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Sinkholes and the Engineering and Environmental Impacts of Karst

Edited by Barry F. Beck

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PERFORMANCE AND EVALUATION OF PUMPING TESTS IN KARSTIC CARBONATE AND EVAPORITE AQUIFERS

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ABSTRACT: During the last four decades P. E. LaMoreaux & Associates performed several pumping tests in karstic terrains, including limestones, dolomites, and evaporates (gypsum/anhydrite, halite). Similarities and differences and/or variations in the size and shape of the cone of depressions formed by pumping in different karst settings are presented.

A wastewater storage lagoon failed due to development of a sinkhole at a site in the Lehigh River valley, Allentown, Pennsylvania. Five saturated zones were identified within the bedrock based on the analysis of cores and interpretation of geophysical logs. An aquifer test was performed to determine hydraulic characteristics (transmissivity, hydraulic conductivity, and storativity) of the karstified carbonate aquifer. The shape of the cone of depression was controlled by the geologic structure of the area and the discharge rate during the test.

Naturally occurring springs and seeps contribute a daily average of 3,300 metric tones of chloride to the Red River, Childress, Texas, through its tributaries. A drilling program was carried out to understand and delineate interconnection of subsurface fracture system and cavities in carbonate aquifers. A pumping test was performed to determine the number and location of wells, and pumping rates to control the brine discharge from the area. Transmissivity of the carbonate/evaporate bedrock aquifer system ranges from 149 m^2/d to 5,840 m^2/d, with an average of 2,108 m^2/d. The high value of transmissivity is indicative of the karst nature of the bedrock aquifer system.

Engineering and constructing a secure hazardous waste landfill in a limestone terrain in New York State (Niagara River corridor) required a geological, structural and hydrogeological investigation. A pumping test was performed to determine the isotropy/anisotropy of the aquifer, the vertical and lateral extent of the interconnected fracture system, and the existence or absence of any geologic and hydrogeologic boundaries.

Comparison of the three sites demonstrates wide variations as expected in hydraulic characteristics of aquifer system. The cones of depressions show anisotropy, and are oriented in a particular direction. Their size, shape, orientation depends on development of fractures system in karst settings, which are being tested. Typical orientations of

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cone(s) of depression in karst carbonate rocks correspond to water-filled primary conduits acting as preferred flow paths.

LEHIGH RIVER VALLEY, ALLENTOWN, PENNSYLVANIA

A process waste-water pond was constructed on the site of an industrial manufacturing plant in Allentown, Pennsylvania. The pond was constructed with a clay liner to prevent, or minimize, vertical infiltration of waste-water into the underlying karst aquifer. In 1979 a long dry weather spell was followed by heavy rains, which caused a sinkhole to develop under the waste-water pond. The pond clay-liner failed and large volume of waste-water moved quickly through the sinkhole into the underlying aquifer. The waste-water moved north of the ground-water divide because of mounding conditions caused by introduction of significant volume of waste-water into the underlying aquifer in a short duration. After the incident, ground-water samples were collected from existing domestic shallow wells in the area and analyzed to determine if ground water from these wells was polluted by waste-water. No pollution was identified in ground water from any of these local wells. Several years after the incident, two public water supply wells, and a test well, were constructed to the northeast of the Plant site, and after a few months of pumping from two public supply wells, pollutants were detected in the ground water. Pumping was suspended.

Surface water from the area to the north drains into tributaries of Coplay Creek (North of site). The surface water from the area south drains into Jordan Creek. Both creeks eventually discharge into the Lehigh River (Figure 1). Ground water in the area, also, ultimately discharges into the Lehigh River. The site is underlain by the Allentown Formation of the Cambrian Period, consisting of black to medium-light-gray dolomite with minor quantities of interbedded limestone, shale, and quartz sandstone (Figure 2). Bedding is generally 0.1 to 0.45 meters thick, but laminae than 1 millimeter and beds as thick as 0.9 meters are present locally. The shales of the Allentown usually occur as thin beds separating carbonate units. The thickness of the residuum varies significantly over relatively short distances, and ranges from 3 to 30 meters at the site. In the vicinity of the site the Epler Formation has been thrust over the Allentown Formation along the Portland Thrust Fault. Subsequently, the Epler, Allentown, and the intervening Portland Thrust Fault were folded into a series of east-west trending anticlines and synclines (Figure 2). Erosion has locally removed the Epler Formation, creating windows, in which the underlying Allentown Formation is exposed. The irregular shape of the windows and the trace of the Portland Thrust Fault are a result of the effect of erosion and the underlying geologic structure.

