USGS
science for a changing world

Commonwealth of Pennsylvania
Bureau of Topographic and Geologic Survey
Department of Conservation
and Natural Resources

Hydrologic Effects of the Pymatuning Earthquake of September 25, 1998, in Northwestern Pennsylvania

*by Gary M. Fleeger, Pennsylvania Bureau of Topographic and Geologic Survey,
and Daniel J. Goode, Theodore F. Buckwalter, and Dennis W. Risser, U.S. Geological Survey*

Within hours after the Pymatuning earthquake of September 25, 1998, in northwestern Pennsylvania, local residents reported wells becoming dry, wells beginning to flow, and the formation of new springs. About 120 household-supply wells reportedly went dry within 3 months after the earthquake. About 80 of these wells were on a ridge between Jamestown and Greenville, where water-level declines of as much as 100 feet were documented. Accompanying the decline in water levels beneath the ridge was an increase in water levels in valley wells of as much as 62 feet. One possible explanation of the observed hydrologic effects is that the earthquake increased the vertical hydraulic conductivity of shales beneath the ridge, which allowed ground water to drain from the hilltops. Computer simulations of ground-water flow beneath the ridge between Jamestown and Greenville indicate that increasing the vertical hydraulic conductivity of shale confining beds about 10 to 60 times from their pre-quake values could cause the general pattern of decreased water levels on hilltops and increased levels in valleys.

An earthquake occurred on the afternoon of September 25, 1998, near the southern end of Pymatuning Reservoir in northwestern Pennsylvania (fig. 1). Seismologists determined the earthquake had a magnitude of 5.2, which is the largest ever recorded in Pennsylvania (Armbruster and others, 1999). Although the Pymatuning earthquake was felt over approximately 125,000 mi^2 (square miles) of the northern United States and southern Canada, structural damage was minor in the communities of Jamestown and Greenville near the epicenter. The most serious consequence of the earthquake was to the ground-water supply tapped by rural domestic wells.

As early as the morning after the earthquake, residents in the vicinity of Greenville and Jamestown observed its effects on their water wells. The Mercer County Department of Public Safety received reports that some wells had lost all water and the yields of others had significantly decreased. Conversely, at the same time that some wells were going dry, others started to flow, some spring discharges increased, and pond levels rose. Complaints of changes in water quality, typically that well water had turned black or smelled of sulfur, also were reported after the earthquake.

This report summarizes findings from a study of the hydrologic effects of the Pymatuning earthquake conducted by the U.S. Geological Survey and the Pennsylvania Bureau of Topographic and Geologic Survey, with assistance from Thiel College and the Mercer County Department of Public Safety. The report documents the location and magnitude of changes in ground-water levels, particularly where wells went dry. The report also presents a hypothesis to explain the documented water-level changes and tests that hypothesis with simulations from a ground-water flow model.

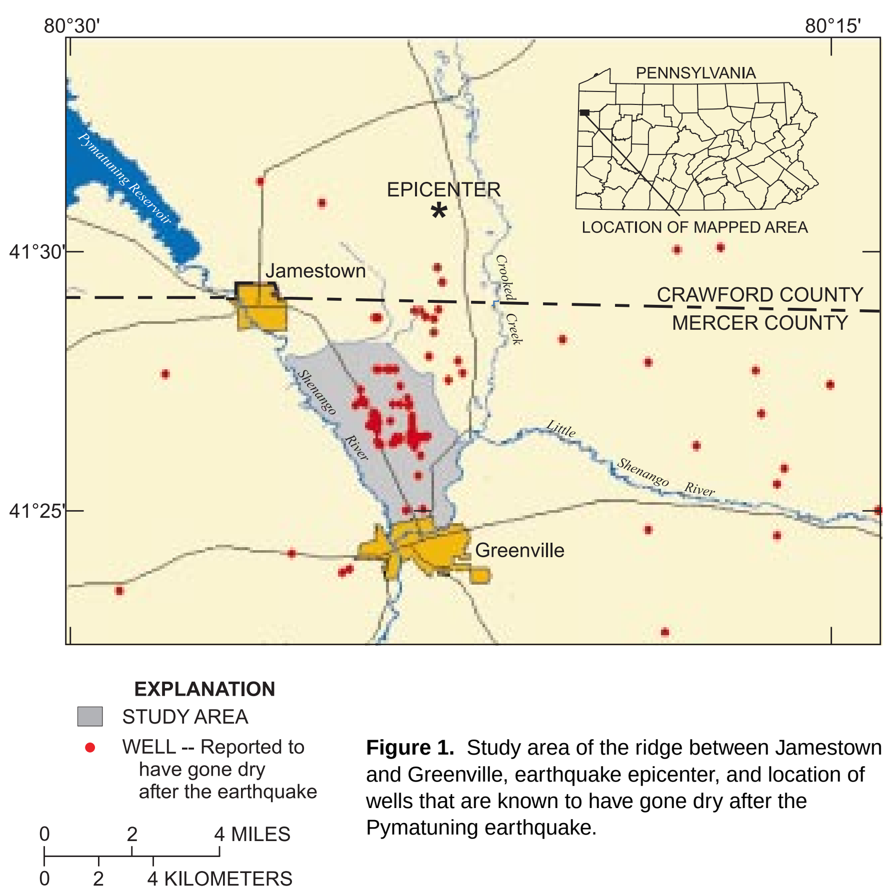


Figure 1. Study area of the ridge between Jamestown and Greenville, earthquake epicenter, and location of wells that are known to have gone dry after the Pymatuning earthquake.

