Hydrogeologic Assessment of the Zeba Creek Watershed

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Executive Summary

Geological information from geophysical surveys, and hydrologic information from static water level measurements and a regional pump-test were collected and compiled from September 2000 through May 2001 in order to characterize the hydrogeology of the Zeba Creek Watershed.

Acknowledgements

This study was conducted by a group of undergraduate students in an MTU Enterprise called Watershed Assessment and Planning under the guidance of Dr. John S. Gierke, Associate Professor of Geological and Environmental Engineering, Department of Geological Engineering, Michigan Technological University. We gratefully acknowledge the technical expertise of Dr. Jimmy F. Diehl, Professor of Geophysics, and Dr. Charles T. Young, Associate Professor of Geophysical Engineering at MTU, Casey Hagbo, Applied Geophysics Undergraduate at MTU. Financial support is provided by a grant from the US EPA, Region 5 Water Division. This study was conducted in collaboration with the Keweenaw Bay Indian Community under the supervision of Mr. Michael Donofrio, Tribal Natural Resources Director, and Ms. Carolyn Garcia, Environmental Specialist.

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1 Introduction and Background

Proper management of water resources for sustainable use and protection of water quality requires quantitative knowledge of various components of the hydrologic cycle (precipitation, evapotranspiration, runoff, etc.) and the watershed conditions (area, land use, etc.) and hydrogeological setting (subsurface geology, geochemistry, etc.). Development of quantitative assessments of the hydrological conditions requires field measurements and monitoring of stream flows, precipitation, groundwater levels, and water chemistry. While many of the needed measurements are based on well-established techniques, their applications to particular watersheds and climatic conditions will depend on factors that are regionally specific and maybe specific to a particular location if conditions are unique in terms of the terrain or land use. Therefore, a comprehensive monitoring plan should be flexible and adaptable to local conditions.

The Keweenaw Bay Indian Community (KBIC) has begun to develop comprehensive monitoring and assessments of their water resources, including both surface water and groundwater. Precipitation, stream runoff and chemistry, and subsurface geology were selected as the starting conditions and properties for long-term study. The Zeba (Little Silver) Creek watershed was selected in this first effort to evaluate watershed hydrology, including the subsurface hydrogeology. Zeba (Little Silver) Creek Watershed in Baraga County exists as a single system that discharges directly to Lake Superior (Figure 1).

This report summarizes the hydrogeologic assessment phase of the study. Data acquired from the following methods: geophysical surveys, static water level measurements, and a pump test were compiled and used to characterize the subsurface hydrology.

1.1 Study Area Location

The Zeba Creek watershed is located east of Keweenaw Bay and its area is approximately 3.3 square miles (Figure 1).

1.2 Watershed Characteristics

Comment: John- I listed what I thought was the pertinent geologic info, I'll let you determine what needs to be included from the ground water flow findings (p 9 of the USGS report).

1.2.1 Land Use

The area is mostly hardwood and aspen forest with fewer than 30 residential homes along Pequaming, Skanee, and Haataja Roads (Figure 1) and no industrial activities other than areas being logged within the watershed boundaries. The topography is characterized as hilly, with an overall elevation difference of 150 meters (Pikes Peak down to L. Superior, over a stream course distance of almost 6000 m).

1.2.2 Soil Types

Surficial deposits are of glacial origin (cf. Sweat and Rheaume, 1998). The importance of the soil types for this work is the influence of soil conditions on surface runoff, base flow to Zeba Creek, and recharge to underlying bedrock aquifers. All of the wells in the study area are fully cased through the glacial deposits overlying the bedrock aquifers, so the unconfined aquifers in the unconsolidated glacial deposits are important only for their ability to transmit water to the underlying rock and laterally towards Zeba Creek.

Soil types have been characterized by the U.S. Department of Agriculture Soil Conservation Service (Figure 2). The soils in this watershed are predominantly loamy sands and sandy loams, containing significant clay fractions (> 5%, which affects the response of the resistivity and ground-penetrating radar geophysical surveys). The soils are considered to be moderately to poorly drained and consist of Munising, Skanee, Assinins, Yalmer, and Gay series, and complexes thereof. The permeability of these soils vary over two orders of magnitude (0.06-6.0 inches/hour according to the SCS survey). Thicknesses vary from almost zero to10 meters.

1.2.3 Geology

Based on drillers' logs, the primary rock type underlying the Zeba Creek Watershed is Jacobsville sandstone (Figure 3 and cf. Sweat and Rheaume (1998)). The surface of the Jacobsville sandstone is weathered in many places and likely not in areas where well yields are low. The Jacobsville sandstone thins towards the southeast boundary of the watershed and is underlain by Michigamme Slate (see the east half of the West-East cross-section in Figure 3 and geologic map in Sweat and Rheaume (1998).

1.2.4 Hydrology and Hydrogeology

Historical hydrological data is available in two publications, Sweat and Rheaume (1998) and Doonan and Byerlay (1973). Groundwater flow in the eastern region of the Keweenaw Bay watershed is generally to the northwest draining into the bay from a divide approximately 5 km inland from the eastern shore. The water level elevations were found to range from 183 m at the bay to about 340 m at the divide.

1.2.5 Climate

Temperature and precipitation are the primary climatic conditions important for this hydrological evaluation. A NOAA weather station is located only a few miles south of this study area. The observations are available from http://www5.ncdc.noaa.gov/cdo/info.html. In April 1999 rain gages were installed at 16 local residences/businesses/agencies across the L'Anse Indian Reservation and monitored by volunteers on a daily basis. In June through October of 1999, the average precipitation was 15.86 inches (Gierke, 2000). Annual average precipitation in Baraga from 1967 through 1980 was 36.93 inches, 18.15 inches from June through October, according the SCS Soil Survey.

2 Objectives and Scope

2.1 Objectives

2.2 Scope

3 Study Approach

The evaluation aspects

3.1 Geophysical Methods

Three geophysical methods were employed in this work. Four resistivity surveys and two seismic refraction survey lines were performed on 11 November 2000. Due to the early snowfall and protracted snow melt, additional surveys were delayed until late April and early May 2001. In addition to more resistivity and seismic-refraction surveys, ground-penetrating radar (GPR) surveys were performed in the spring. The underlying principles and details for performing these types of geophysical surveys are summarized in the Workplan for this project and reported in detail by Reynolds (1997).