The Allentown Formation consisting of limestone and dolomite exhibits little or no intercrystalline porosity. Ground-water movement in the karst aquifer occurs along solutionally enlarged fractures and bedding planes. During drilling numerous voids or cavities were penetrated, some of which were clay-filled. Heights of the cavities range from a few centimeters to 1.5 meters. Caliper logs indicate that many smaller cavities may exist which were not identified during drilling. The carbonate rocks of the Allentown Formation act as a hydrogeologic unit under artesian conditions. These rocks contain and transmit ground water through fracture systems and cavities, which are developed within 50 meters to 146 meters bellow land surface. Secondary porosity and

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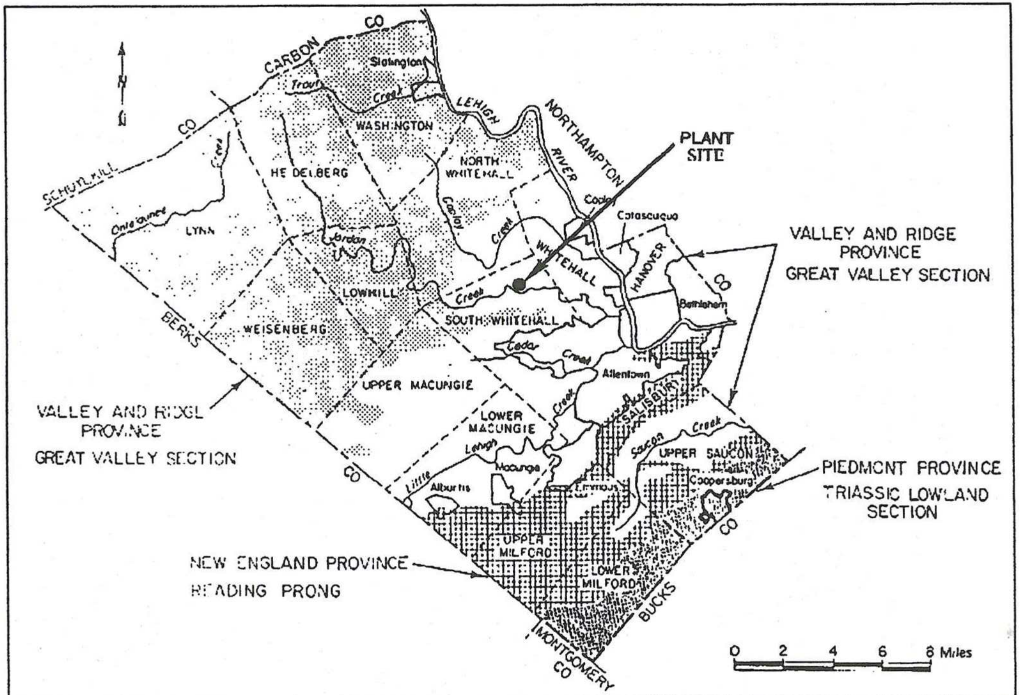

FIG. 1. Physiography of Lehigh County.

