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A FEASIBILITY STUDY FOR USING COMPUTERIZED WATER WELL RECORDS TO DELINEATE AREAS OF RECHARGE-DISCHARGE POTENTIAL

by

Lauren D. Hughes

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How do we begin to acknowledge those individuals who have supported and sustained us as we have struggled to reach a life's goal? I must begin by thanking my husband, Bill, who has always encouraged me so enthusiastically to reach for my own dreams. Even when I would have retreated he has been there to remind me why I started on this journey and to help me hold the line. I have to thank our daughters, Rachel and Sara, who do not know what it is to have a mother who is not in school and who are now in college themselves. They have always been there to applaud my efforts and to tell me to go for it. There are not words to truly express my gratitude.

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It is with relief that I reach this ending. It is with enthusiasm that I look to the future!

Lauren D. Hughes

A FEASIBILITY STUDY FOR USING COMPUTERIZED WATER WELL RECORDS TO DELINEATE AREAS OF RECHARGE-DISCHARGE POTENTIAL

Lauren D. Hughes, M.S.

Western Michigan University, 1995

A method for delineating areas of recharge-discharge potential has been developed utilizing computerized water well records. The methodology is based on the vertical head differences found between wells with shallow depths of submergence and those with deeper depths of submergence. The residual values generated represent the magnitude of vertical potential and can be contoured to delineate areas of recharge-discharge potential. Well data were obtained from the Kalamazoo County Groundwater Database. Well selection was based on depth of submergence and total well depth.

The methodology was tested in Texas and Schoolcraft Townships, the Donnell Lake Study Area, and Kalamazoo County. Regularly spaced, estimated values for static water elevations were generated using minimum curvature, inverse distance squared and kriging methods of interpolation. Statistical evaluation of the computer generated surfaces was conducted using simple regression analysis.

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CHAPTER I

INTRODUCTION

Purpose

The purpose of this study was to develop and validate a computer technique for mapping recharge, transition, and discharge potential using computerized water well record data. The advantage of the recharge-discharge potential methodology is its ability to readily access an already existing body of computerized water well records with ground-water software programs designed for manipulation and interpretation of water well data. If effective, this methodology would permit a faster and less costly method for initial evaluation of ground-water flow systems over larger geographic areas. The source of the well record data used in this study was the Kalamazoo County Groundwater Database which contains over 6,000 computerized water well records. The study focused on Texas and Schoolcraft Townships in Kalamazoo County. The methodology was also evaluated at a smaller, research site and at the county level.

County Demographics

Kalamazoo County is located in southwestern Michigan (Figure 1). The county is 24 miles by 24 miles (576 square miles) and is the 8th largest in the state.