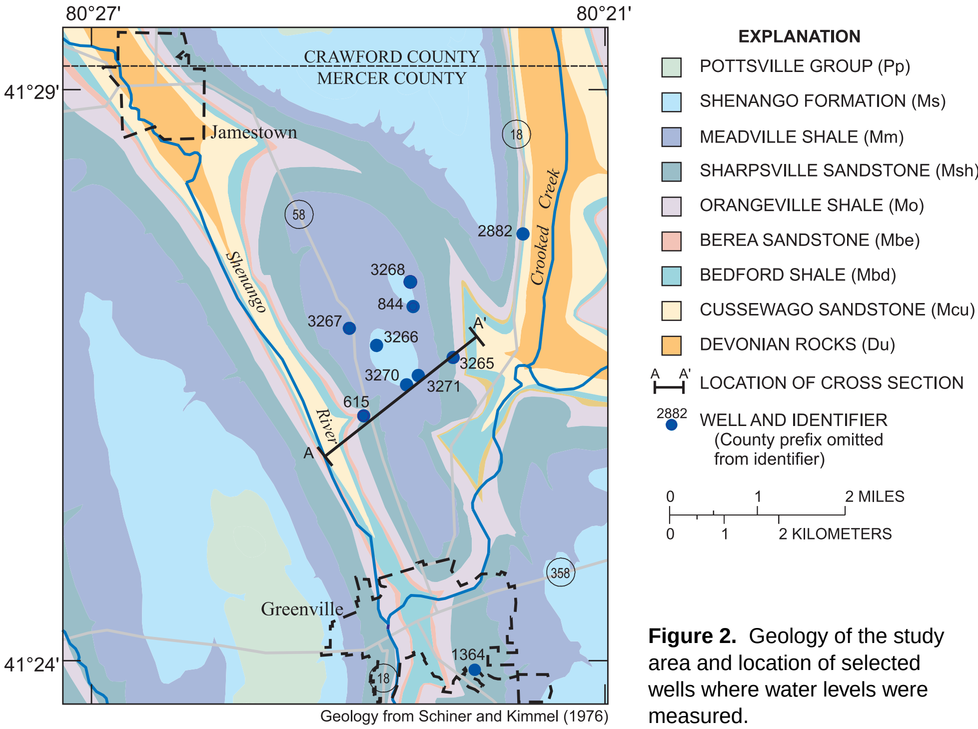


Figure 2. Geology of the study area and location of selected wells where water levels were measured.

Study Area

The study area is a northwest-southeast trending ridge about 5 mi (miles) long and 2 mi wide between Greenville and Jamestown in northern Mercer County, Pa. (fig. 1). The ridge is centered about 5 mi south-southwest of the epicenter of the Pymatuning earthquake. The elevation at the ridge top is 1,204 ft (feet) above sea level. The valleys of the Shenango River, Little Shenango River, and their tributaries completely encircle the ridge. The maximum relief from the ridge top to the adjacent valley is about 250 ft.

Hydrogeologic Setting

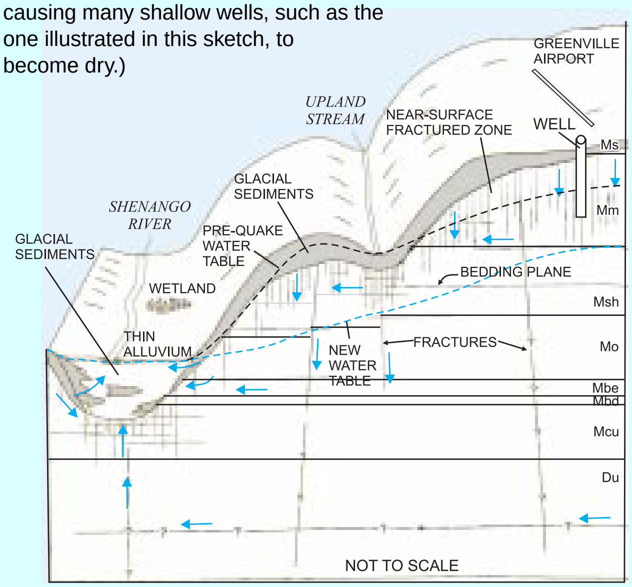
The bedrock comprising the ridge (fig. 2) consists of interbedded sandstone, siltstone, and shale of Mississippian age (about 350 million years old). From oldest to youngest, the bedrock units in the ridge are the Cussewago Sandstone, Bedford Shale, Berea Sandstone, Orangeville Shale, Sharpsville Sandstone, Meadville Shale, and the Shenango Formation. Each unit contains all the rock types present in the area but in different proportions. The area has been glaciated, but the glacial sediment on the ridge is generally less than 15 ft thick. The adjacent Shenango and Little Shenango River valleys are partially buried with glacial sediments up to a maximum depth of 200 ft.

The ability of a geologic material to transmit water is described by its hydraulic conductivity (or permeability). The hydraulic conductivity of solid bedrock is usually not great unless the rock contains open fractures. Near the surface, where weathering agents have been able to penetrate the rock, fractures are usually open. In addition, as valleys are eroded, the lateral support for the adjacent hills is removed, and stress-relief fractures tend to form on the hillsides parallel to the valley. Deeper into the ridge, hydraulic conductivity is low because fewer fractures exist, and they are more tightly closed.

The origin of all ground water beneath the ridge is precipitation, which infiltrates to the water table mostly during the fall and spring when evapotranspiration is low and the ground is not frozen. The ridge is the ground-water recharge area. Precipitation that falls on the ridge filters through the glacial sediments and upper part of the bedrock until it reaches the water table, below which water is stored in all openings in the rock. The water table is deeper beneath the ridge top than beneath the slopes or valleys.