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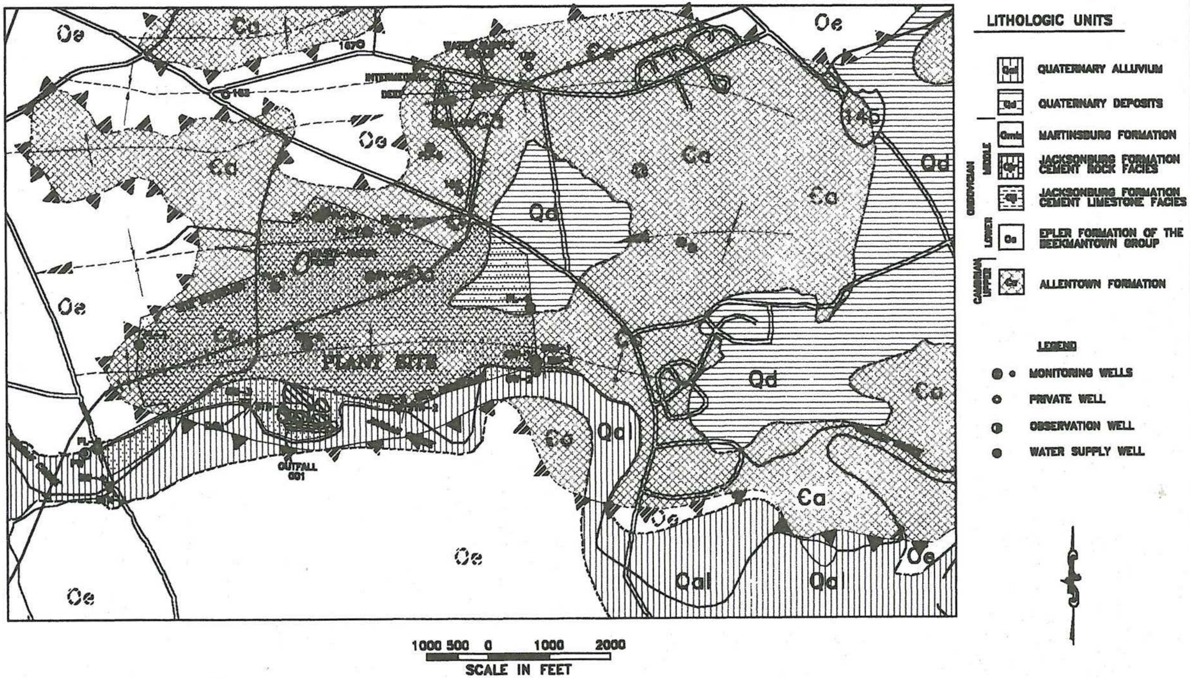

FIG. 2. Geologic map of the Lehigh River Valley, Pennsylvania.

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permeability due to karstification primarily control the ground-water flow regime in the area (location of wells and water level date are provided in Figure 3).

Aquifer tests were performed to determine hydraulic characteristics (transmissivity, hydraulic conductivity, and storativity) of the carbonate aquifer and evaluate the hydrogeologic conditions at the site. Test wells, observation wells, stilling wells, and pumping wells were equipped with Stevens recorders and/or electronic data loggers to collect water-level data on a continual basis prior to initiation of pumping tests, during, and after termination of pumping. The flow in Jordan Creek was measured at four stations during the pumping tests to determine if a hydraulic communication existed between surface water and the underlying carbonate aquifer (see Figure 2). The evaluation of ground-water level data collected during pumping test at the monitoring wells, surface-water hydrographs and flow data for Jordan Creek, indicated that there was no hydraulic communication between the creek and the aquifer during the pumping tests, at these locations.

The borehole for well PW was drilled 15 inches in diameter to a depth of 56 meters BLS (bellow land surface). Casing of 12 inches in diameter was set inside the well to a depth of 40 meters BLS. The well was completed as open hole between 40 and 56 meters BLS. Well PL-9 was drilled and constructed as an observation well for the pumping test. A borehole of 8-inch diameter was drilled using the air-rotary drilling method. The well was completed as an open hole from 39.6 to 49.0 meters BLS.

Pumping tests were conducted for 72 hours. The pumping well was pumped at a rate of 1.5 m^3/m. The maximum drawdown of 4.14 meters occurred in the pumping well PW. The total drawdown in observation well PL-9 located 55 meters northeast of pumping well PW was 1.92 meters. The drawdown and recovery data collected during the tests were analyzed. The value of transmissivity, computed from time-drawdown and time-recovery field data, ranges from 180 m^2/d to 600 m^2/d. Using a saturated thickness of the aquifer as 17 meters (depth of fractured open hole), the hydraulic conductivity was calculated to be in the range 10 m/d to 35 m/d. The coefficient of storage ranges from 1.1×10^{-2} to 9.8×10^{-3}.

Evaluation of cones of depression, which is in general circular, indicates little degree of anisotropy and non-homogeneity. The data further suggest that there is a well-developed fracture system, and karst aquifer behaves as a porous media continuum, and does not show a preferential flow system.

RED RIVER, CHILDRESS, TEXAS

Naturally occurring brine springs and seeps contribute a daily average of 3,300 metric tons of chloride to the Red River. The study area is located in Childress County, Texas (Figure 3). Brine discharge from this area is transported to the Prairie Dog Town fork of the Red River via Jonah Creek and contribution a daily average of 127 metric tons of chloride during the test period.