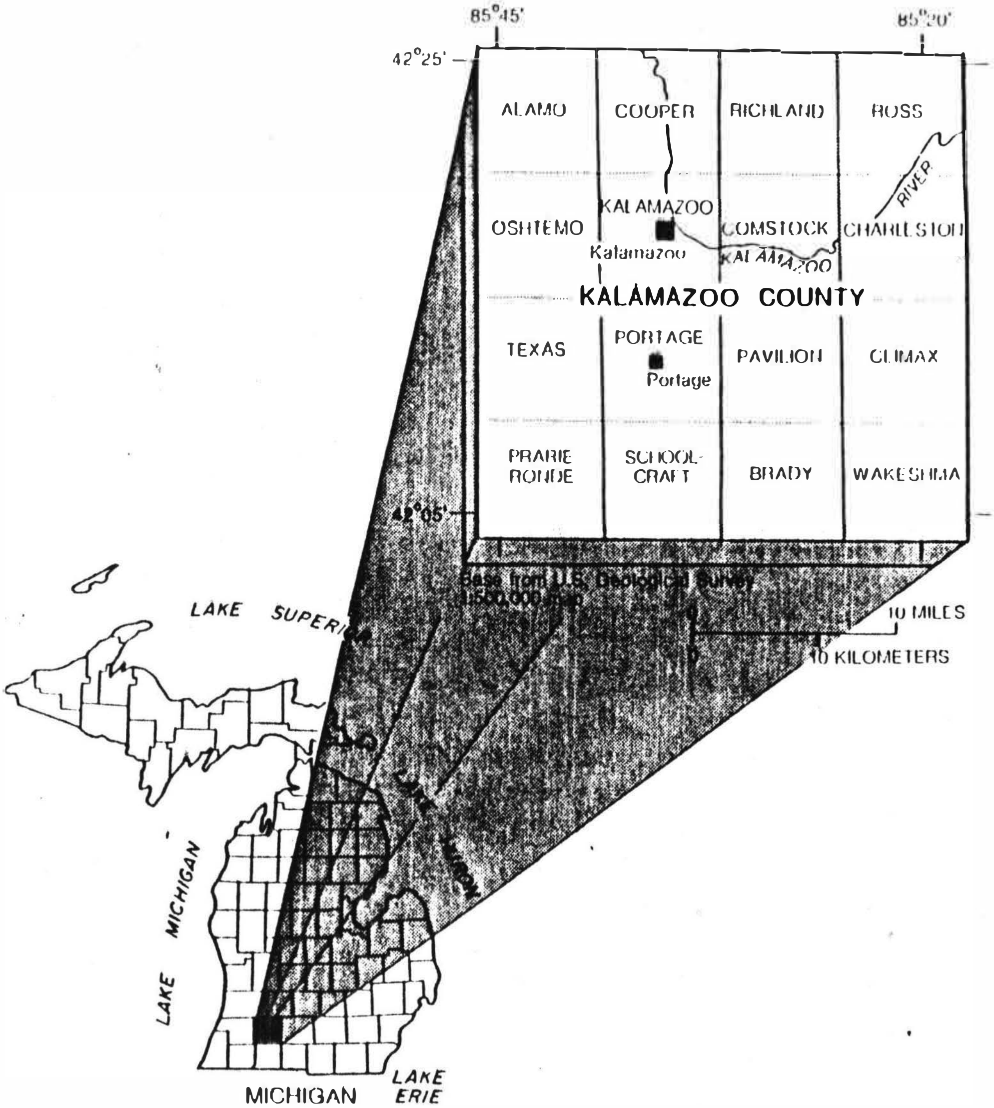


Figure 1. Location of Kalamazoo County.

Source: Rheaume, S.J., (1988), Geohydrology and water quality of Kalamazoo County, Michigan, 1986-1988.

The county population is 223,411. Urban population makes up 73.3% of the whole with 26.3% of the population derived from rural areas of which 0.9% are farm residents and 25.5% are non-farm residents. The county has 40.3% agricultural land, with 6.5% of the total county area designated as rivers, lakes and marshes. Texas Township has a population of 7,711, an increase of 36.6% over the past 10 years with 32.7% of its land listed as agriculture and 5.6% as rivers, lakes and streams. Schoolcraft Township has a population of 3,695, an increase of 3% for the same ten year period with 51.4% of its land designated as agriculture and 14.4 % listed as rivers, lakes and streams (Kalamazoo County , 1994).

Surface Water Drainage

Kalamazoo County is comprised of three major surface-water drainage basins (Figure 2). The Kalamazoo River Basin, located to the north, drains approximately 54% of the county. The St. Joseph River Basin drains approximately 41% of the southern portion of the county with the remaining 5 % draining into the Paw Paw River Basin to the west. Numerous subbasins make up the three major drainage basins. There are approximately 356 lakes and ponds located within Kalamazoo County ranging from 1 acre to 2,050 acres in area with an additional 3% of the county land attributed to marsh and/or wetlands. Total surface water area comprises about 11,700 acres. Contributing to the total surface water in the county are 44 miles of main river channel and 321 miles of tributary streams (Cousins-Leatherman, Faust, West, 1993).