After reaching the water table, ground water flows through the ridge mainly in fractures through the rock and between layers of rock (fig. 3). In the ridge, ground water moves under the influence of gravity, downward and laterally toward the valleys. Ground-water flow has its greatest downward component beneath hilltops and more of a lateral component along the ridge slopes. Beneath the valleys, water moves upward, under pressure, toward the surface to

Figure 3. Schematic cross section showing conceptualized flow of ground water (blue arrows) from ridge top to valleys. Geologic unit abbreviations are defined in figure 2. (As a result of the earthquake, fractures through which ground water moves were enhanced, allowing rapid movement of water out of the hill into discharge areas. The drainage of ground water stored in the hill lowered the water table, causing many shallow wells, such as the one illustrated in this sketch, to become dry.)



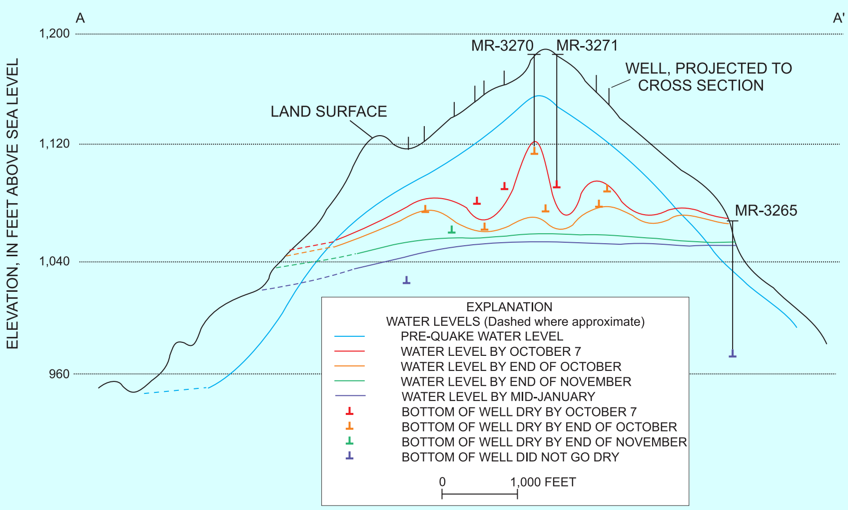


Figure 4. Cross section through the "hydrologic island" showing the interpreted change in ground-water level from before the earthquake through mid-January 1999. The section is based on the reported date that each well went dry, and the depth of the well. Note that the water level increased along the sides of the ridge, reflected in newly flowing wells after the earthquake. Also note the zones of depression in the water table near the center of the ridge, especially at the October 7 level. These zones presumably developed along the earthquake-enhanced fractures, and extended deeper and spread laterally over several months. Well MR-3271 went dry by October 7. Well MR-3270 did not go dry until late in October. Well MR-3265 began to flow immediately after the earthquake and stopped in late November. It began flowing again in March after the precipitation and snowmelt had recharged the ground-water system. Location of the cross-section is shown on figure 2.

discharge through springs and seeps. Almost all water entering the ground-water system on the ridge will eventually (in months or years) discharge into the adjacent stream valleys. The ridge forms a "hydrologic island" as described by Poth (1963) in that its ground-water flow is almost totally isolated from the ground-water flow in adjacent hills and ridges.

HYDROLOGIC EFFECTS OF THE EARTHQUAKE

Within hours of the earthquake, residents began to notice changes in the quantity of their well water. The most significant effect was the decline of ground-water levels (fig. 4). As early as the morning after the earthquake, some residents had lost water in their wells. Additional residents lost water over the next 3 months. The timing of the water loss depended on the elevation and well depth. In general, shallow wells (primarily those completed in the Meadville Shale) near the ridge top went dry first. Deeper wells (drilled to the upper Sharpsville Sandstone) and wells toward the margins of the hill went dry over the next several months. The declining water levels were exacerbated by drought conditions through the summer and fall of 1998. A few wells above elevation 1,100 ft on the ridge did not go dry because they were drilled deeper (to the lower Sharpsville Sandstone or Orangeville Shale) than the wells that went dry.

At the same time that wells on the ridge top were going dry, some residents in the valley and along the base of the ridge noticed an increase in the flow of springs and streams, and several wells began to flow. The streamflow-gaging station on the Little Shenango River at Greenville recorded a small increase in streamflow beginning about 4:00 a.m. on September 26, 1998, the morning after the earthquake.

CHANGES IN GROUND-WATER LEVELS AND DISCHARGE

Water-level declines causing water loss in household-supply wells were documented in 121 wells. Eighty of those wells were on the ridge between Greenville and Jamestown (fig. 1). Water-level increases were documented along the base of the ridge.