Pumping tests were completed to determine hydraulic characteristics of the karst aquifer. These aquifer characteristics were to be used to design a shallow collection well system to control brine discharge from the springs and seeps by lowering the potentiometric surface of the karstified carbonate aquifer system, and thereby improving the quality of the water in the Red River. Pumped water from the shallow collection

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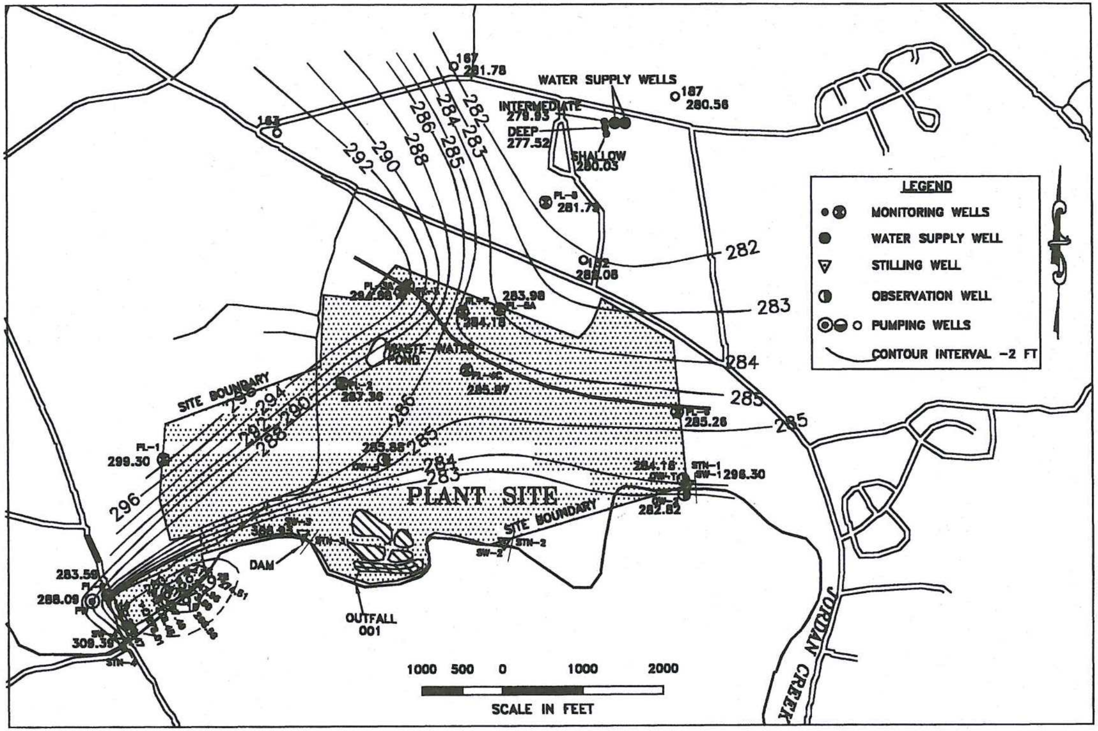

FIG. 3. Ground-water surface map of the Lehigh River Valley, Pennsylvania.

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wells after treatment was expected to be disposed of by injection into a deep brine aquifer at the site.

The study area is located just east of the High Plains in the Rolling Plains subdivision of the Central Lowlands physiographic province. Interbedded shale, dolomites and evaporites were deposited in a shallow Inland Sea, which covered the site during the Permian Period. The evaporites included gypsum, and halite. The Flowerpot Formation overlies the San Angelo Formation, and consists of shale interbedded with gypsum in the upper portion. Overlying the Flowerpot Formation is the Blaine Formation, 76 meters thick, containing numerous evaporite cycles of gypsum and dolomite separated by thin shale beds. Approximately 90 percent of the formation is evaporites. The lower member, the Elm Fork Member, has 3 evaporite cycles, each underlain by a thin dolomite. The upper member, the Van Vacter Member, has 7 evaporite cycles. The Acme Dolomite, the thickest dolomite of the Van Vacter Member, is part of the sixth evaporite cycle.

Within the salt-encrusted depression of the brine emission area, numerous springs and seeps are visible. The major source of salt water, a number of small springs with a west-to-east orientation, is along the southern boundary of the area. Springs within Jonah Creek are a direct conduit from the underlying bedrock. The salt flat area is devoid of vegetation and, under most climatic conditions, there is a thin crust of salt, 1 mm to 2 mm thick, covering the entire salt flat area. The groundwater is under artesian condition and potentiometric surface is relatively close to land surface. Capillary action brings saltwater to land surface, and the evaporation rate of the area precludes any accumulation of water, at the surface for runoff. In the vicinity of the seeps, the salt crust attains thicknesses of 7.6 centimeters. During rainstorms, the salt crust is dissolved and the upper portion of the alluvium is flushed with fresher water, sending the salt downstream. Springs and seeps occur because the potentiometric head of the brine is higher than the creek bed elevation, and the permeability of materials, in the discharge area is low compared to the surrounding area. As salt-laden ground water moves through bedrock with a relatively high permeability in conduit or fracture flow, it encounters the discharge area comprised of alluvium, with a relatively low permeability, intermixed with bedrock. Seeps flow from alluvium, and springs flow from fractures and openings in bedrock.