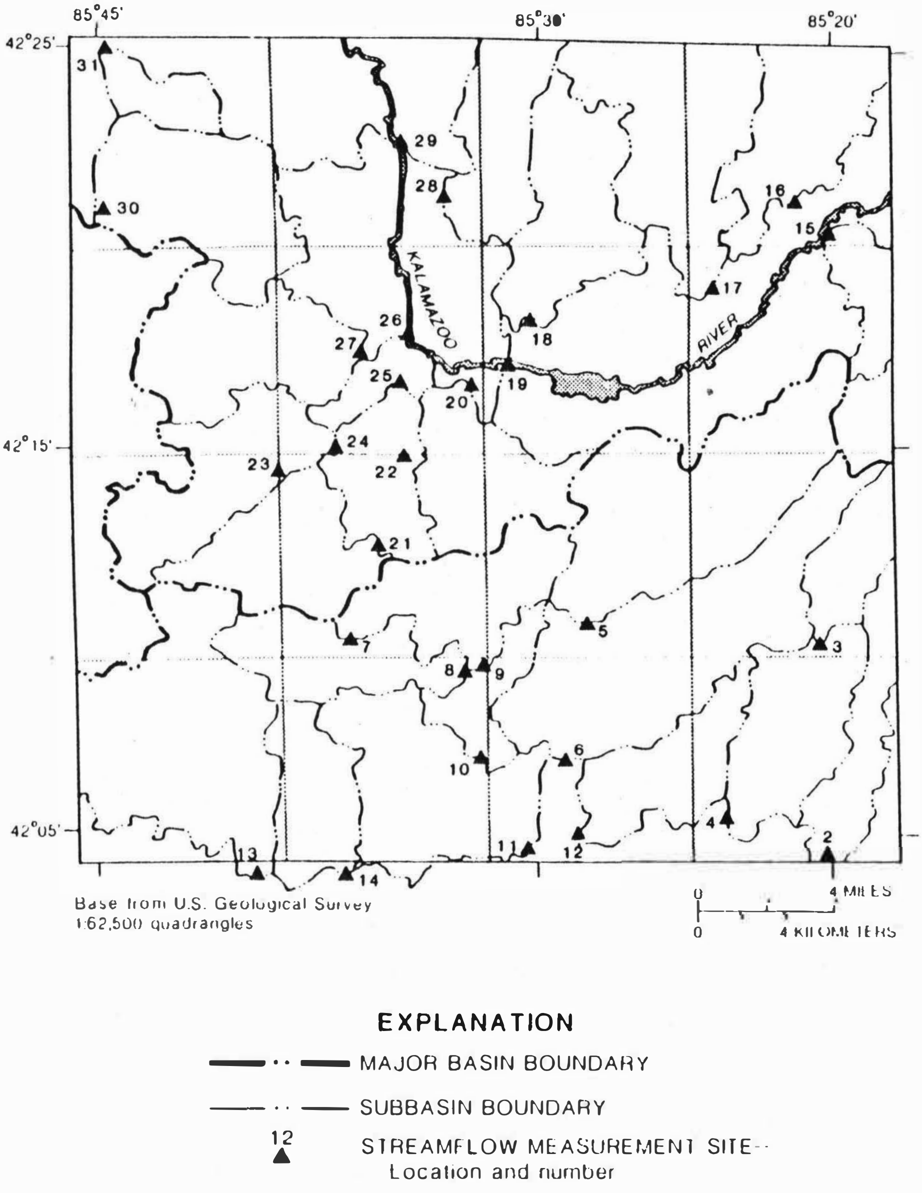


Figure 2. Major Surface-Water Drainage Basins in Kalamazoo County.

Source: Rheaume, S.J., (1988), <u>Geohydrology and water quality of Kalamazoo County, Michigan, 1986-1988</u>.

Geology

Most of Kalamazoo County is underlain by the Coldwater Shale, a stratigraphic unit of the Michigan structural basin. A bedrock formation of Mississippian Age, the Coldwater Shale is composed primarily of shale but contains limestone and clayey limestone in some areas of the county. The shale is 500 or more feet thick and dips slightly to the northwest (Rheaume,1983). The Coldwater Shale is overlain by the Marshall Sandstone (Mississippian) which subcrops beneath the glacial drift in the northeast corner of the county (Figure 3). The bedrock surface in Kalamazoo County is buried beneath Wisconsinan glacial drift varying in thickness from less than 50 feet to greater than 600 feet (Figure 4). The glacial drift is thickest where moraines overlie bedrock valleys and thinnest where till plains overlie bedrock highs. The most recent ice advance from which the main topographic features in the county were derived occurred 15,000 to 17,000 years ago. At this time, the ice advanced as two major ice lobes, the Lake Michigan which advanced from the west and northwest, and the Saginaw, which advanced from the northeast (Figure 5). The Lake Michigan lobe was the most influential factor in the development of the western and central most topographic features in the county with the Saginaw lobe most influential in development of the topography in the northeastern portion of the county (Figures 6 & 7). With the exception of the Kalamazoo River Valley, the Kalamazoo County landscape remains today much as it was following the last ice advance (Kalamazoo County, 1978).