The most reliable results were obtained with the seismic refraction surveys. They surveys and data analysis were designed and interpreted, respectively, by assuming that the underlying soil and rock layers were horizontal and that the velocity of the seismic waves were faster in the rock than in the soil.

The resistivity surveys were used, in part, to check the validity of the slower-over-faster seismic-velocity assumption. Resistivity alone yields a non-unique solution, because both depth and electrical conductance are unknown. The assumption of two horizontal layers (more electrically resistive overlying less electrically resistive) was also used in the resistivity data analysis.

Uncertainty about the reliability of the seismic and resistivity surveys conducted in the Fall of 2000 led us to think that using a third geophysical survey method, ground-penetrating radar (GPR), would be a worthwhile addition to our subsurface characterization activities. Although relatively faster to perform compared to seismic refraction and resistivity, the data interpretation requires highly skilled, experienced personnel. We collected and interpreted the data under the guidance of Dr. Charles T. Young, Associate Professor of Geophysical Engineering at Michigan Technological University. The results corroborated the trends observed in with the seismic refraction surveys, but the actual depths differed between the two. Like resistivity, GPR relies on assumed subsurface sound velocities and so the depth results from GPR are non-unique.

3.1.1 Seismic Refraction

Seismic refraction is an active method of geophysical testing that is used to determine variations in the depths and thickness of geological layers and can also be used to locate the groundwater table (Figure 5). A high-energy output source is used to create a vibration at the surface that propagates through the subsurface and is refracted by the changes in geology and/ or water content. A line of geophones at the surface are used to measure the propagating waves and the times of their arrivals. The arrival times at the geophones are recorded and used by a seismograph (SmartSeis) to calculate the depths.

Seismic surveys were conducted at locations 16NS and 16EW in the Fall of 2000 A "Betsy Seisgun" was used to generate an energy source via an 8-gauge Betsy Downhole

Percussion Firing Rod firing between 350- and 500-grain black powder charges. Standard operating and safety guidelines were followed as outlined in the Betsy Seisgun manual. Compared to a sledgehammer source, the Betsy Seisgun produces a higher energy output source. The increased energy output increases the frequency acoustic impulse to allow for better data acquisition at shallow stratigraphic depths.

The refracted waves were received at twelve geophones spaced 5-meters apart along a 180-meter long survey line. An inertial switch attached to the hammer was used to trigger the timer in the seismograph when the Betsy Seisgun was fired. The survey consisted of 90-meter forward and reverse off-end shots, 1-meter forward and reverse off-end shots and a split shot. The depth of the BDP for each shot was approximately 18 inches below the ground surface.

Two seismic refraction survey lines were performed at 8NS (Figure 4) at the end of April 2001. Both surveys were conducted using 12 geophones spaced 1-meter apart. Due to high water contents in the soils at this time of year, sound waves were produced by repeatedly hitting a steel ball on the ground surface with a sledgehammer, a procedure called "stacking." In order to stack the seismic data. Shots with the hammer were done at 1-m off-end and 5 m off-end, forward and reverse to the geophone array. Split shots, in the middle of the geophone array, were also conducted. The first geophone of the first survey was located at 5184883.935 m N, 392907.235 m E. The twelfth geophone on the second survey was located at 5184917.043 m N, 392907.543 m E.

3.1.2. Ground-Penetrating Radar (GPR)

Ground-penetrating radar (GPR) is a geophysical technique using radar attributes to investigate the location of bedrock and the water table. There were several physical and logistical restraints in this project regarding the use of GPR. One physical restraint was the winter season with high levels of snow and cold temperatures. This prevented the surveys from being performed until most of the snow was gone and the roads were accessible. The surveys were performed in April of 2001. Another constraint involved the level of expertise that the undergraduates held in the area of GPR interpretation. Data from a GPR survey is difficult to interpret and can have several different interpretations, even for experts with several years of experience. This made it difficult to use GPR as a sole form of subsurface delineation. In addition to the lack of expertise in interpretation, it was also necessary to have a professor in the department perform the surveys with the students at all times. This was because of the complexity of the equipment and the computer.

The approach taken with using the GPR began with identifying appropriate survey areas that would assist us in characterizing the watershed corroborate past and future geophysical surveys using other methods. It was decided that a GPR survey would be performed at 16EW (Figure 4), where previous surveys were done in the fall. It was also decided that a second survey would be performed in a new area combined with Resistivity. The new survey area was on the southeastern side of the Zeba watershed (21SE & 28EW, Figure 4This survey area was also chosen due to the close proximity of well logs with subsurface data for comparison of the survey results.

3.1.3 Resistivity

Resistivity surveys were conducted along survey lines 16NS, 15EW, 28EW, and 21SE. Resistivity instruments measure the ability of subsurface layers to conduct an applied current and measures vertical changes in the hydrogeology of the survey area (Figure 6). In the field, ground resistance is measured and then multiplied by a geometric constant. The geometric constant is unique to the particular electrode array being employed. This results in the apparent resistivity values that are plotted on log-log graph paper as a function of current electrode half spacing. The data are then modeled with the Resist3 computer program to determine depths and thicknesses of subsurface layers, such as the water table and bedrock.

The electrode array employed was a Schlumberger array (Reynolds, 1997). The potential electrode half spacing was fixed at 0.4, 2, 4 and 20 meters as the current electrode half spacing was increased progressively from 3 to 250 meters along each survey line. The current electrodes were steel rods, the potential electrodes were copper sulfate porous pots, and an ABEM SAS 300 Terrameter recorded ground resistance readings.

3.1.4 Global Positioning System (GPS)

A Trimble GPS receiver was used to record survey locations. Before any readings, the height from the ground to the base of the GPS receiver was measured and entered into the Trimble hand unit.

For every seismic survey, five point locations were taken at each sounding source. The seismic sources were located in the middle, each end, and 90 meters off each end of the geophone spread. Five readings were recorded at each point as more readings increase the accuracy of the data.

For the resistivity surveys, the electrode line was recorded along each survey. Also, the center point of the resistivity line was recorded as a nested point on the Trimble receiver.

The hand unit files were transferred onto the computer using Pathfinder Office software. The coordinates were then differentially corrected with correction files attained from the Michigan Technological University GPS Base Station, which is the nearest base station to the Zeba Creek Watershed. The correction files were downloaded from http://emmap.mtu.edu/gps/mtu/.

