Drought-Trigger Ground-Water Levels and Analysis of Historical Water-Level Trends in Chester County, Pennsylvania

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CHESTER COUNTY WATER RESOURCES AUTHORITY

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ABSTRACT

The Chester County observation-well network was established in 1973 through a cooperative agreement between the Chester County Water Resources Authority (CCWRA) and the U.S. Geological Survey. The network was established to monitor local ground-water levels, to determine drought conditions, and to monitor ground-water-level trends. Drought-warning and drought-emergency water-level triggers were determined for 20 of the 23 wells in the Chester County observation-well network. A statistical test to determine either rising or declining water-level trends was performed on data for all wells in the network. Water-level data from only 2 of the 23 wells showed a trend. Water-level data from both of these wells showed a rising trend. A decrease in ground-water pumping in the area near these wells was probably the reason for the rise in water levels.

WHAT IS THE CHESTER COUNTY OBSERVATION-WELL NETWORK?

The Chester County observation-well network was established in 1973. The network currently (1997) consists of 23 wells in which water levels are measured monthly. The wells are located throughout the county in various geologic units or types of bedrock (fig. 1 and table 1). Most wells in the network are used to assess the natural fluctuations in ground-water levels. However, wells Ch-89 and Ch-2561 are monitored to assess the effect of quarry pumping on the local water levels.

The network was established (1) to monitor water levels in different aquifers in different parts of the county, (2) to make a realistic determination of drought conditions on the basis of local ground-water levels, and (3) to monitor long-term trends in ground-water levels. The network is unique in Pennsylvania because Chester County is the only county in the Commonwealth that has a program to establish drought-trigger ground-water levels on the basis of local water-table conditions.

In the past decade, the Pennsylvania Department of Environmental Protection (PaDEP) has issued drought warnings four times and the Governor has declared two drought emergencies for southeastern Pennsylvania. The most recent drought emergency was declared in the summer and fall of 1995, when mandatory water conservation was imposed.

Ground-water levels are measured during the middle of each month over a 1- or 2-day period so comparisons among wells can be made. A measuring tape is lowered down the well to measure the distance from the ground surface to the water-level surface (fig. 2). The water level is reported in feet below the ground surface. Thus, a water level of 15 ft (feet) below the ground surface is deeper than a water level of 10 ft below the ground surface.

HOW ARE DROUGHT-TRIGGER WATER LEVELS DETERMINED?

In 1990, a set of monthly drought-trigger water levels were developed for all wells in the network, except Ch-89 and Ch-2561 (Sloto, 1991). The drought-trigger water levels are defined as drought-warning and drought-emergency water levels, which are the same as the drought watch and drought warning indicators used by the PaDEP. The drought-warning and drought-emergency water levels were determined for each month because of the natural fluctuations of ground-water levels during the year. Ground-water levels are usually highest (closer to the ground surface) in the spring around March and April and are usually lowest (farther from the ground surface) in September and October. The drought-trigger water levels listed in this report are updates of the 1990 drought-triggers using data collected through December 1996.