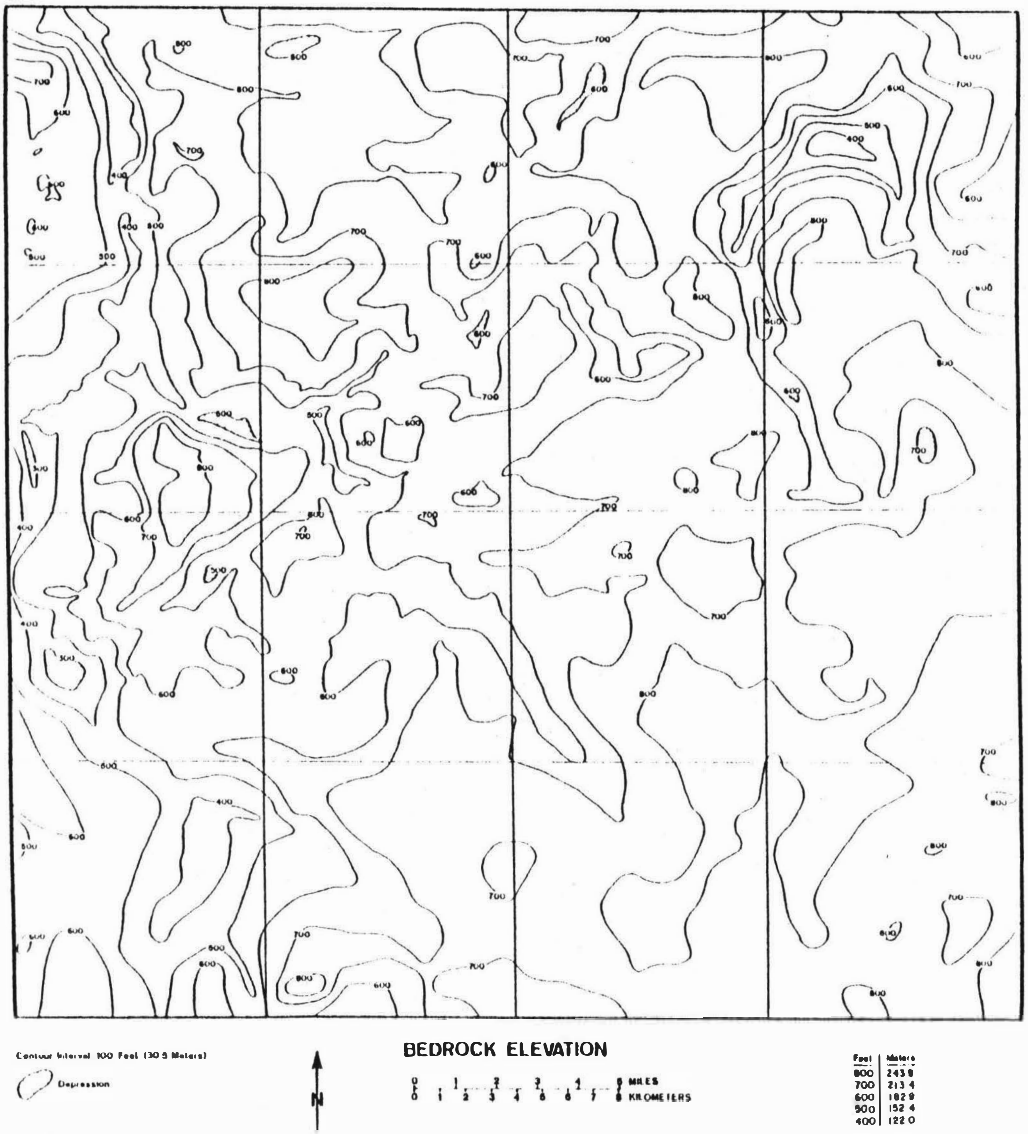