Declines

Water-level declines were recorded in all wells measured on the top and upper slopes of the ridge between Greenville and Jamestown. One of the most dramatic changes in water level occurred in well MR-844 (fig. 5),

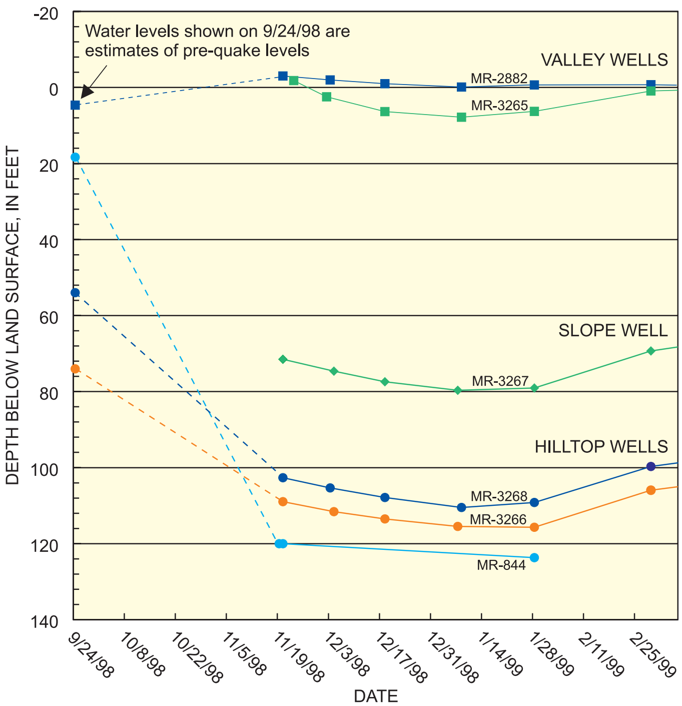


Figure 5. Water-level fluctuations in selected wells. (Pre-quake levels are estimated on the basis of historical measurements and reports from well owners.) Location of wells are shown on figure 2.

located near the highest point on the ridge. The water level in that 65-ft deep well was 18 ft below land surface in June 1967 (Schiner and Kimmel, 1976). The well was dry by the morning after the earthquake. Assuming that the water level was within 25 ft of the surface immediately prior to the Pymatuning earthquake, the water level decreased about 40 ft overnight. Well MR-844 was deepened to 120 ft in October. By early November, however, the water level had dropped below 120 ft and the well went dry again. It was subsequently deepened to 155 ft.

Most wells on the ridge were less than 100 ft deep, and almost all went dry over a 3-month period. Several wells were more than 150 ft deep. These deeper wells experienced significant water-level declines but did not go dry. The water levels in wells stopped dropping temporarily after precipitation and snowmelt in January, then resumed their decline. The water levels in the hilltop wells continue to be substantially below pre-quake levels (as of June 1999).

Increases

An increase in water levels in wells and spring flow near the base of the ridge accompanied the decline in water levels in wells on the ridge. Although the declines caused more problems, the increases were much more dramatic. Most increases are never reported, however, because the owner is not aware of the increase unless the well or spring begins to flow. Examples of documented increases in water level or flow include:

1. The water levels in some wells rose.
   - In USGS observation well MR-1364, the sudden rise was documented with a graphical recorder. Within hours of the earthquake, the water level in the well rose about 2 ft and did not immediately decline (fig. 6).
   - The greatest documented increase of water level was at least 62 ft, in well MR-615.
   - Five wells started to flow (fig. 7), including one in the basement of a house. The discharge of a previously flowing well also reportedly increased.
2. The flow of existing springs reportedly increased and new springs developed.
3. The water level in a 1/2-acre, spring-fed pond reportedly rose 6 inches within several hours after the earthquake.
4. Wet areas developed in fields after the earthquake, and one resident reported "mini-geysers."
5. The streamflow of the Little Shenango River increased slightly [about 0.4 ft^3/s (cubic feet per second) during the first 24 hours after the earthquake].

Explanation for Observed Water-Level Changes

The observed water-level changes indicate that ground water stored in the ridge between Jamestown and Greenville moved more rapidly from the recharge area (hilltop) to the discharge area (surrounding valleys)

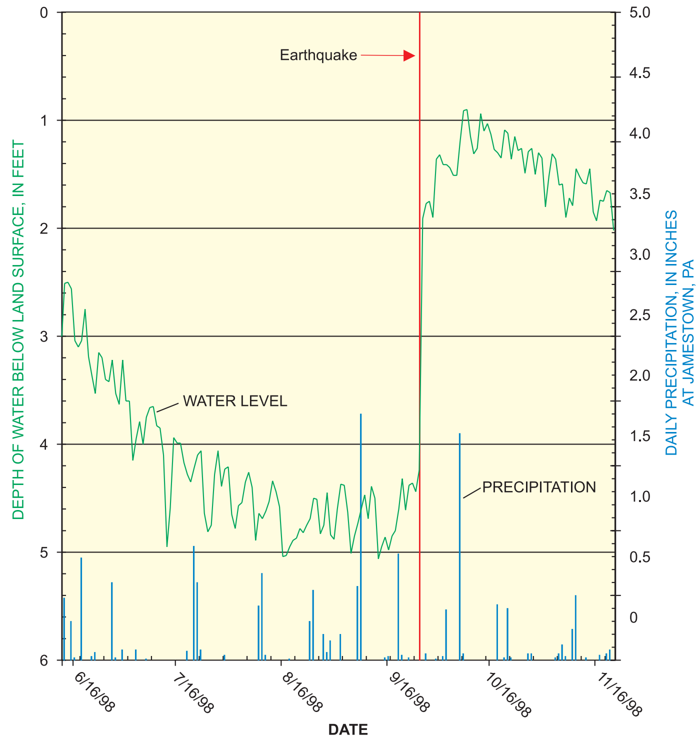


Figure 6. Sudden rise in water level in U.S. Geological Survey observation well MR-1364 within hours of the Pymatuning earthquake.

Figure 7. Well MR-3269 reportedly began flowing immediately after the Pymatuning earthquake.

after the earthquake than it did prior to the earthquake. Because almost all ground water in the ridge flows through fractures, either between layers of rock or through the layers, one hypothesis is that the earthquake either created new fractures or widened existing fractures in the rock. Increasing the size and (or) number of fractures increased the rock's hydraulic conductivity, which allowed the ground water to flow more rapidly to the discharge areas.