3.2 Slug Test

A slug test was conducted to determine the hydraulic characteristics of the Jacobsville sandstone formation underlying the Zeba Creek Watershed. The well used for the pump test was located on Skanee Road at the residence of R. Haataja 46°47’46.6” North; 88°23’44.6” West in an abandoned water well. This well was abandonded because it would not yield sufficient flow for the Haataja household. It was selected because of its availability.

The slug test was conducted by first installing a Solinst LT Levelogger Model 3001, which was capable of recording water level and temperature at prescribed time intervals. The well was pumped down 85 feet from the static water level in a very short time (< 11 minutes). The Levelogger recorded the recovery of the water level in the well.

The pertinent assumptions for analyzing the slug test recovery are:

- Darcy's Law is valid.
- Only the pumping causes changes the potentiometric surface.
- The geologic formation is horizontal and of infinite extent.
- The potentiometric surface is horizontal prior to pumping.
- The aquifer is bounded by a top and bottom-confining layer.
- The aquifer is homogeneous and isotropic.
- The potentiometric surface does not change with time.
- Ground-water flow is horizontal and flows radially into the well.
- The pumping well and well screen are fully penetrating.
- The pumping well has an infinitesimal diameter and is 100% efficient.

The water level before pumping began was approximately 17.5 ft below the well casing, as measured with a Solinst water level meter Model 101-P4/M2. Larson Well Drilling located in L'Anse Michigan pumped the water out of the well at an average rate of 12.9 gal/min for 10 minutes and 58 seconds. Flow rates were measured six times throughout the pumping and averaged. When pumping ceased, the Levelogger recorded waterlevel readings for about 48 hours.

The equipment used for measuring the pump flow consisted of a 5-gallon bucket and a stopwatch. The 5-gallon measurements were divided by the time it took to fill the bucket and the flow rate was recorded. From the time-weighted average of the flow rate measurements, the volume of water removed from the well was about 150 gallons. The measured flow rate does not affect the analysis of the recovery data and was recorded to insure that the water withdrawn from the well could be attributed to the pumping of the well down.

The head readings from the logger were saved as an Excel file and exported to AQTESOLV version 3.0 for Windows. Analysis of the data was interpreted using the Cooper-Bredehoeft-Papadopulos (1967) method.

3.3 Potentiometric Surface

Data for constructing a potentiometric map was obtained by direct readings of static water levels in residential wells (Figure 4). Priority was given to locating wells within the watershed and measuring their static water level. After acquiring data from these wells, in order to create the most complete contour map possible, data was obtained from 4 wells outside the watershed, including two wells within the adjacent Silver River watershed. Fieldwork was delayed due to snow coverage, which put a time constraint on the process of gathering data.

Based on previously documented well locations from well log data, GPS (Trimble, Sunnyvale, CA) coordinates and elevations were determined for selected wells within the watershed boundaries. The GPS measured locations to submeter accuracy. The static water level was measured in each well using a Solinst (Solinst Canada Ltd., Ontario, Canada) water-level meter. The locations, elevations and static water level measurements were contoured using the Surfer contouring software to produce a potentiometric surface contour map.

4 Results and Discussion

4.1 Geophysical Surveys

4.1.1 Seismic Refraction

Frozen soil was a limiting factor when conducting the surveys. A theoretically faster-velocity top frozen layer masks or attenuates the sound wave to the layers beneath. This feature prevents sound waves from refracting off the lower layers, and a complete characterization of the subsurface is not possible. Time constraints also made it difficult for group members to meet and to conduct the surveys.

The refraction data were interpreted using a 3-layer best fit model. The program, SIPQC, is contained within the SmartSeis seismograph that was used to record the data. Layer 2, presumably glacial till, is approximately 1-2 m deep (Figures 1 & 2). The velocity for this layer is approximately 550 m/s, a typical velocity for an unsaturated gravel/sand deposit. The third layer is presumably saturated till. The depth to the top of the saturated till is approximately 4-5 m (Figures 1 & 2). Its velocity is approximately 1200 m/s, faster than the above-unconsolidated unsaturated sediments. This velocity is slower than the expected Jacobsville bedrock velocity of approximately 2000 m/s. When comparing the depth to bedrock at location 5184802.010 m N, 392882.803 m E, the elevation of a Jacobsville outcrop is 216.784 m. The elevation of the 2 seismic surveys along Johnson Rd. were approximately 223 m. If the Jacobsville bedrock continues to be uniform over that short distance (80-100 m) from the outcrop to the Johnson Rd surveys, the seismic waves attenuated before the bedrock by 2-3 m.

Observing the data on Table 1, depths and velocities are approximately the same as the above SIPQC solution. The solutions to Table 1 were done using the travel time calculations for a three-layer case on pp. 284-285 of Reynolds (1997). Figures 3 & 4 have the hand drawn layers for the solutions in Table 1.

Using the sledgehammer, sound waves may not have penetrated as deep into the bedrock if one was using a more powerful sound source. A longer geophone array or more geophones may have let the survey record deeper arrivals. On the second survey conducted, geophones 10 and 11 were malfunctioning and recording a time arrival that was much too shallow compared to the other data. These 2 geophones arrivals were not used in the data interpretation, and time picks could be interpolated due to correct picks at geophones 9 and 12. The SIPQC files can be found on the MTU SmartSeis seismograph, with the file paths: D:\99\LANSE\042508.BKP & \042503.BKP.

Additional geophysical surveys were not conducted at this particular location. Because of this, the interpreted seismic data cannot be confirmed by other methods other than surveys in other areas of the watershed and/or well logs.

4.1.2 Ground-Penetrating Radar

The results of the GPR survey from the Gated Road are displayed in Figure 1. This is a cross section of the radar data collected using a subsurface velocity of .062 meters per nanosecond.

The velocity was obtained through a common midpoint GPR survey. The results of the common midpoint survey are displayed in Figure 2. The survey line was 100 meters long. The UTM endpoint coordinates taken using the Global Positioning System (GPS) were a North of 5185169.872 meters with an East of 395271.848 meters and a North of 5185170.920 meters with an East of 395172.396 meters. The antenna used had a 50 MHz frequency. The GPR was able to obtain data to a depth of approximately 10 meters based upon the capacity of the GPR equipment used and the velocity of the subsurface. Figure 3 displays the seismic data obtained from the SIPQC function off of the seismograph. This figure displays the interpreted depth to the bedrock in this area.