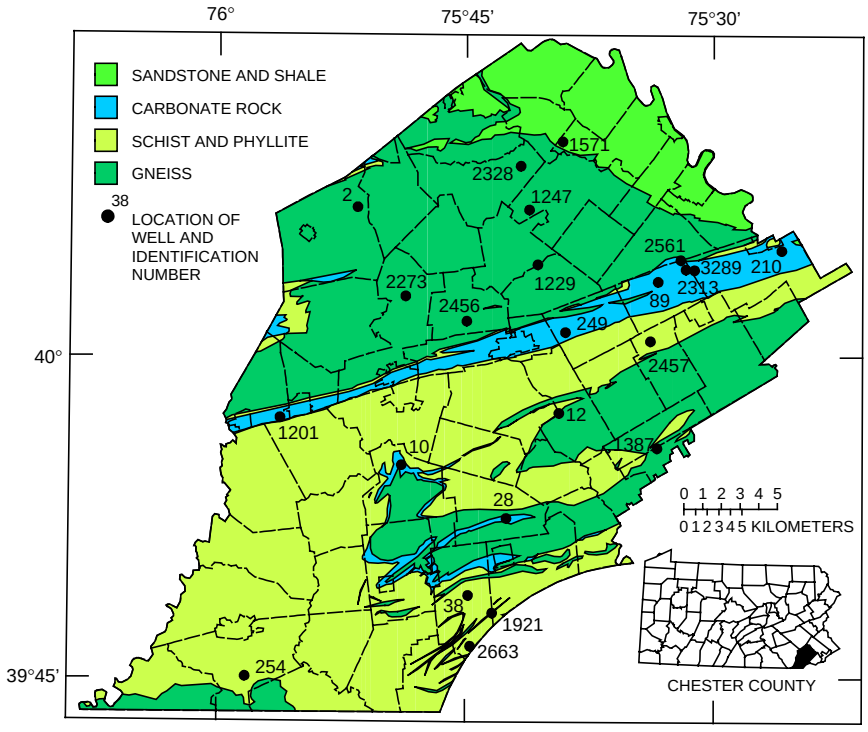

Figure 1. Location of wells in the Chester County Observation-well network. (Ch-prefix omitted)

Table 1. Description of wells in the observation-well network, Chester County, Pennsylvania

Well number	Type of bedrock	Well depth, in feet	Year measurements started
Ch-2	Gneiss	15	1973
Ch-10	Carbonate rock	34	1951
Ch-12	Gneiss	38	1973
Ch-28	Carbonate rock	25	1974
Ch-38	Schist	18	1974
Ch-89	Carbonate rock	265	1988
Ch-210	Carbonate rock	600	1978
Ch-249	Carbonate rock	600	1987
Ch-254	Schist	250	1987
Ch-1201	Carbonate rock	83	1973
Ch-1229	Gneiss	165	1974
Ch-1247	Gneiss	75	1973
Ch-1387	Gneiss	159	1974
Ch-1571	Sandstone and shale	16	1974
Ch-1921	Schist	65	1974
Ch-2273	Gneiss	298	1975
Ch-2313	Carbonate rock	507	1978
Ch-2328	Gneiss	323	1975
Ch-2456	Gneiss	225	1982
Ch-2457	Schist	285	1982
Ch-2561	Carbonate rock	240	1984
Ch-2663	Carbonate rock	150	1984
Ch-3289	Carbonate rock	202	1988

Two different methods are used to determine monthly drought-trigger water levels for the wells. The first method is used for wells in which more than 20 years of water-level measurements have been collected. Wells for which this method was used were Ch-2, Ch-10, Ch-12, Ch-28, Ch-38, Ch-1201, Ch-1229, Ch-1247, Ch-1387, Ch-1571, Ch-1921, Ch-2273, and Ch-2328.

The monthly water-level measurements were listed (ranked) from the smallest value (closest water level to the ground surface) to the largest value (farthest water level from the ground surface). The drought-warning water level was chosen to be the 75th percentile of the ranked measurements, which is the PaDEP drought-watch indicator value. Seventy-five percent of the time or three-quarters of all water-level measurements collected over the entire period of record are above the 75th-percentile level, and 25 percent or one quarter of the measurements are equal to or below the 75th-percentile level of the ranked measurements. The drought-emergency water level for each month was chosen to be the 90th percentile of the ranked measurements, which is the PaDEP drought-warning indicator value. Ninety percent of the time, or 9 out of every 10 water-level measurements collected over the entire period of record, are above the 90th-percentile level, and 1 out of every 10 measurements are equal to or below the 90th-percentile level of the ranked measurements.

The second method of determining drought-trigger levels was used for wells in which less than 20 years of water-level measurements have been collected. Wells for which this method was used were Ch-210, Ch-249, Ch-2313, Ch-2456, Ch-2457, Ch-2663, and Ch-3289. This method relates the mid-month water-level measurement in an observation well to a mid-month water-level measurement in an index well. An index well is a well in which water-level measurements have been made during differing climate conditions over a long period of time. Because the index well has long-term data, the effects of extremely wet or extremely dry periods would not bias the data analysis. If drought conditions were based on an index well with only 5 years of water-level measurements made during a dry period, the analysis would be biased towards drier conditions and would not reflect average climate conditions.

The index well in Chester County is well Ch-10. Ch-10 was chosen as an index well because it is part of a USGS national observation-well network, and water levels have been measured since 1951.