Ten piezometers were installed to measure water levels, determine the relationship between groundwater and surface water, and to serve as observation points for a pumping test. Two pumping wells (TWl and TW2) were constructed to perform the pumping test. Two Parshall flumes were installed in the creek to measure stream discharge (location of wells and flumes are shown in Figure 4).

Well TW1 was pumped at a rate of 3.8 m^3/m. Well TW2 was pumped at a rate of 3.2 m^3/m. The combined discharge rate from both wells was 7 m^3/m. A total of 65,970 cubic meters of brine were pumped from wells TW1 and TW2 during the pumping period of 7 days. No precipitation occurred during the test. Maximum drawdown in wells TWI and TW2 was 4.58 and 2.56 meters, respectively. Minimum flow at the upstream and downstream flumes, 1.35 m^3/m and 0.12 m^3/m occurred after the fifth day of pumping. Recovery began at 13:00 on 16 April 1996, when pumping from both wells (TW1 and TW2) was terminated.

Recovery data were collected for four days. In four days, the ground water had recovered to its pre-pumping level. Recovery data were also used to compute aquifer characteristics (transmissivity, coefficient of storage).

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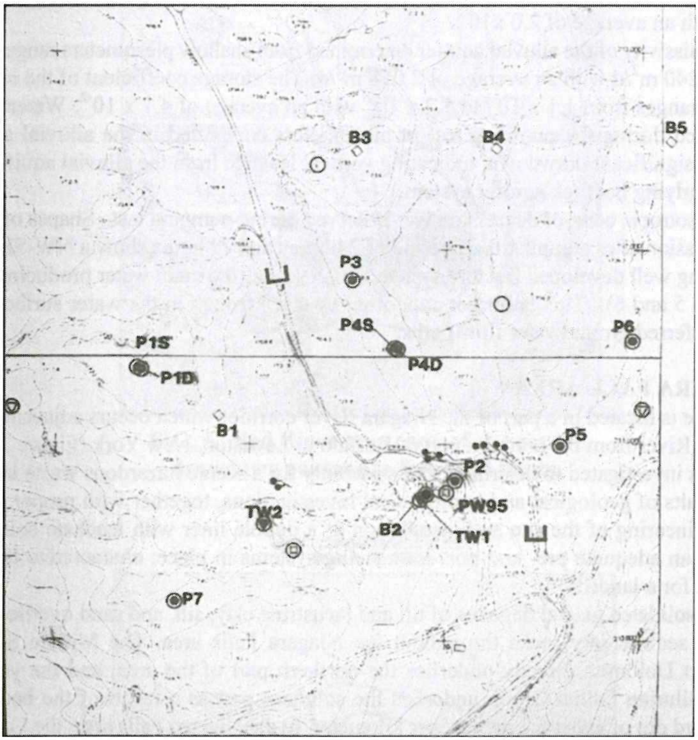

FIG. 4. Location of wells and flumes.

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Transmissivity values of the bedrock aquifer range from 149 to 5,840 m^2/d. Average transmissivity of the bedrock aquifer system is 2,108 m^2/d. The high value of transmissivity is indicative of the karst nature of the bedrock aquifer and its ability to transmit brine to the surface. The coefficient of storage ranges from 9.1×10^{-6} to 1.0×10^{-1}, with an average of 2.0×10^{-2}.

Transmissivity of the alluvial aquifer determined from shallow piezometers ranges from 50 to 4,240 m^2/d with an average of 2,058 m^2/d. The storage coefficient of the alluvial aquifer ranges from 1.1×10^{-1} to 5.2×10^{-3} with an average of 4.7×10^{-2}. Water levels monitored during the pumping test in piezometers completed in the alluvial aquifer showed significant drawdown, indicating vertical leakage from the alluvial aquifer into the underlying bedrock aquifer system.