The results from the GPR survey for the Two Track Road are displayed in Figure 4. This is a cross section that was formulated using a velocity of .062 meters per nanosecond. The results from the common mid point are displayed in Figure 5. This survey had a combined length of 200 meters. Figure 6 displays the GPR data from the first 20 meters of the survey using an AGC gain function. The UTM coordinates of the end points of the survey line were a North of 5183088.814 meters with an East of 396120.357 meters and an altitude of 285.414 meters, and a North of 5182936.090 meters with an East of 396120.357 meters and an altitude of 290.375 meters. This survey also utilized a 50 MHz antenna frequency.

The interpretation of the GPR at the Gated Road was difficult and allowed for a high degree of interpretation. The velocity obtained from the common midpoint survey clearly indicated that the subsurface down to 10 meters was saturated sand. Due to this distinct velocity, it is hard to distinguish a clear bedrock surface. In observation of the cross section, it is also difficult to see a distinct layer in Figure 1. A possible explanation for this inconclusive data is that the soil above the bedrock may be similar in characteristics as the upper region of the bedrock. The upper region of the bedrock may be fractured with clay and sand filling in the cracks. If this is the case, it explains the lack of discrete layers and velocities. However, when compared to the seismic survey that was performed at this location in the fall of 2000, there appears to be a similar trend in the subsurface occurring. Following the seismic survey from East to West, the bedrock begins dipping downward and is about at 4 to 5 meters below ground surface. In observation of the GPR results, there also appears to be a dipping of subsurface from the East to West direction. With this comparison to the seismic, it is best estimated that the top of the bedrock is approximately located at 4 to 5 meters below ground surface.

The interpretation of the GPR at the Two Track Road is also highly interpretable. In observation of Figure 6, there appears to be a continuous signal at approximately 7 meters. This can be seen if the figure is observed looking down the page horizontally rather than looking directly at the printout with a "birds eye view". The near by well logs in Section 22 indicate that the depths to sandstone vary from 5.5 meters to 7.6 meters. This correlates well with the GPR interpretation.

In observation of Figure 4, the Two Track Road cross section, the GPR signal from 100 to 200 meters appears very sporadic and unnatural in a subsurface sense. After the survey was completed, it was observed that there were several metal objects alongside the road. These large metal objects, such as old washing machines and bedsprings, interfered with the GPR signal and left this part of the survey line unusable for interpretation.

4.1.3 Resistivity

The resistivity readings do not show depth to the water table for the survey area. This could be due to the near proximity of the water table to the surface. The measured depths to the bedrock are 15.7 meters to sandstone bedrock at Logging Two-track, 16.5 meters to bedrock at Haataja road, 5.6 meters to bedrock at Pikes Peak road, and 7.9 meters to bedrock at Lost Carcass road. These readings are about fifty percent larger than those found from seismic surveys. This may or may not be a problem. Sometimes, resistivity readings are off by a geometric factor of the real depths. This may be the case with the data collected for this study.

Comment: Do we need to say more about this, is further investigation of the site area needed to dispel this uncertainty?

Comment: What needs to be done to determine if this is this case? Looking for an answer to this in the recommendations.

4.2 Slug Test

Data collected from the Levelogger is listed in Table 2. The head data was plotted against time in AQTESOLV and the curve was matched using the Cooper-Bredehoeft-Papadopulos solution as shown in Figure 10.

Comment:

When fit to the Cooper-Bredehoeft-Papadopulos curve, the aquifer transmissivity was calculated to be 0.045 m^2/day (0.49 ft^2/day or 3.7 gal/ft/day) and the storativity was $2.3(10^{-5})$. The data fit the curve well with a standard error of 0.003 and the variance was less than $1.2(10^{-5})$. The Cooper-Bredehoeft-Papadopulos automatic curve fit in AQTESOLV computes the standard errors of the estimated parameters to make a best possible fit. This method of analysis is based on the assumption that the aquifer acted as if confined. The Levelogger has a published accuracy of ±0.1 ft.

The measured transmissivity gives a lower limit for potential well yields in the Jacobsville sandstone, that is one could expect at least 3.7 gallons of water per day per foot of depth into the sandstone. This value is much too low for even low water demands, such as a family. The observation of the slug test results are interpreted to represent the flow characteristics of relatively unweathered, unfractured Jacobsville sandstone. Wells that produce water at useable rates are probably drilled in more weather and/or more fractured sandstone areas.

4.3 Potentiometric Surface

Twelve wells were located via GPS. Four of these were found to correlate to past well logs. Water levels were measured in all twelve wells. These elevations were then contoured onto a map using Surfer software.

5 Conclusions

The depth to unconsolidated glacial till along Johnson Rd. is approximately 1-2 m deep. The depth to the water table/saturated glacial till is approximately 4-5 m deep. GPR and resistivity surveys were not conducted at the same location of these 2 seismic surveys. Approximate depths to the Jacobsville from global positioning system (GPS) coordinates, well logs and previous geophysical surveys were between 5-15 m.

Despite the inconclusive data from the resistivity surveys the data compiled by the other geophysical methods is consistent with previous information based on well log data. With data from the pump test and the static potentiometric surface plot for wells in the watershed, enough data has been obtained to proceed with the hydrogeologic modeling. Increased reliability and accuracy could be achieved by conducting more surveys where a backup method is lacking. As was mentioned previously even without a backup, the data checks between the individual survey methods and with previously acquired information. The geophysical surveys allow for a broader area of coverage and more accurate interpolation between survey lines,. Most of the data was collected along the western extent of the watershed. Along with the individual recommendations mentioned within the report further investigation of the eastern or southeastern reach is recommended for a more complete hydrogeologic perspective of the watershed.

6 Recommendations

New seismic surveys should be conducted in the southern region of the watershed, so that the majority of the watershed can have refraction surveys conducted over it. Resistivity and/or GPR surveys should be done at the same locations as the seismic, so that data can be correlated and be more concrete. The geophysics surveys should be done as early as possible in the school year, and emphasis on getting the surveys done should be a priority. Data should be interpreted as quickly as possible. Field interpretation is helpful to see if the time arrivals are stacked adequately or whether the geophone arrays need to be changed. It is helpful when different groups can go out into the field together, but this is not essential.