Shallow wells on top of the ridge went dry first because (1) the water table is deepest beneath the hilltop, and those wells probably had less water in them at the time of the earthquake than those on the ridge slopes, and (2) the greatest downward component of ground-water flow is beneath the hilltops, allowing for the most efficient drainage. Deeper wells on top of the ridge went dry later as the water table continued to decline. Wells further down the ridge slope did not go dry until later, probably because the ground-water flow has less downward component and more lateral component away from the ridge top. Also, the water table decline was not smooth over the ridge; zones of depression probably developed in the water table near the earthquake-enhanced fractures. For several months, these depression zones probably deepened and spread laterally (fig. 4). As the depression zones spread from the fractures toward the margins of the ridge, wells along the upper slopes were intercepted, causing them to go dry. Multiple enhanced fractures in various locations created complicated patterns of water-table decline.

The greatest concentration of water losses (80 wells in 10 mi^2) was on the ridge extending northwest from Greenville to Jamestown. Water-level declines were documented in almost every well above elevation 1,100 ft. Within a radius of about 15 mi from the ridge, water losses were reported for only 41 additional wells. An explanation for the concentration of water losses on this ridge may lie in the size of the ridge because:

1. The ridge contains less ground-water storage than other ridges, and ground water has a shorter distance to travel to its discharge area along stream valleys and at springs. The amount of ground water drained from storage is a much larger percentage of the total storage in this ridge than in adjacent larger ridges, allowing the water table to drop more quickly than in larger ridges.
2. Stress-relief fractures concentrated along the margins of a ridge comprise a larger percentage of the volume of this small ridge than larger ridges. Ground water, which flows more easily through these fractures, thus drains more quickly from this small ridge than from larger ridges.

Simulating the Observed Hydrologic Effects

A 3-dimensional, ground-water flow model was constructed of the ridge between Greenville and Jamestown where most hydrologic effects were reported. The model tests the hypothesis that the earthquake increased the hydraulic conductivity of geologic units, which caused the observed hydrologic effects (water-level declines beneath the ridge top and water-level and spring-flow increases on the lower hillsides and in the adjacent valleys). The model was constructed and adjusted to simulate hydrologic conditions that existed prior to the earthquake and then used to simulate the effect of the earthquake on water levels and streamflow.

Model Construction and Adjustments

The modeled area (same as the study area) was bounded by the Shenango River, Little Shenango River, and their tributaries (fig. 1). The area was divided for modeling purposes (Harbaugh and McDonald, 1996) using a grid with 77 rows, 36 columns, and 8 layers. Hydraulic properties were assigned to represent each geologic unit in the grid (fig. 8 and table 1). Except for the overburden and shale units, initial horizontal hydraulic conductivities were estimated by use of pumping-test data for wells in Crawford and Mercer Counties. The vertical hydraulic conductivity of alluvium and sandstone were assumed to be one-tenth of the horizontal value; for the overburden / weathered zone and shale, the horizontal and vertical hydraulic conductivities are assumed to be equal. Ground-water recharge of 10 inches per year was estimated from the average annual base flow of Little Shenango Creek from 1927 to 1997.

Figure 8. Cross section showing layers in the ground-water flow model that represent the geologic units of the ridge between Greenville and Jamestown. (Approximate location of the section is the western half of the trace shown in figure 2).

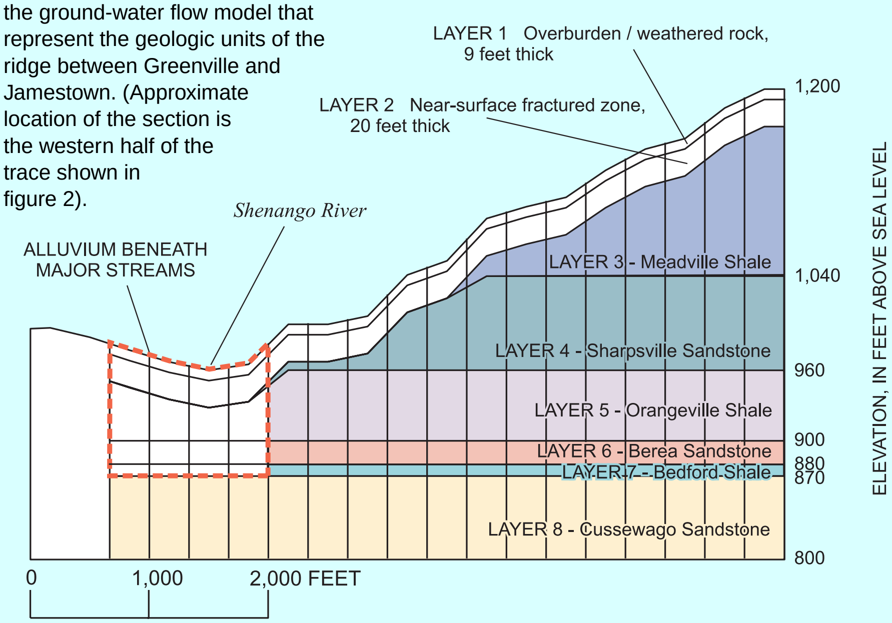


Table 1. *Hydraulic properties used to simulate the ground-water flow system before and after the Pymatuning earthquake (shaded blocks indicate change in property between pre-quake and post-quake simulation)*

[NC, no change; —, pumping test data not used for these layers, instead, a value of 0.003 foot per day was assumed]