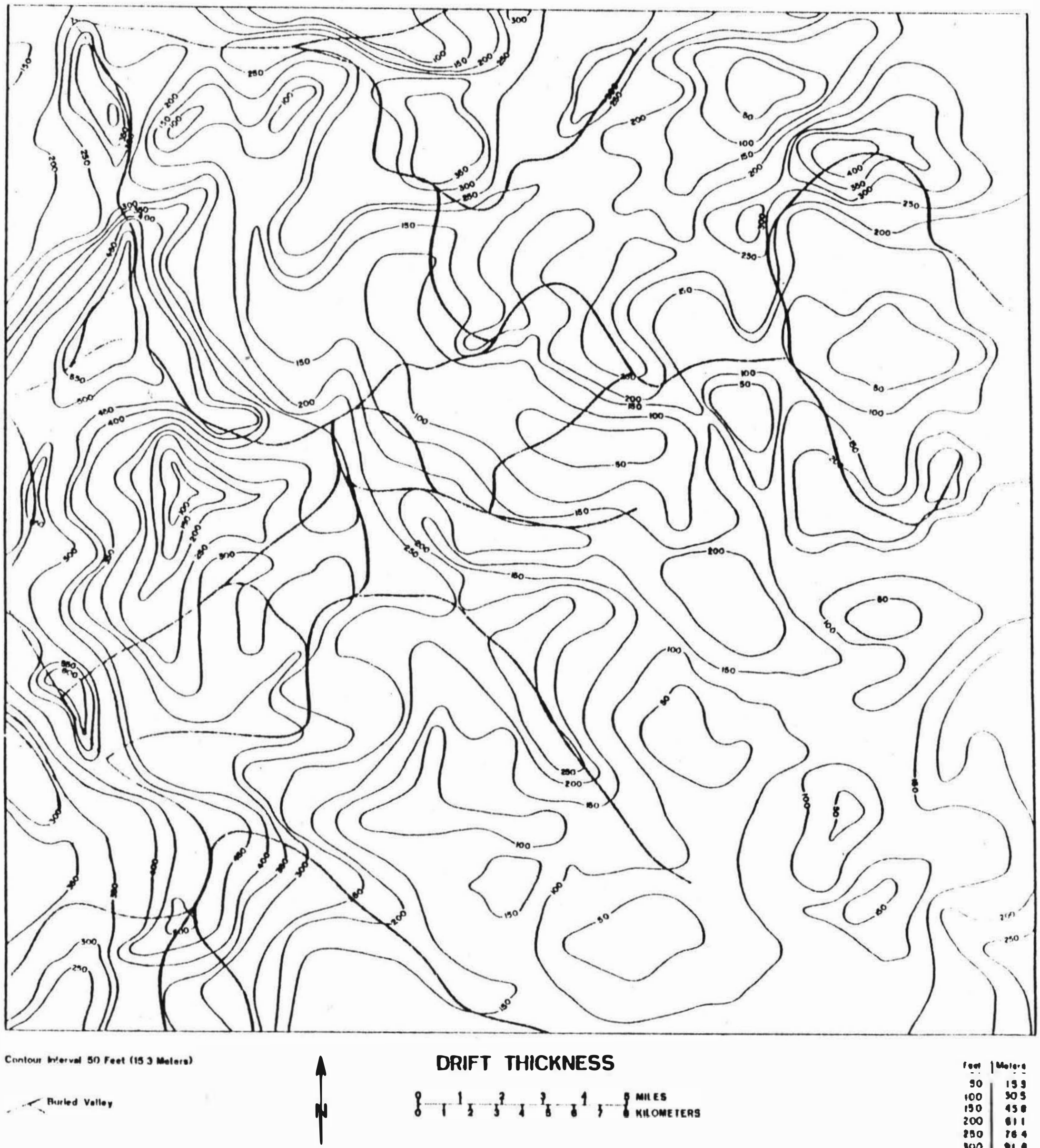