An anisotropic cone-of depression was observed during pumping test. Shapes of cone-of depression after pumping for a period of 24 hours and 72 hours show a NW-SE trend indicating well developed fracture system which acts as the main water producing zone (Figures 5 and 6). This is further supported by steep trough in the water surface map over preferred groundwater flow paths.

NIAGARA FALL AREA

The site is located in a part of the Niagara River corridor which occurs adjacent to the Niagara River from the northern part of Buffalo to Lewiston, New York (Figure 7). The area was investigated to determine site suitability for a secure hazardous waste landfill. The results of geological and hydrological investigations, together with proper design and engineering of the site and installation of a double liner with leachate collection system; an adequate pre- and post-monitoring systems in place; characterize this site suitable for a landfill.

Unconsolidated glacial deposits of till and lacustrine clay, silt, and sand overlie gently dipping sedimentary rocks throughout the Niagara Falls area. The Middle Silurian Lockport Dolomite directly underlies the northern part of the area, and the younger Upper Silurian Salina Group underlies the southern part as a result of the bedrock's southward dip of about 6.2 meters per kilometer. In the Niagara Falls area, the Lockport Dolomite ranges from 40 to 49 meters in thickness and consists of five members that have been differentiated on the basis of lithologic characteristics and fossil evidence.

The Middle Silurian Lockport Formation, consisting of relatively competent dolomite, lies beneath the overburden in the Niagara Falls area. This unit thickens to the southeast and thins to the west toward the Niagara Gorge and to the north toward the Niagara Escarpment.

The Lockport Formation, which has also been referred to as the Lockport Dolomite (or Dolostone), is subdivided into five principal members: the Oak, Orchard, Eramosa, Goat Island, Gasport, and DeCew Members.

The Lockport' Formation is primarily dolomitic and characterized generally by brownish-gray to dark gray color, medium granularity, medium to thick bedding, stylolites, carbonaceous partings, vugs, and poorly preserved fossils. The Lockport is subdivided into its five principal members based on variations, within this general description.

The Rochester Shale Formation lies below the DeCew Member and is typically 17 to 20 meters thick in the Niagara Falls area. It is considered to be a principal marker

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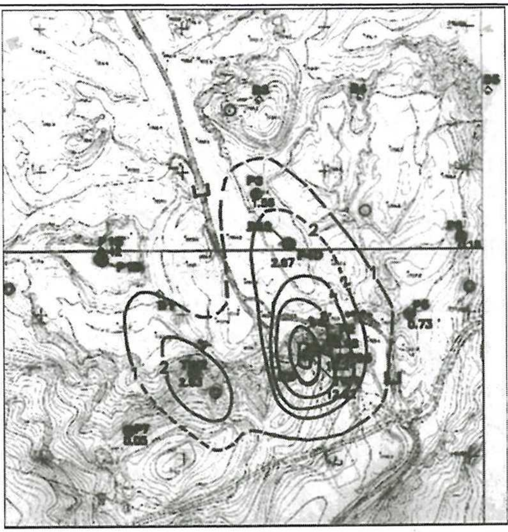

FIG. 5. Red River area cone-of-depression drawdown contour in feet at 24 hours.

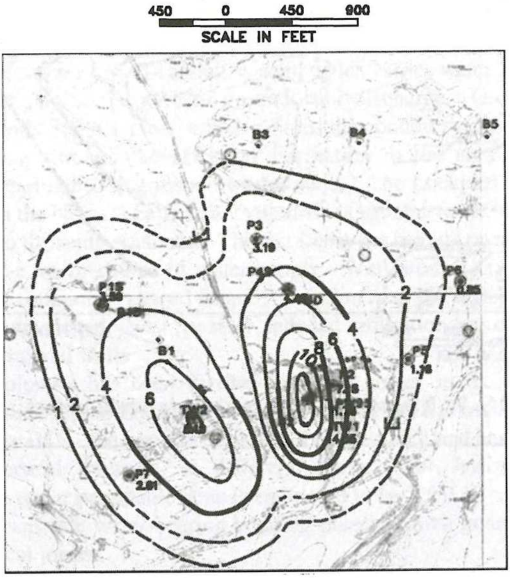

FIG. 6. Red River area cone-of-depression drawdown contour in feet at 72 hours.