Geologic unit	Model layer	Estimates of horizontal hydraulic conductivity from pumping tests (feet per day)	Final values used to simulate: Pre-quake conditions		Final values used to simulate: Post-quake conditions		Storage value—specific yield (dimensionless) or specific storage (per foot)
			Horizontal hydraulic conductivity (feet per day)	Vertical hydraulic conductivity (feet per day)	Horizontal hydraulic conductivity (feet per day)	Vertical hydraulic conductivity (feet per day)	
Overburden/weathered rock	1	—	0.004	0.004	NC	NC	Specific yield = 0.01
Near-surface fractured zone	2	[1] 0.7	.228	.0228	NC	0.228	3×10^{-7}
Meadville Shale	3	—	.004	.004	0.0228	.228	3×10^{-7}
Sharpsville Sandstone	4	3.5	1.14	.114	NC	NC	3×10^{-7}
Orangeville Shale	5	—	.004	.004	.0228	.228	3×10^{-7}
Berea Sandstone	6	7.0	2.28	.228	NC	NC	3×10^{-7}
Bedford Shale	7	—	.004	.004	.04	.04	3×10^{-7}
Cussewago Sandstone	8	3.5	1.14	.114	NC	NC	3×10^{-7}
Alluvium beneath major streams	Parts of layers 1-7	17.1	17.1	1.71	NC	NC	Same value as respective layer

[1] Initial estimate was from pumping-test data from wells completed in fractured-shale units.

Hydraulic properties in the model were adjusted (calibrated) until the model could closely simulate pre-quake water levels (fig. 9). The final hydraulic conductivities used in the pre-quake model are listed in table 1. During the model-adjustment process, increasing the vertical hydraulic conductivity of sandstone layers 4, 6, and 8 caused a decrease in the simulated water levels in all model layers. Increasing the hydraulic conductivity of shale layers 3, 5, and 7, however, resulted in a decrease in the simulated water levels in overlying units and an increase in the simulated water levels in underlying units. The adjustment procedure also showed that an increase in hydraulic conductivity of the shale (layers 3, 5, and 7) will result in a larger change in water level beneath the ridge top than beneath the hillside, which is consistent with observations that most wells that went dry were located on the ridge.

Ability to Simulate Post-Quake Conditions

The general pattern of water-level change observed after the earthquake was approximately simulated in the ground-water model by increasing the vertical hydraulic conductivity of the near-surface fractured zone and shale (model layers 2, 3, 5, and 7) by 10 to 60 times their pre-quake values (table 1). The general features of “observed” water-level changes (estimated on the basis of historical measurements and reports from homeowners and drillers) are large decreases in water levels in shallow units on the ridge and increases in water levels beneath valleys. Simulated water-level changes in the near-surface fractured zone (model layer 2) are compared to observed changes in figure 10. The model closely simulates where 25 ft of water-level decline was estimated but fails to simulate the estimated declines of more than 100 ft at the ridge top. Water-level increases were simulated by the model but not in the near-surface fractured zone (model layer 2) shown in figure 10.

Increasing the vertical hydraulic conductivity of shale also caused simulated water levels to rise in model layers 3 through 8 beneath the near-surface fractured zone (fig. 11). Because most deep wells in the area are open to the near-surface fracture zone, few measurements of water level are available for comparison to model simulations. The estimated water-level rise of about 62 ft in well MR-615 (open only to the Orangeville Shale, model layer 5), however, indicates that the large magnitude (20 to 80 ft) of water-level rise simulated in

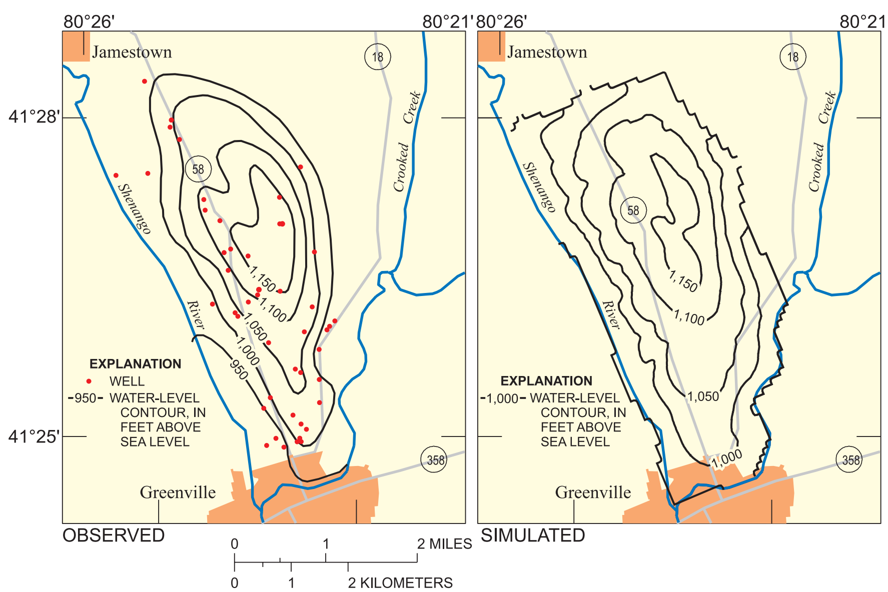


Figure 9. Comparison of pre-quake water levels “observed” in wells and simulated in layer 2 of the ground-water flow model. (Observed levels were estimated from historical measurements and reports from homeowners and drillers.)

the model for geologic units beneath the near-surface fractured zone may not be unreasonable.