Figure 11.--Elevations of the bedrock surface beneath the glacial sediments in Kalamazoo County are shown by contour lines on a bedrock map. The bedrock varies from less than 400 feet (120 m) to over 800 feet (244 m) above sea level. (Map adapted from Ibrahim, 1969.) ▲

Figure 3. Bedrock Elevation.

Source: Departments of Geology, Geography, and Biology, Western Michigan University (1978), Kalamazoo County: geology and the environment. Adapted from Ibrahim, 1969.



Feet	Meters
50	15.3
100	30.5
150	45.8
200	61.1
250	76.4
300	91.6
350	106.9
400	122.2
450	137.5
500	152.8
550	168.1
600	183.4

Figure 5.--The glacial ice which covered much of the Midwest as recently as 15,000 years ago carried large amounts of rock debris which it deposited over the existing landscape. The thickness of the glacial drift in Kalamazoo County, Michigan, as shown in the above map, varies from less than 50 feet to over 500 feet. (Data from J. Smith, 1975, and Ibrahim, 1969.) A

Figure 4. Drift Thickness.

Source: Departments of Geology, Geography, and Biology, Western Michigan University (1978), Kalamazoo County: geology and the environment.

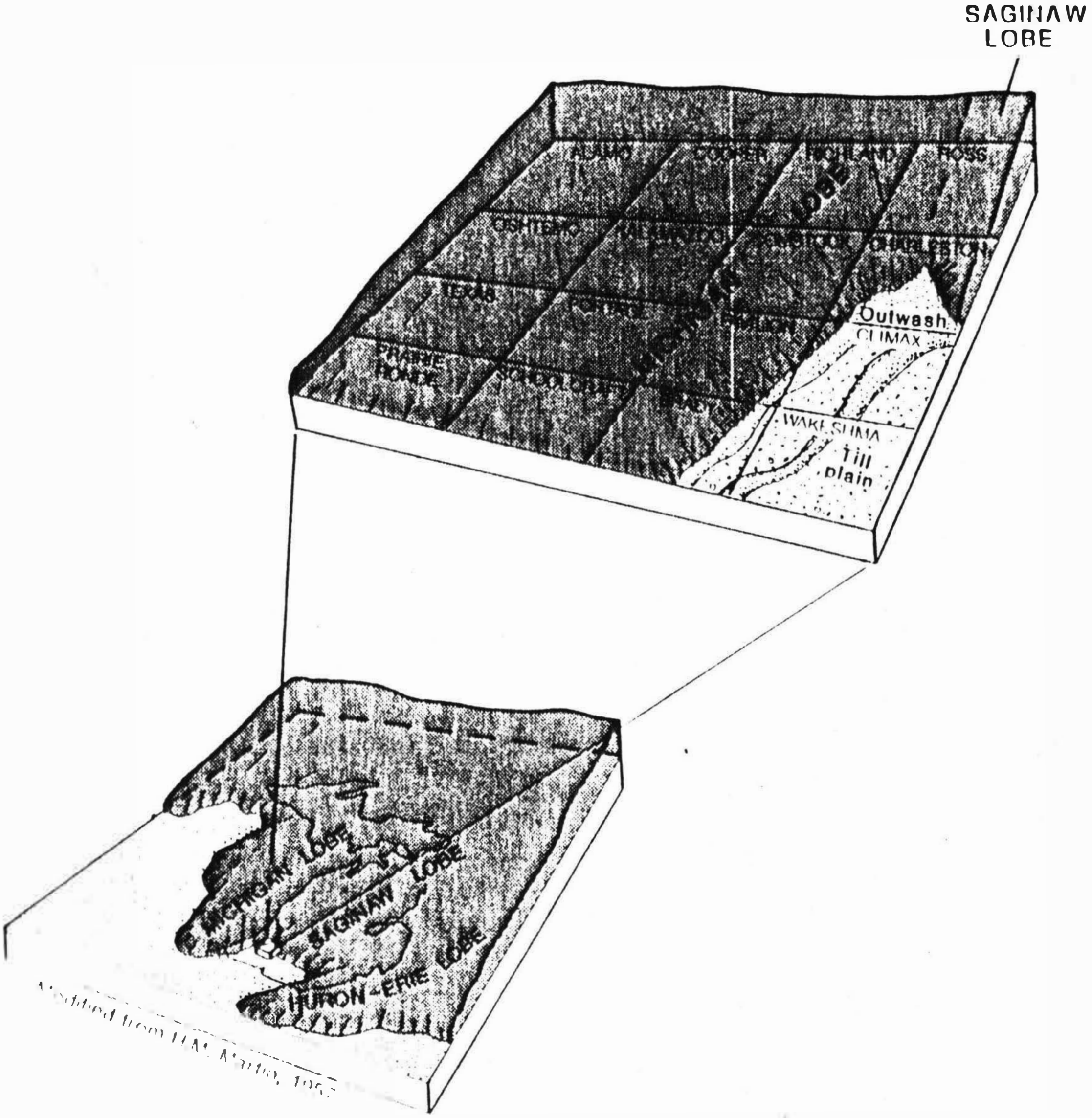


Figure 5. Wisconsinan Ice Lobes in Michigan During the Most Recent Continental Glaciation.

Source: Rheaume, S.J., (1988). Geohydrology and water quality of Kalamazoo County, Michigan 1986-1988.

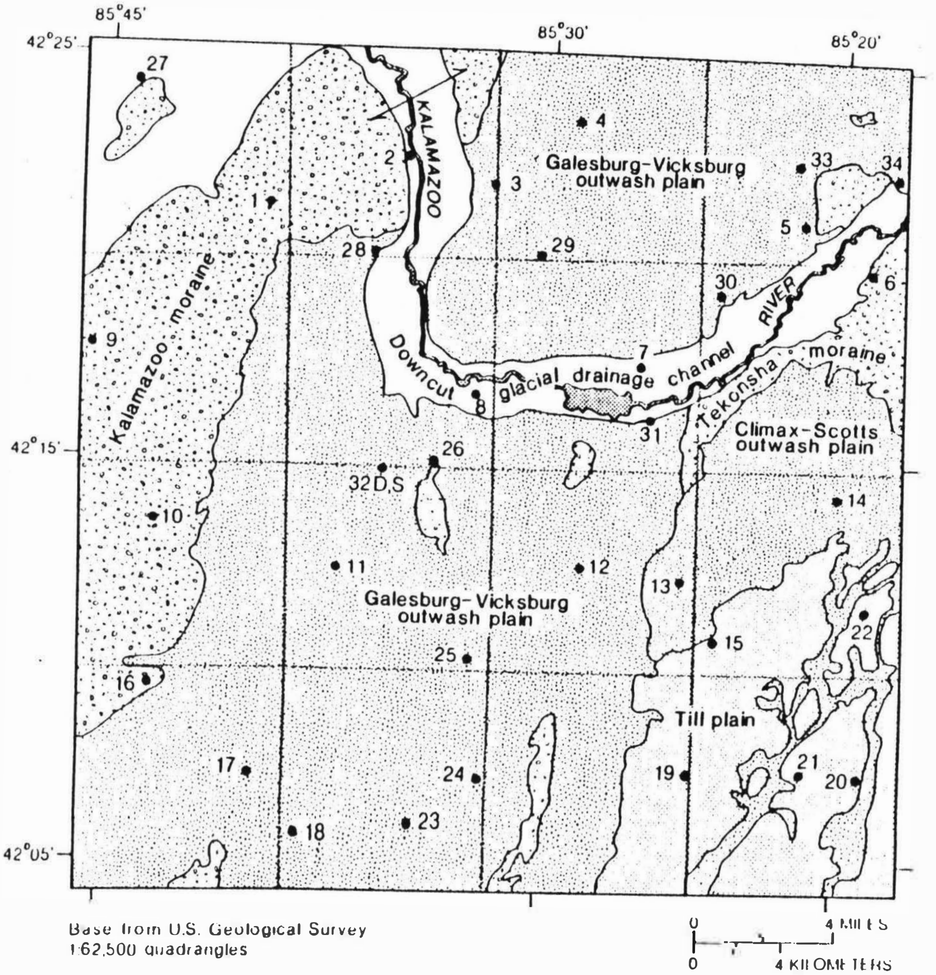


Figure 6. Areal Extent of Surficial Deposits.