The use of GPR to find the subsurface bedrock depths was somewhat helpful in the overall characterization of the watershed. The surveys tend to be quick and simple as long as the equipment is in working order relative to the resistivity and seismic surveys. However, as stated above, this technique involves heavy interpretation of results and may not always be best to use as the sole source of interpretation. For future use, it is recommended to use GPR as a backup form of geophysics versus as a primary technique. First, try to create a cross section of the subsurface from well log data. Second, use a seismic survey to find the depth to bedrock or the water table. If the well logs are too few and far between to achieve enough small-scale data, it may be worthwhile to perform a GPR in conjunction with a seismic survey. It is also recommended that the surveyors take note of the surroundings in case there is a high amount of metal that may interfere with the signal before performing the survey.

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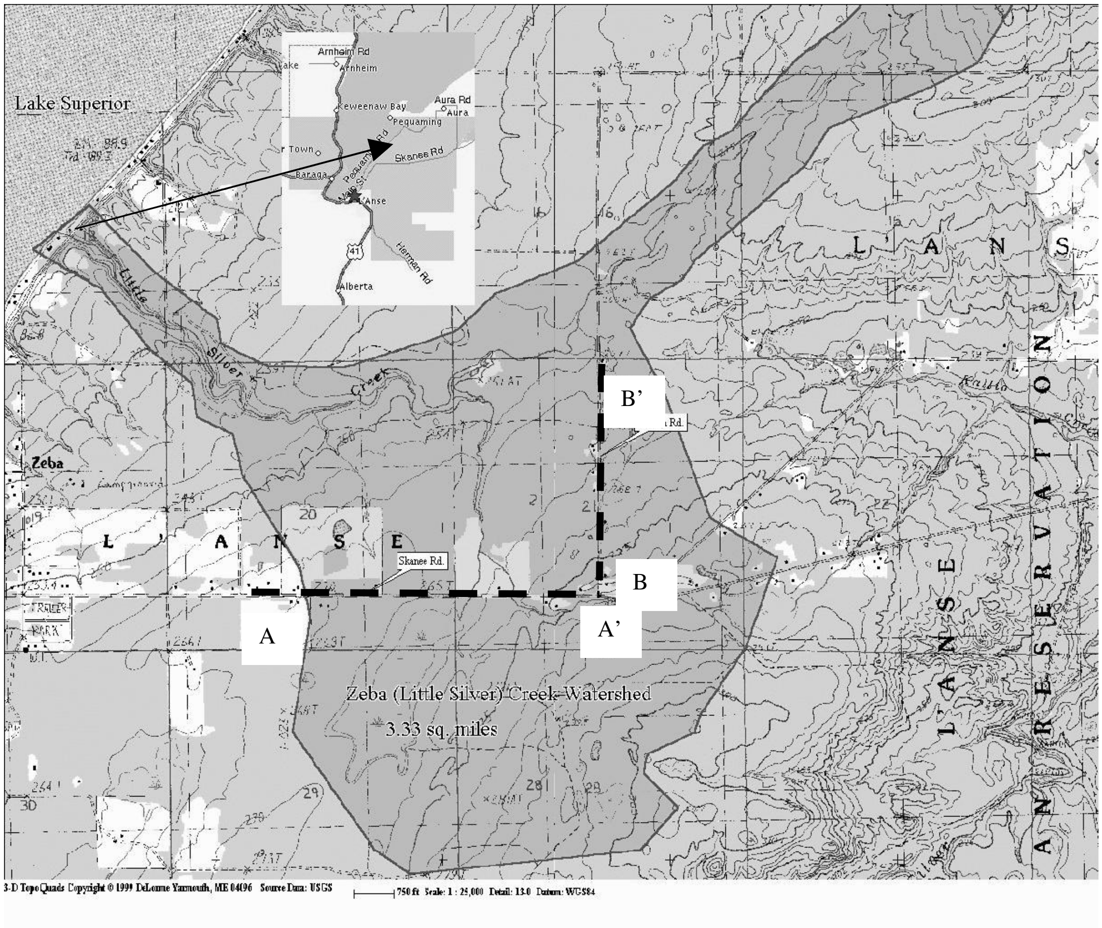


Figure 1. Zeba (Little Silver) Creek watershed depicted on U.S.G.S. topographic map. Inset map shows the location of the watershed within the L'Anse Indian Reservation boundary.