Although it is difficult to directly compare the results of model simulation of hydraulic head in specific geologic units to water levels in household-supply wells that are open to several units, in general, the simulations of post-quake water-level changes lend plausibility to the hypothesis that the changes were caused by an abrupt increase in vertical hydraulic conductivity of the shale. Simulation results corroborate observations that (1) water levels declined rapidly within the first few hours after the earthquake in the shallow fractured zone, (2) water levels increased rapidly within the first few hours after the earthquake in deeper units that subcrop beneath the valley and ridge slope, and (3) water levels declined gradually for 3 months after the earthquake in all units; greatest declines were beneath the ridge top. In the deeper units, even after 3 months of decline, water levels are still higher than pre-quake levels, which also is consistent with observations that new flowing artesian wells and springs continue to flow in June 1999.

The simulated changes in hydraulic conductivity in the ground-water model also caused changes in simulated streamflow that are generally consistent with observations. During the first 24 hours after the earthquake, model simulations indicate ground-water discharge should have increased streamflow an average of 0.3 ft^3/s from pre-quake conditions. In comparison, streamflow at the Little Shenango River at Greenville increased an average of 0.4 ft^3/s during the first 24 hours after the earthquake.

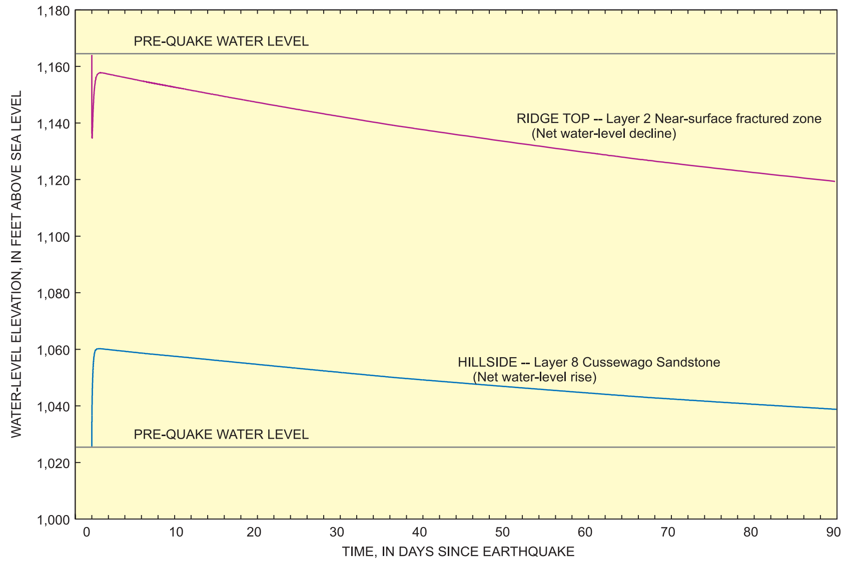


Figure 11. Examples of simulated water-level changes in different geologic units after the earthquake.

Comparison to Other Studies

Previous reports of earthquakes causing hydrologic effects in Pennsylvania have been limited to the observation of water-level fluctuations in wells lasting only several minutes (Vorhis, 1967). Longer-term hydrologic changes lasting for days, weeks, or months, such as those reported after the Pymatuning earthquake, have been documented outside of Pennsylvania by a number of other investigators (Rojstaczer and Wolf, 1992; Wood and others, 1985; Eaton and Takasaki, 1959; and Nicholson and others, 1988). For example, an earthquake in northeastern Ohio in 1986 caused hydrologic effects similar to those observed after the Pymatuning earthquake. Nicholson and others (1988, p. 192) attribute those hydrologic effects to the squeezing and expansion of aquifers caused by the earthquake. In northern California, the Loma Prieta earthquake of October 17, 1989 (magnitude 7.1), caused ground-water levels in the upland parts of watersheds to decline by as much as 70 ft within weeks to months after the earthquake. Rojstaczer and Wolf (1992) concluded that those declines resulted from an earthquake-induced increase in the hydraulic conductivity of bedrock. Similarly, an increase in hydraulic conductivity caused by the Pymatuning earthquake in northwestern Pennsylvania is believed to have resulted in the hydrologic changes reported in the vicinity of Greenville and Jamestown.

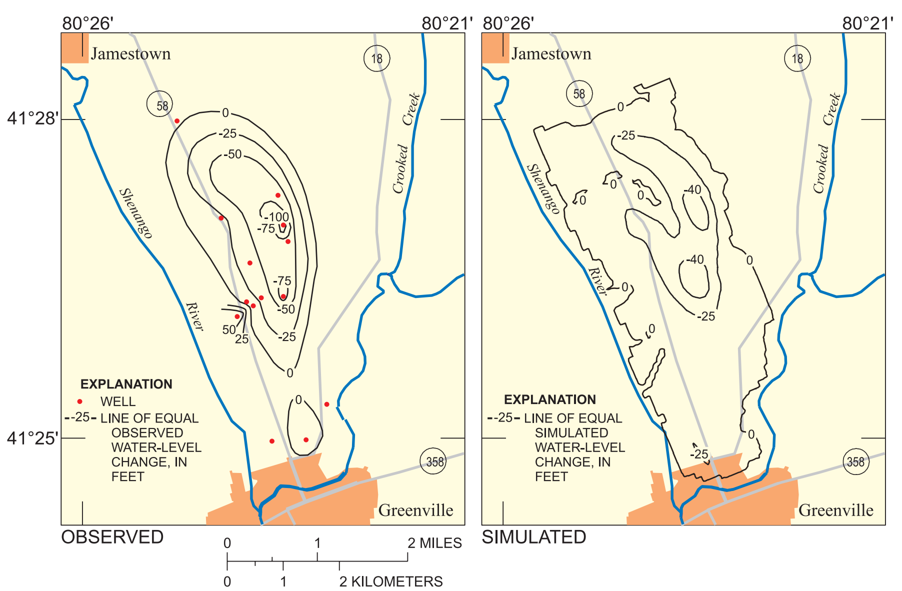


Figure 10. Comparison of water-level change "observed" in wells and simulated in layer 2 of the ground-water flow model from before the earthquake through January 29, 1999. (Observed levels were estimated from historical measurements and reports from homeowners and drillers.)