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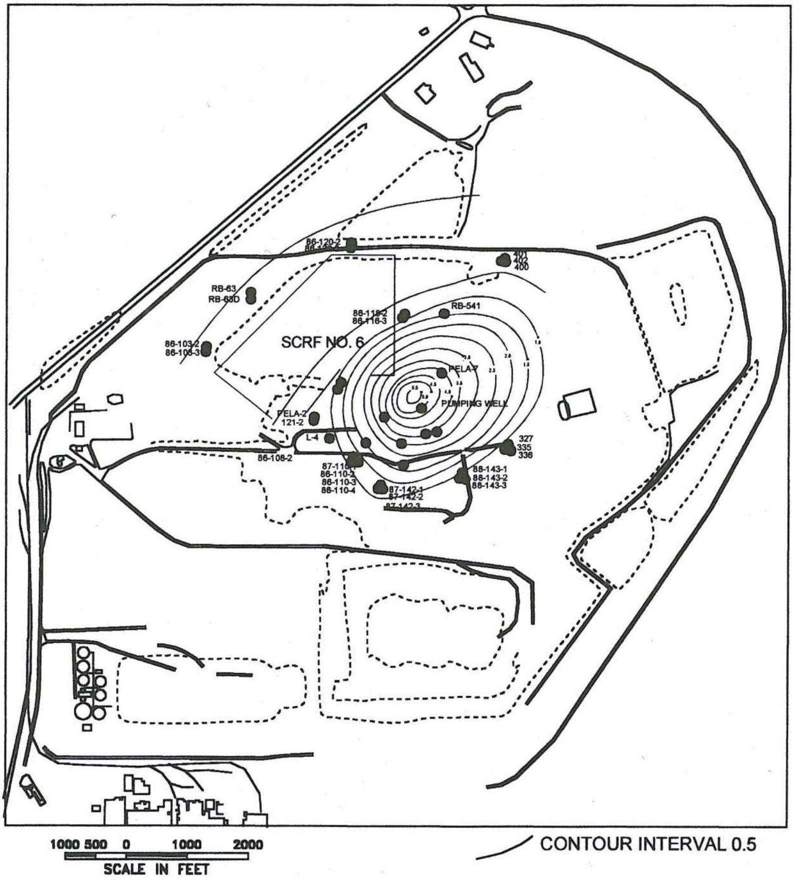

FIG. 7. Niagra Fall area contour interval in feet.

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horizon within the study area. It is described as dark bluish- to brownish-gray, calcareous shale with occasional argillaceous limestone layers. The upper Rochester Shale tends to be more dolomitic than the lower, especially at the contact with the DeCew. This contact, although gradational at most locations, tends to be more abrupt and undulating in the Niagara Falls area. This has been attributed to localized channeling at the top of the Rochester Shale in the Niagara Falls area prior to the deposition of the DeCew Member.

A south-dipping homocline, which affects the Paleozoic rocks of western and southern New York, is the dominant structural feature in the Lockport Formation, as well as in the sedimentary formations beneath it. Bedding dips are characteristically gentle. Local deviations in the dominant regional structure do occur, and may be attributed to monoclinal flexures and faulting. A large scale, tectonically related, structural pattern is believed to affect the rocks of western New York.

A series of bedding plane fracture zones were identified during site investigations. Over two hundred core observations were used to verify the depth of a fracture zone. Usually a weathered fracture or series of fractures were observed at approximately the same depth as noted by drilling fluid losses. A pumping test was performed to determine hydraulic characteristic of the aquifer. Moderate to high hydraulic conductivity test results, greater than 1×10^{-4} cm/sec, usually corresponded to water-bearing fracture zones where fluid loss was observed. Low hydraulic conductivity values, less than or equal to 1×10^{-4} cm/sec, usually corresponded to intervals where no circulation loss occurred.

Ground water in the Niagara Falls region generally flows southwestward from recharge areas near the escarpment toward the Niagara River, the major discharge zone. Near the city of Niagara Falls, however, the direction of flow has been altered by man-made structures. The Niagara Power Project Reservoir is a source of additional recharge to the Lockport Dolomite, and the buried-conduit system, which carries water from the Niagara River to the power plant, is a point of groundwater discharge. Ground water also discharges to the Falls Street Tunnel, which crosses the conduit system.

Ground water flow through the Lockport Formation in the area occurs through horizontal water-bearing bedding plane fracture zones. The Lockport Dolomite is the principal aquifer in the Niagara Falls area. The flow of ground water in the top-of clay and top-of rock is to the south-southeast. This aquifer is not heavily pumped because the Niagara River is the major source of water supply. Well production not affected by induced infiltration commonly, ranged from 55 to 545 m^3/day but high production 5178 m^3/d has also been developed. Near the river, induced infiltration augments yields from the Lockport to industrial wells.