Drought-trigger water levels were determined for each month of the year by ranking mid-month water levels in well Ch-10 from smallest value (highest water level) to largest value (lowest water level) for the period from August 1951 to December 1996. The 75th- and 90th-percentile water levels for each month were then determined for Ch-10.

Water-level measurements from observation wells with less than 20 years of measurements were related to water levels in Ch-10 by graphing the water levels from each well in relation to water levels in Ch-10 for the same time periods (fig. 3). A computer graphing program was used to calculate a "line of relation" between the water levels in each network well and Ch-10, and a mathematical equation was derived from that line. The drought-trigger water levels then can be estimated on the basis of the relation to Ch-10, which represents average climate conditions.

How accurately the line represents the relation between the two sets of water-level measurements can be evaluated by looking at a statistical parameter known as R^2, or the coefficient of determination. The closer the R^2 value is to 1, the better the line represents the relation. The R^2 values, the derived mathematical equations, and the number of data points used in each analysis are shown in table 2.

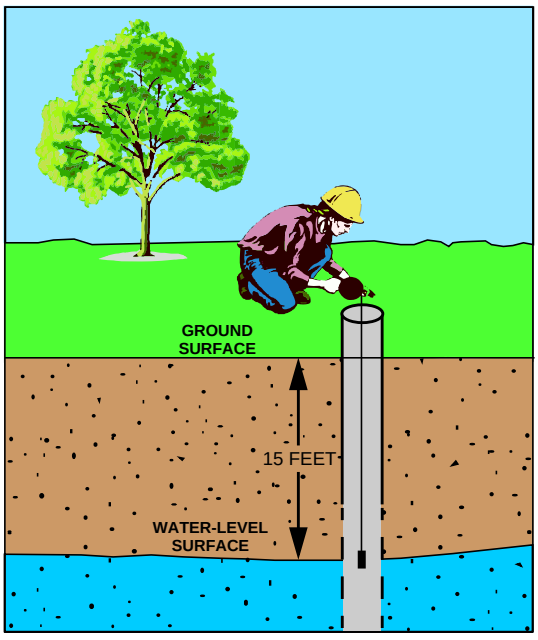

Figure 2. Hydrologic technician making a water-level measurement in an observation well.

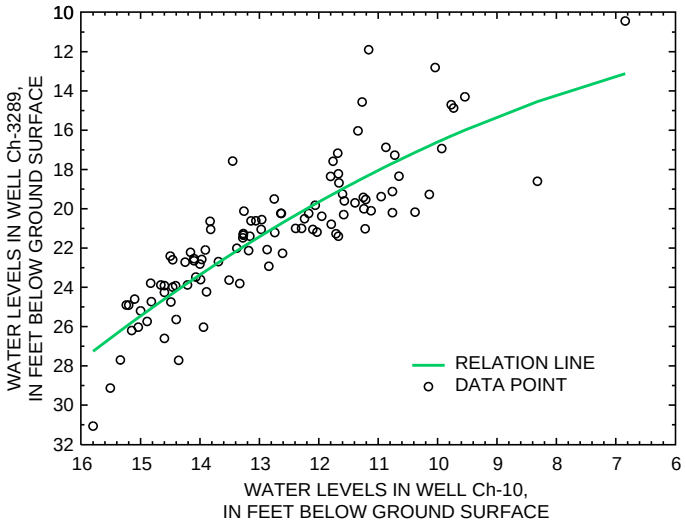

Figure 3. Water levels in well Ch-3289 in relation to water levels in well Ch-10.

The determination of drought-trigger water levels for well Ch-2313 is shown in the following example. For Ch-2313, the mathematical equation describing the relation between water levels measured in Ch-2313 and Ch-10 is:

$$Y_{Ch\text{-}2313} = 8.69 - 2.47X_{Ch\text{-}10} + 0.177X^2_{Ch\text{-}10}$$

In the equation, Y is the predicted water level in Ch-2313 in relation to X, which is the water level in Ch-10. For example, the 75th-percentile water level in well Ch-10 for the month of January, which is based on 45 years of measurements, is 13.53 ft below ground surface. By substituting 13.53 ft for X in the equation, the computed value for Y is 7.68 ft, the predicted 75th percentile or the January drought-warning trigger water level for Ch-2313. Monthly drought-warning and drought-emergency water levels computed for well Ch-2313 using the relation equation are shown in figure 4. The monthly measurements made in well Ch-2313 during 1995 also are shown on figure 4. The water levels fell below the drought-emergency level in February and from June to sometime in October.

