shales, mudstones, siltstones, medium to coarse sandstones, pebbly sandstones) and the

Chemung-Hamilton lithofacies (shales, mudstones, siltstones, fine to medium sandstones). Median transmissivities were similar (0.000425 foot squared per second in the Catskill lithofacies and 0.00055 foot squared per second in the Chemung lithofacies), as were the distributions of transmissivity values in each lithofacies. Hillside position (upper, middle, and lower hillsides) likewise had little influence on water-transmitting properties in this region. Results of these easily arranged and analyzed test procedures may be appropriate for calculating groundwater flux under the low gradients that prevail under natural conditions, but not under the larger drawdowns and steeper gradients that prevail near clusters of domestic wells. Transmissivities calculated by PICKINGmodel from data for time intervals of 120 seconds or less may be of limited practical value because they apply only to a small volume of bedrock close to the pumped well. If a computation could be developed to estimate an effective transmissivity from late recovery data that depart from PICKINGmodel type curves that fit the earlier data, brief aquifer tests such as described in this report might be more widely applicable.

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