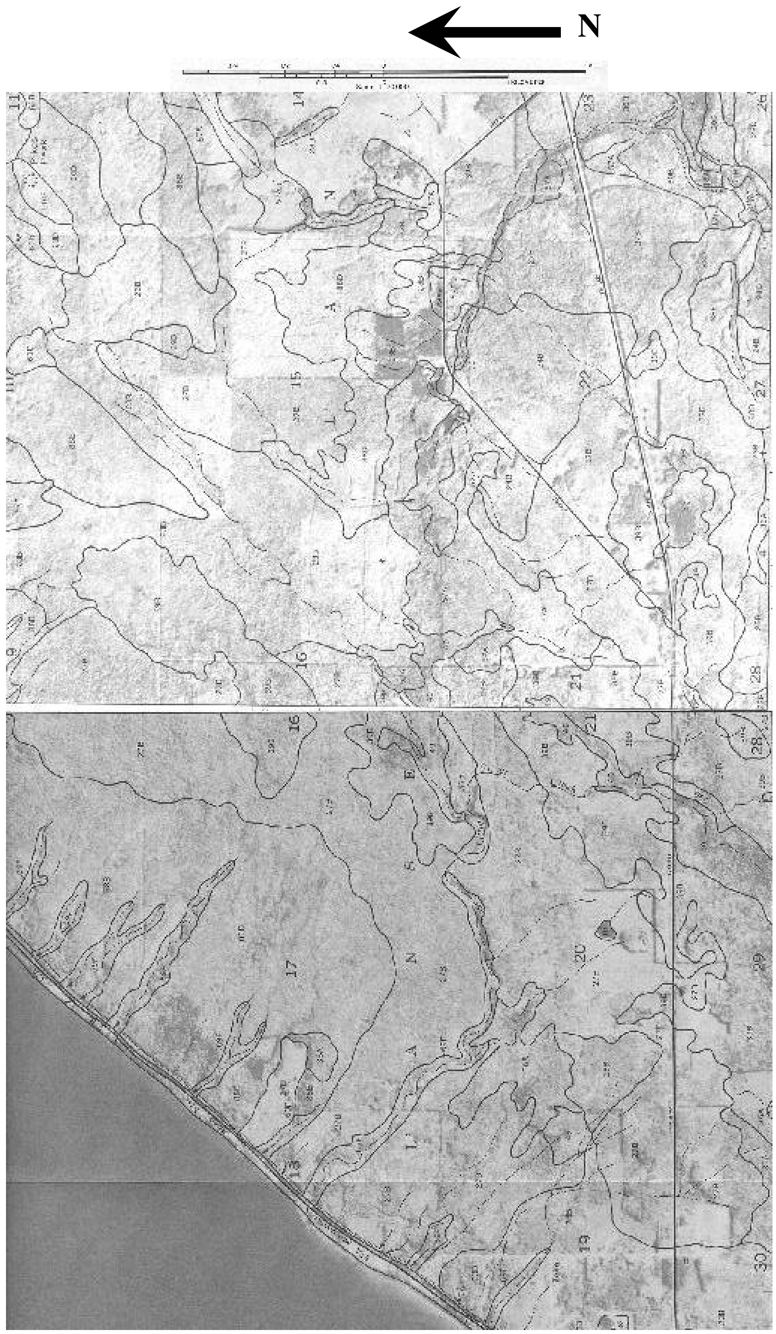
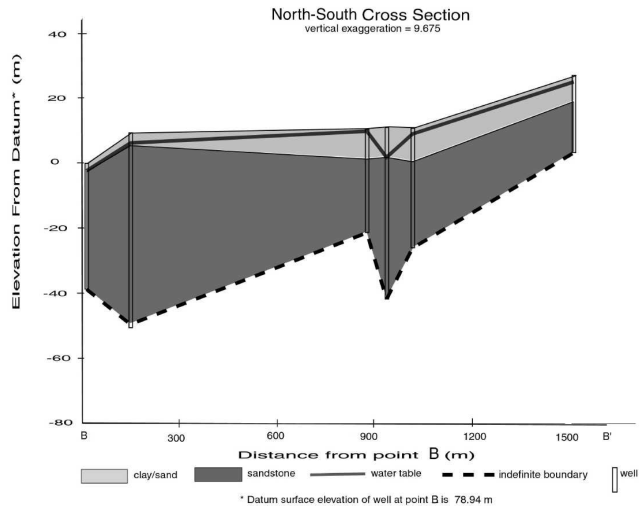


Figure 2. Distribution of soil types in the Zeba Creek Watershed according to the U.S.D.A. Soil Conservation Service (images scanned from Berndt, L.W., Soil Survey of Baraga County Area Michigan). Scale as shown is 2 miles.



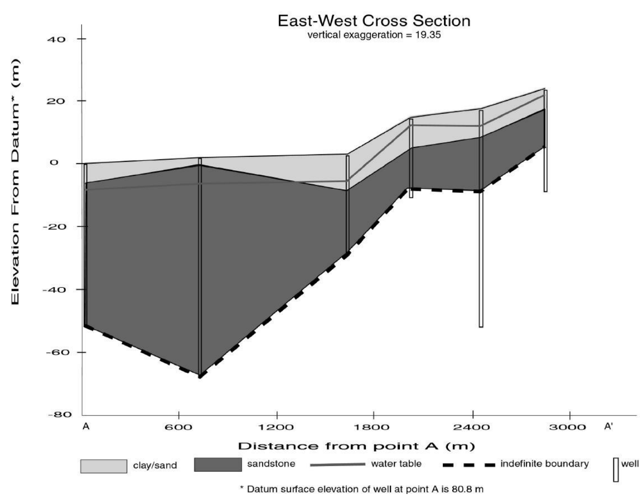


Figure 3. North-South and East-West geologic cross-sections derived from geologic descriptions on drillers' logs for wells along Haataja and Skanee Roads, respectively. The locations of the cross-sections are depicted in Figure 1. The water level indicated by the solid line in the glacial drift is also derived from the drillers' logs, which include wells drilled at various times of the year and over a 3-decade time span.