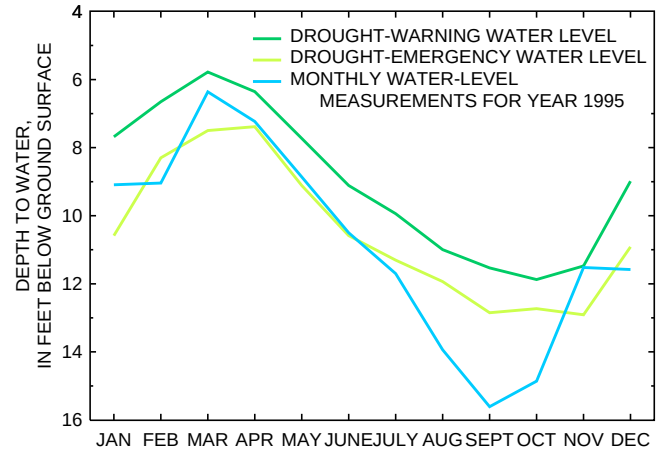

Figure 4. Drought-warning, drought-emergency, and 1995 monthly water levels for well Ch-2313.

Table 2. R^2 values and derived equations describing the mathematical relation between Ch-10 and wells having less than 20 years of water-level data

[R^2, coefficient of determination; X, Water-level in Ch-10; Y, Predicted water level in well with less than 20 years of data; N, number of data points]

Well	Polynomial regression equation	R^2	N
Ch-210	$Y = 17.4 - 0.71X + 0.075X^2$	0.66	221
Ch-249	$Y = 25.39 - 2.43X + 0.146X^2$	.75	108
Ch-2313	$Y = 8.69 - 2.47X + 0.177X^2$	.67	223
Ch-2456	$Y = 17.44 + 0.02X + 0.011X^2$	.55	176
Ch-2457	$Y = 1.57 + 1.25X + 0.013X^2$	.72	177
Ch-2663	$Y = 5.62 + 0.41X - 0.004X^2$	.63	137
Ch-3289	$Y = 11.17 - 0.28X + 0.082X^2$	.75	102

WHY ARE DROUGHT-TRIGGER WATER LEVELS IMPORTANT?

If water levels in network wells approach or surpass drought-trigger levels, Chester County officials and residents will be alerted of an impending or existing drought, and continued water-level measurements will assess the duration and severity of the drought. Being warned of an impending or existing drought is important to local residents, water purveyors, and water-dependent commercial operators because the continued lowering of ground-water levels could result in reduced water production or wells going dry. The negative effects of a drought can be lessened if water-management practices are implemented before or at the onset of drought conditions.

If the mid-month water-level measurements in a majority of observation wells reach or exceed the 75th percentile, Chester County officials may issue a drought-watch advisory to county residents through local radio stations and newspapers encouraging voluntary conservation of water. If the water levels in a majority of wells exceed the 75th percentile for two consecutive months, PaDEP may issue a drought warning, which is a voluntary ban on nonessential water use. Should water levels in a majority of wells fall below the 90th percentile, PaDEP may declare a drought emergency, which imposes a mandatory ban on all nonessential water use through the regulatory processes of the Commonwealth of Pennsylvania. Drought-warning and drought-emergency declarations also consider other hydrologic conditions, such as precipitation and streamflow.

WHAT ARE THE DROUGHT-TRIGGER WATER LEVELS?

The monthly drought-warning and drought-emergency water levels for the observation wells that have more than 20 years of measurements are shown in tables 3 and 4. The monthly drought-warning and drought-emergency water levels for wells that have less than 20 years of measurements are shown in tables 5 and 6.

For example, if the water level measured in well Ch-3289 in March is 21 ft below ground surface and similar conditions occur in the majority of observation wells (table 5), a drought warning could be issued by Chester County officials. If the water level in the well in April was more than 22.2 ft below ground surface (table 6), and similar conditions occur in a majority of observation wells, a drought emergency could be declared by County officials.