The Lockport Dolomite has been divided into two zones on the basis of water-transmitting properties. Upper Zone starts at depth of 4 meters and second zone starts at a depth of 12 meters BLS. The upper zone is 3 to 8 meters thick and has well-connected horizontal and vertical fractures, at different depth. The horizontal hydraulic conductivity of the upper permeable zone is estimated to be 1.5×10^{-2} m/d. The lower zone contains the separate water-bearing bedding planes, which generally are poorly connected by vertical joints.

The design of the pumping test included the selection of the location of the pumping well and 56 wells, which were used as observation wells during the test. The selection of 56 observation wells was based on the review of the design and construction of these wells, (tapping separately three zones) and distance of each observation well from the

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pumping well to obtain as much hydrogeologic information for the site as possible. The observation wells were selected for all three transmissivity zones, top-of clay, top-of-rock, and bedrock wells.

The selected wells were equipped with instruments that included Stevens recorders, In-Situ meters, and a Data Logger to obtain a continuous recording of the fluctuation of water level in order to determine the water-level trend, effects of variation of climatological conditions, the impact of drilling and construction of wells at the site, and the grouting activities at adjacent sites. Continuous water-level data were also collected during the pumping test.

Before pumping, the groundwater levels in the well clusters were 1.72 to 3.61 meters higher in the top-of-clay zone than in the top-of-bedrock zone. The water level difference between the top-of-bedrock zone and bedrock zone was less than 0.3 meters. Therefore, the potential for gradient and vertical movement was downward during prepumping conditions.

A step-drawdown test was performed using four steps, pumping at rates of 0.5, 1.5, 2.0, and 3.0 liters/per second, to determine the rate at which the pumping well could be pumped during the 72-hour test. The step drawdown test was also performed to determine the extent of the impact so that the locations for the observation wells could be modified to collect all critical water-level data during the test. The step-drawdown test was performed for approximately 6 hours.

A 72-hour pumping test was performed. During the test, the well was pumped at an average rate of 86.4 m^3/d and 56 observation wells were monitored to determine the impact of the pumping on water levels. After termination of the pumping, water level recovery data were collected for a period of 48 hours from all observation wells and from the pumping well.

Water level measurements in the three zones indicated that the majority of vertical flow is between the bedrock and top-of-rock zones with relatively minimal flow between the top-of-clay and top-of-rock zones. The head difference between the top-of-clay and top-of-rock zones ranges from 1.5 to 3.6 meters, while the head difference between the top-of-rock and bedrock zones ranges from 0 to 2.4 meters.

The drawdown was computed and plotted in the form of contour maps for various time periods from 1 hour to 72 hours for the top-of-rock to determine the extent and configuration of the cone of depression, the degree of anisotropy, associated geological structural features, and solution channels and trends, and to graphically portray the impact on the water level in top-of-rock.

The results of the pumping test determined that the permeability of the top-of-rock, in the area of the test, ranges from the 10^{-2} to 10^{-3} cm/sec and that of bedrock ranges from 10^{-2} to 10^{-3} cm/sec. The storage coefficient in the area of the test generally ranged from 10^{-3} to 10^{-6} for top-of-rock and 10^{-2} to 10^{-5} for bedrock. The cones of depression were drawn for both top of rock and bedrock aquifer and evaluate through out the test period to determine the degree of anisotropy. Results obtained from the pumping test were indication of lateral and vertical extent of the cone of depression in the bedrock wells for a period of 72 hours (Figure 7). Evaluation of cone of depression, which is in general circular, indicates little degree of anisotropy and non-homogeneity. The data further indicate that there is a fracture system with a northeast southwest orientation.

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CONCLUSIONS

Pumping testes were performed in three karst-carbonated areas. The results of pumping tests show wide variations as expected, in values of hydraulic characteristics (conductivity, transmissivity, and coefficient of storage).

The cones of depression show anisotropy, and are oriented in a particular direction. Their size, shape, orientation depends on development of fractures system in karst settings, which are being tested. Typical orientations of cone(s) of depression in karst carbonate rocks correspond to water-filled primary conduits acting as preferred flow paths.

Highly jointed, fractured aquifer however behave as a continuous porous media system. In this case, cone(s) of depression are generally isotropic, and do not show preferred flow paths.

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