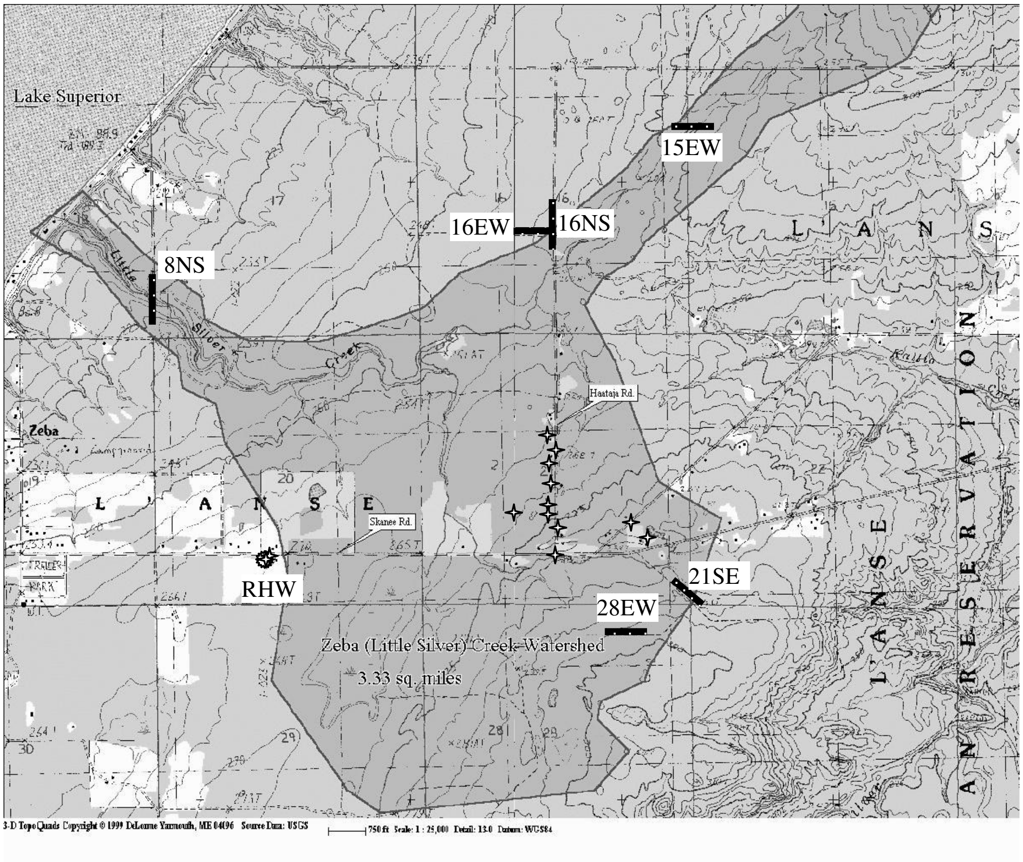


Figure 4. Locations of geophysical surveys and R. Haataja's abandoned well, which was used for the pumptest (denoted "RHW"). The cross symbols (✧) denote the locations where static water levels were measured. The numbers for the geophysical surveys indicate the section number in which the survey was located and the letters indicate the orientation of the survey line (EW=East-West, NS=North-South, and SE=Southeast). Not all geophysical survey methods were employed at every site.

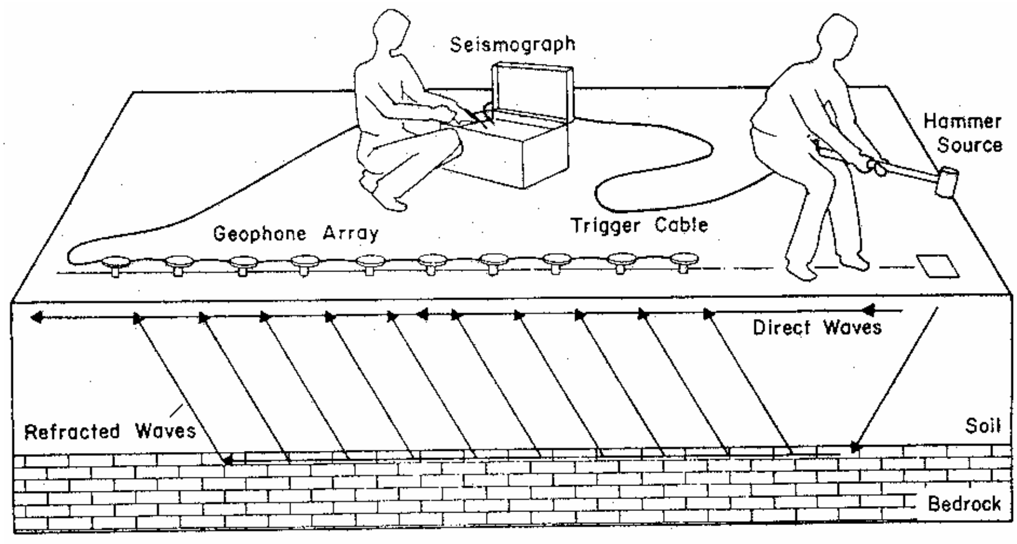


Figure 5. Schematic of a seismic refraction survey.

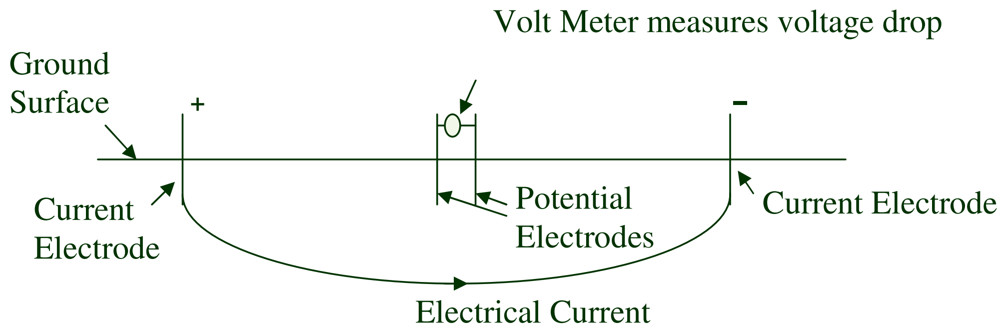


Figure 6. Schematic of a resistivity array.

Table 1. Depths to subsurface layers, cross-over times, and velocities based on seismic refraction survey at location 8NS (Figure 4, 5184917.0 m North, 392907.5 m East).

	Depth (m)	**Avg. Depth (m)**	**Cross-over Times (s)**	**Velocities (m/s)**	**Avg. Velocity (m/s)**
Layer 1 (Forward)	1.54		0.014	202.5	
Layer 1 (Reverse)	0.62	1.08	0.005	205	203.75
Layer 2 (Forward)	6.37		0.022	521.74	
Layer 2 (Reverse)	2.48	4.425	0.017	370.37	446.055
Layer 3 (Forward)				1200	
Layer 3 (Reverse)				684.21	942.105

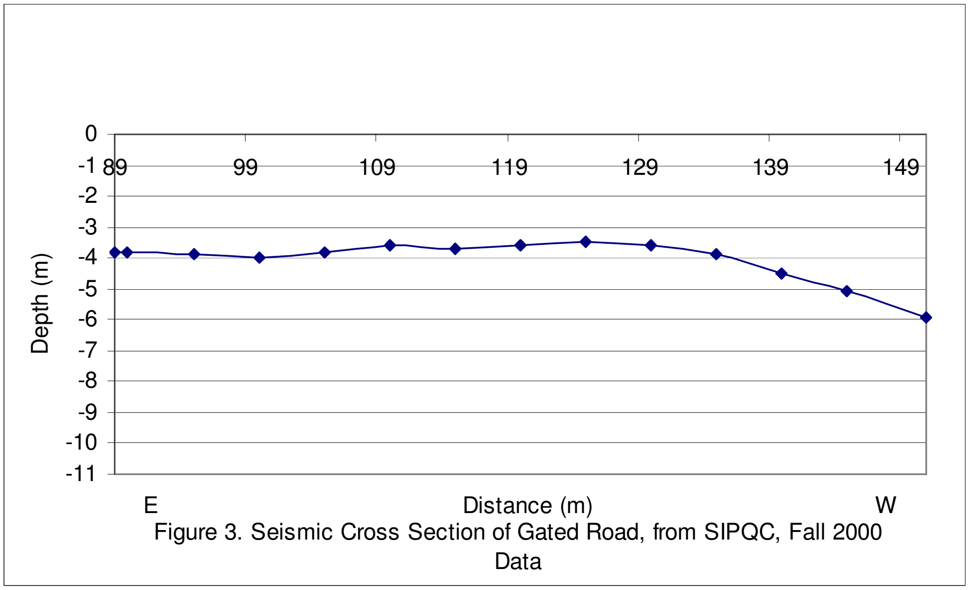


Figure 7. Inferred bedrock depth at 16EW (Figure 4) from seismic refraction survey.