Table 3. Monthly drought-warning water levels for wells with 20 or more years of measurements in the Chester County observation-well network, Pennsylvania, start of record to December 1996

[A negative value means the water level is above the land surface]

Well	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Ch-2	9.39	9.20	8.42	8.56	8.98	9.46	9.71	10.62	11.48	11.24	11.39	9.88
Ch-10	13.53	13.10	12.64	12.92	13.56	14.14	14.46	14.82	15.14	15.14	15.08	14.16
Ch-12	[1]39.00	[1]39.00	36.67	36.49	36.01	36.03	36.74	37.26	[1]39.00	[1]39.00	[1]39.00	[1]39.00
Ch-28	18.71	18.70	17.68	17.52	18.17	18.63	19.67	20.91	21.88	23.02	22.92	20.25
Ch-38	10.12	8.97	7.85	8.12	8.26	8.83	10.04	11.29	12.62	11.97	11.98	11.04
Ch-1201	6.24	6.01	5.78	5.41	5.73	6.18	6.31	6.57	6.92	6.96	6.76	6.08
Ch-1229	39.52	38.40	38.48	36.23	36.64	38.22	38.99	40.21	40.36	40.90	41.25	39.82
Ch-1247	31.79	31.66	30.45	28.80	28.47	29.36	30.26	31.54	32.38	32.68	33.56	32.17
Ch-1387	35.82	35.05	34.32	34.45	34.10	35.30	35.08	35.68	36.43	36.85	36.30	35.95
Ch-1571	7.14	6.80	6.09	6.10	6.82	8.67	10.07	10.44	10.55	10.51	9.77	7.78
Ch-1921	46.53	47.06	45.82	44.55	44.46	45.06	44.94	45.42	46.37	46.34	46.76	46.59
Ch-2273	.98	.54	-.76	-.72	-.82	-.18	.96	1.79	2.67	2.74	2.64	1.23
Ch-2328	3.10	2.81	2.17	2.00	2.26	2.62	3.19	4.02	4.62	4.35	4.15	3.00

[1] Well dry.

Table 4. Monthly drought-emergency water levels for wells with 20 or more years of measurements in the Chester County observation-well network, Pennsylvania, start of record to December 1996

Well	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Ch-2	10.89	10.39	9.85	9.55	9.57	10.34	11.19	11.60	12.65	12.43	12.21	11.16
Ch-10	14.68	13.87	13.45	13.94	14.14	14.71	14.94	15.18	15.49	15.43	15.53	14.80
Ch-12	[1]39.00	[1]39.00	[1]39.00	38.68	37.44	38.54	[1]39.00	[1]39.00	[1]39.00	[1]39.00	[1]39.00	[1]39.00
Ch-28	20.02	19.01	19.36	20.44	20.71	21.62	22.72	23.48	22.99	23.60	24.16	23.50
Ch-38	12.89	12.99	11.88	10.11	10.23	10.57	11.14	12.07	12.99	13.52	13.85	13.49
Ch-1201	7.26	6.44	6.47	6.37	6.77	6.98	7.37	7.11	7.59	7.06	6.92	6.67
Ch-1229	41.08	41.02	39.93	39.14	38.73	39.97	41.64	41.93	41.37	42.35	42.05	41.14
Ch-1247	34.02	31.95	32.27	31.74	31.02	31.00	31.78	32.48	33.23	33.95	34.66	33.66
Ch-1387	36.87	36.82	36.33	35.85	35.58	35.93	36.04	37.10	37.06	38.38	37.16	36.86
Ch-1571	8.59	9.21	6.76	6.59	7.38	8.93	10.10	10.71	10.92	10.70	10.75	9.12
Ch-1921	48.31	47.87	47.54	46.56	45.96	46.16	46.35	47.54	48.39	49.09	47.98	49.18
Ch-2273	4.02	3.50	2.80	1.72	1.38	1.38	1.71	2.72	3.66	3.95	4.28	3.98
Ch-2328	3.93	3.60	3.40	3.44	3.35	3.50	3.76	4.64	5.44	5.28	4.77	4.69

[1] Well dry.