SUMMARY AND CONCLUSIONS

The Pymatuning earthquake of September 25, 1998, in northwestern Pennsylvania caused a number of hydrologic changes that were documented in this study. Within hours after the earthquake, local residents reported domestic wells becoming dry, wells beginning to flow, the formation of new springs, and black and sulfur-smelling water. The most serious effect of the earthquake probably was that about 120 domestic-supply wells went dry in the vicinity of the epicenter within 3 months after the earthquake. Drought conditions that persisted throughout the latter part of 1998 contributed to the problem.

Eighty of the wells that lost water were on a ridge between Greenville and Jamestown, which was the focus of this study. On that ridge, water levels declined a maximum of about 100 ft in one well. The ridge can be described as a "hydrologic island" where a shallow, local ground-water flow system in fractured bedrock is hydrologically isolated from local flow systems in adjacent hills by deeply incised stream valleys. The small size of the ridge compared to other ridges in the area probably was a factor that caused more wells to go dry on this ridge than on other ridges closer to the epicenter.

One possible explanation of the observed hydrologic phenomena is that the earthquake either created new fractures or widened existing fractures in the shale confining beds beneath aquifers. Increasing the size and (or) number of fractures increased the hydraulic conductivity of the shales and allowed the ground-water flow to increase. The increased ground-water flow would manifest itself as decreased ground-water levels beneath hilltops and increased spring flow and increased water levels at the base of ridge slopes.

Computer simulations of ground-water flow beneath the ridge between Jamestown and Greenville indicate that increasing the vertical hydraulic conductivity of shale confining beds about 10 to 60 times from their pre-quake values could produce a rapid decline in water levels in the shallow fractured zone on the ridge and a rapid rise in water levels in the deeper sandstone units that subcrop on margins of the ridge.

FOR MORE INFORMATION

For more information on the Pymatuning Earthquake, visit these web sites:

http://groundmotion.cr.usgs.gov/pym/pym.htm
http://www.dcnr.state.pa.us/topogeo/hazards/pymatuning.htm

For information on Pennsylvania Bureau of Topographic and Geologic Survey programs and activities in Pennsylvania, please visit their web site at ***http://www.dcnr.state.pa.us/topogeo*** or contact

Director
Pennsylvania Bureau of Topographic and Geologic Survey
P.O. Box 8453
Harrisburg, PA 17105-8453
Phone: 717.787.2169
Fax: 717.787.7267
email: dhoskins@dcnr.state.pa.us

For information on USGS programs and activities in Pennsylvania, please visit our web site at ***http://pa.water.usgs.gov*** or contact

District Chief
USGS, WRD
840 Market Street
Lemoyne, PA 17043-1584
Phone: 717.730.6900
Fax: 717.730.6997
email: dc_pa@usgs.gov

Additional earth science information can be found by accessing the USGS Home Page at ***http://www.usgs.gov***

For information on all USGS products and services, call

1.888.ASK.USGS
Fax: 703.648.5548
email: esic@usgs.gov

REFERENCES CITED

Armbruster, John, Barton, H., Bodin, P., Buckwalter, T.F., Cox, J., Cranswick, E., Dewey, J., Fleeger, G.M., Hopper, M., Horton, S., Hoskins, D., Kilb, D., Meremonte, M., Metzger, A., Risser, D.W., Seeber, L., Shedlock, K., Stanley, K., Withers, M., and Zirbes, M., 1999, Preliminary results from the investigation of the Pymatuning earthquake of September 25, 1998: Pennsylvania Geology, v. 29, no. 4, p. 2-14.

Eaton, J.P., and Takasaki, K.J., 1959, Seismological interpretation of earthquake-induced water-level fluctuations in wells: Bulletin of the Seismological Society of America, v. 49, no. 3, p. 227-245.

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for Modflow-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Nicholson, C., Roeloffs, E., and Wesson, R.L., 1988, The northeastern Ohio Earthquake of January 1986—Was it induced?: Bulletin of the Seismological Society of America, v. 78, no. 1, p. 188-217.

Poth, C.W., 1963, Geology and hydrology of the Mercer quadrangle, Mercer, Lawrence, and Butler Counties, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 16, 149 p.

Rojstaczer, Stuart, and Wolf, Stephen, 1992, Permeability changes associated with large earthquakes—An example from Loma Prieta, California: Geology, v. 20, p. 211-214.

Schiner, G.R., and Kimmel, G.E., 1976, Geology and ground-water resources of northern Mercer County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 33, 136 p.

Vorhis, R.C., 1967, Hydrologic effects of the earthquake of March 27, 1964, outside Alaska: U.S. Geological Survey Professional Paper 544-C, 54 p.

Wood, S.H., Wurts, Caroline, Lane, Ted, Ballenger, Nick, Shaleen, Mary, and Totorica, Delores, 1985, The Borah Peak, Idaho Earthquake of October 28, 1983—Hydrologic effects: Earthquake Spectra, v. 2, no. 1, p. 128-150.

Wyrick, G.G., and Borchers, J.W., 1981, Hydrologic effects of stress-relief fracturing in an Appalachian valley: U.S. Geological Survey Water-Supply Paper 2177, 51 p.