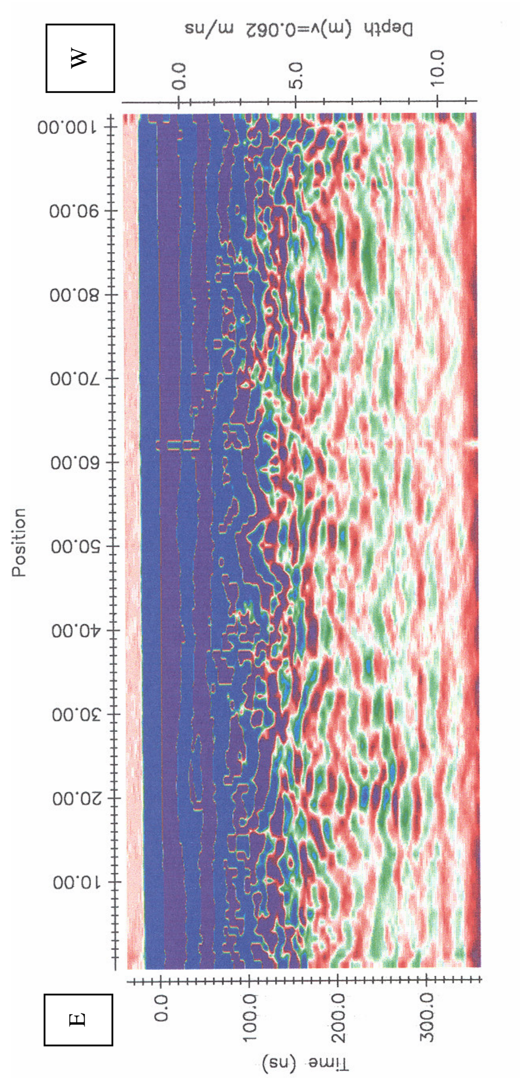


Figure 8. GPR-derived subsurface cross-section at 16EW (Figure 4). Depths are inferred based on a measured average sound wave velocity of 0.062 m/ns.

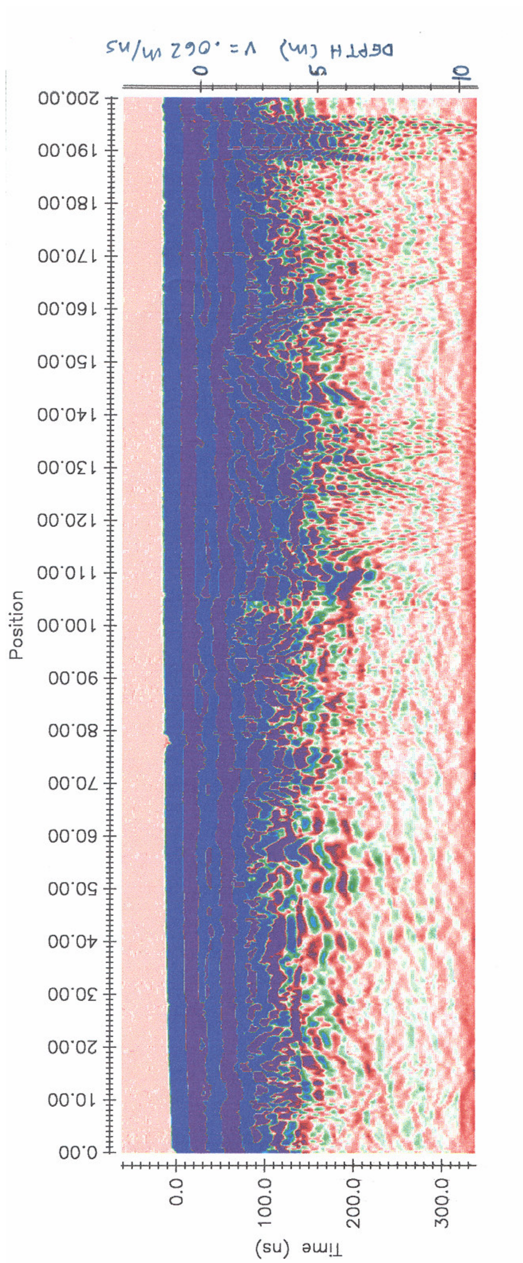


Figure 9. GPR-derived subsurface cross-section at 21SE (Figure 4). Depths are inferred based on measured average sound wave velocity of 0.062 m/ns.

Data Set: H:\Senior Design\KBIC Test1.aqt
Date: 05/10/01
Time: 21:55:22

AQUIFER DATA

Saturated Thickness: 175. ft
Anisotropy Ratio (Kz/Kr): 1.

SLUG TEST WELL DATA

Initial Displacement: 1. ft
Casing Radius: 0.25 ft
Wellbore Radius: 0.25 ft
Well Skin Radius: 0.25 ft
Screen Length: 175. ft
Total Well Penetration Depth: 175. ft

No. of observations: 25

Observation Data

Time (min)	Displacement (ft)	Time (min)	Displacement (ft)	Time (min)	Displacement (ft)
0.	0.	4.2	0.9906	32.7	0.9232
0.2	0.9975	4.7	0.9892	72.7	0.8505
0.7	0.9947	5.2	0.9878	152.7	0.7286
1.2	0.9928	5.7	0.9862	312.7	0.5484
1.7	0.9909	6.2	0.9848	632.7	0.3409
2.2	0.9961	6.7	0.9837	1272.7	0.1423
2.7	0.9947	7.2	0.9825	2896.2	0.0374
3.2	0.9933	7.7	0.9809		