Table 5. Monthly drought-warning water levels in wells with less than 20 years of measurements in the Chester County observation-well network, Pennsylvania, start of record to December 1996

Well	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Ch-210	21.55	20.96	20.45	20.78	21.58	22.36	22.82	23.40	23.69	23.88	23.66	22.29
Ch-249	19.20	18.53	17.98	18.34	19.23	20.15	20.71	21.42	21.79	22.03	21.75	20.06
Ch-2313	7.68	6.65	5.78	6.35	7.73	9.11	9.94	11.00	11.53	11.88	11.48	8.99
Ch-2456	19.76	19.62	19.49	19.57	19.77	19.96	20.07	20.20	20.27	20.31	20.26	19.94
Ch-2457	20.81	20.08	19.42	19.86	20.85	21.76	22.28	22.91	23.22	23.42	23.19	21.68
Ch-2663	10.41	10.27	10.14	10.22	10.41	10.58	10.68	10.79	10.85	10.88	10.84	10.57
Ch-3289	22.39	21.54	20.77	21.28	22.45	23.59	24.25	25.07	25.48	25.75	25.44	23.48

Table 6. Monthly drought-emergency water levels in wells with less than 20 years of measurements in the Chester County observation-well network, Pennsylvania, start of record to December 1996

Well	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Ch-210	23.17	21.90	21.45	21.38	22.36	23.17	23.57	23.91	24.40	24.34	24.44	23.36
Ch-249	21.14	19.61	19.08	19.01	20.15	21.14	21.64	22.07	22.70	22.62	22.74	21.37
Ch-2313	10.58	8.30	7.50	7.38	9.11	10.58	11.31	11.93	12.85	12.73	12.91	10.91
Ch-2456	20.15	19.85	19.74	19.72	19.96	20.15	20.24	20.32	20.43	20.42	20.44	20.19
Ch-2457	22.67	21.23	20.69	20.61	21.76	22.67	23.09	23.45	23.96	23.89	23.99	22.86
Ch-2663	10.75	10.48	10.38	10.37	10.58	10.75	10.82	10.89	10.98	10.97	10.98	10.78
Ch-3289	24.75	22.92	22.26	22.16	23.59	24.75	25.31	25.79	26.48	26.39	26.53	25.01

Drought-trigger water levels were not determined for wells Ch-89 and Ch-2561 because water levels in these wells are affected by pumping at a nearby quarry. Also, drought-trigger water levels were not determined for well Ch-254 because an acceptable mathematical relation between water levels in Ch-254 and in index well Ch-10 could not be determined.

HOW ARE TRENDS IN WATER LEVELS DETERMINED?

The ability to determine if local ground-water levels are rising or declining over time is important to individual, commercial, and public-supply purveyors who rely on wells, as well as to the ecological health of county streams and surface-water supplies, because ground-water and surface-water systems are well connected in Chester County (Sloto, 1994, p. 45). It is especially important to identify declining

trends in ground-water levels because it could indicate areas where the ground-water resource is being overdeveloped and local water resources may not sustain additional withdrawals.

A statistical test known as the seasonal Kendall test for trend was used to determine if water levels are either rising or declining in the network wells (Hirsch, 1982). The test was performed on water levels for the entire period of measurements for each well. The trend analysis is summarized in table 7 and the results for two statistical parameters, Kendall's tau value and the p-value are given. Kendall's tau value lies between -1 and +1. A value close to 0 indicates that either no trend exists or a weak trend may exist. A value close to -1 indicates a strong rising water-level trend, and a value close to +1 indicates a strong declining water-level trend. The p-value measures the "believability," or level of significance, of the statistical test. If the p-value is less than 0.05, then the test is considered significant and the trend is assumed to be real.

WHAT TRENDS IN WATER LEVELS WERE IDENTIFIED?

Only two wells, Ch-89 and Ch-2457, showed a statistically significant trend in water levels (p-value less than 0.05). For all other wells in the observation-well network, no rising or declining trends were found. Figure 5 shows water levels for well Ch-10 from August 1951 to December 1996 with no evident rising or declining water-level trend.

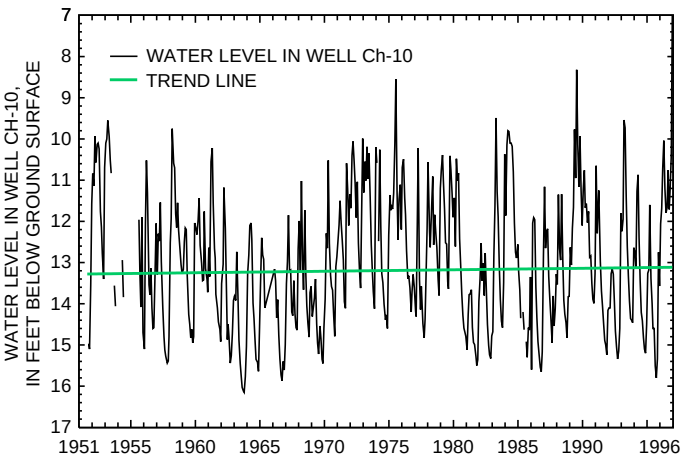

Figure 5. Water levels and trend line for the period of record for well Ch-10.

Table 7. Results of seasonal Kendall test for trends in wells in the Chester County observation-well network

[p-value, probability statistically significant if less than 0.05; n, number of data values]

Well	Kendall's tau	p-value[1]	Apparent trend	n
Ch-2	0.02	0.875	None	303
Ch-10	–.03	.754	None	517
Ch-12	.12	.313	None	276
Ch-28	–.13	.197	None	256
Ch-38	.00	.971	None	265
Ch-89	–.660	.012	Rising	95
Ch-210	–.047	.646	None	221
Ch-249	.132	.445	None	108
Ch-254	.220	.265	None	118
Ch-1201	–.110	.350	None	273
Ch-1229	.101	.387	None	271
Ch-1247	.206	.129	None	273
Ch-1387	–.030	.784	None	266
Ch-1571	.037	.650	None	269
Ch-1921	.007	.968	None	261
Ch-2273	.112	.367	None	260
Ch-2313	.204	.150	None	223
Ch-2328	.057	.600	None	256
Ch-2456	–.138	.247	None	176
Ch-2457	–.300	.030	Rising	177
Ch-2561	.322	.073	None	150
Ch-2663	–.282	.087	None	137
Ch-3289	.085	.550	None	102

[1] p-value adjusted for serial correlation (Hirsch and Slack, 1984).

Water levels in well Ch-89, which is near an active quarry, showed a significant rising trend from 1988 to 1996. The water level rose from 180 ft below ground surface in 1988 to 155 ft below ground surface in December 1996.

A rising trend in water levels over the period of record, February 1982 through December 1996, also was identified in well Ch-2457. The rising water level was probably due to the cessation of ground-water pumping from a nearby public-supply well. That production well, located approximately 1,500 ft to the southwest of Ch-2457, was pumped from 1981 to 1986, when it was taken out of service. When the trend test is applied only to the time when the public-supply well was pumping (1981 to 1986) or only to the post-pumping period (1987-96), it shows no statistically significant rising or declining trend. When the test is applied to the combined pumping and post-pumping periods, however, it indicates a rising water-level trend (fig. 6).

CONCLUSIONS

Monthly drought-trigger water levels are calculated and presented for 20 of the 23 wells in the Chester County observation-well network. These water levels are consistent with PaDEP statewide drought-management water-level triggers and are used by Chester County and PaDEP for issuing drought warnings and drought emergencies. An analysis of water-level trends performed on the entire period of monthly measurements for each well in the network showed no declining ground-water levels in Chester County. However, ground-water levels in two wells were shown to be rising. The rising water-level trends in these wells were most likely due to discontinuing or decreasing withdrawals from nearby aquifers.

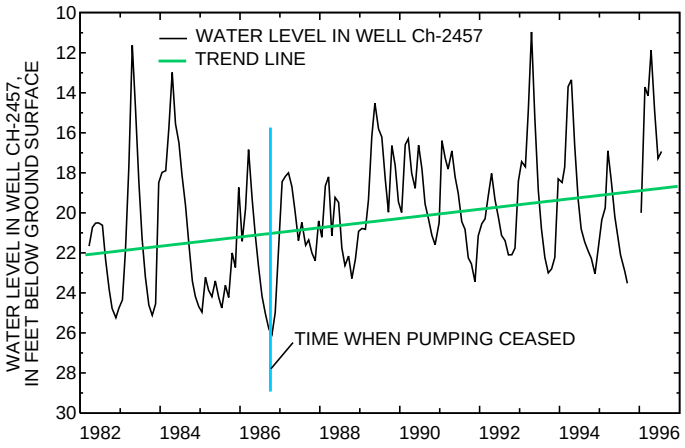

Figure 6. Water levels and trend line for the period of record for well Ch-2457.

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