Source: Rheaume, S.J., (1988). Geohydrology and water quality of Kalamazoo County, Michigan 1986-1988.

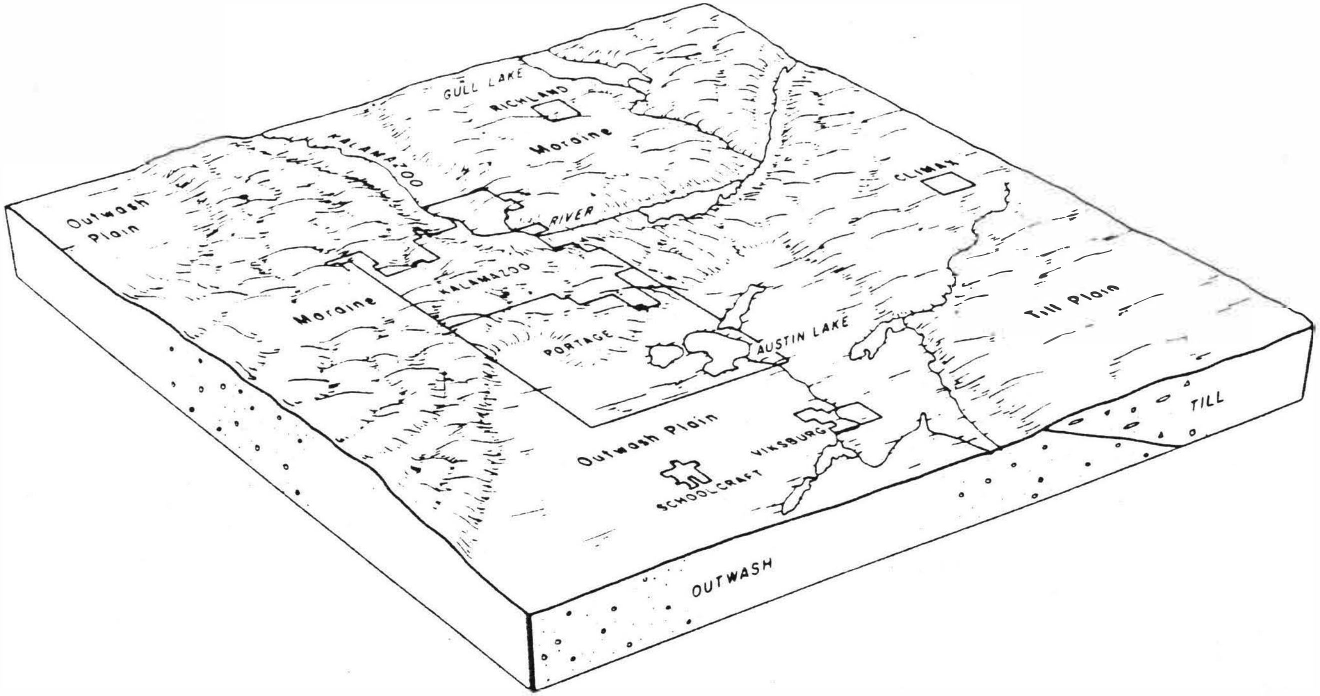


Figure 7. Major Glacial and Drainage Features of Kalamazoo County.

Source: United States Department of Agriculture Soil Conservation Service. Soil survey of Kalamazoo County, 1993, Michigan.

One of the main topographic features of Kalamazoo County and one which plays a significant role in this study, is the Kalamazoo Moraine which was formed when the retreating Lake Michigan lobe paused and stagnated at the western edge of the county. The moraine rises more than 100 feet above the Galesburg-Vicksburg outwash plain to the east and has been traced over 80 miles. Studies conducted on the Kalamazoo Moraine in Oshtemo Township characterize the moraine as having an uppermost sequence consisting of two relatively thin tills interbedded with glaciofluvial deposits, and a lower sequence consisting of a relatively thick till with a coarse upper facies and a lower fine grained facies, overlying a coarse outwash unit. These studies also described significant lateral variability (Straw, Passero, Kehew, 1992).

East of the Kalamazoo Moraine lies the Galesburg-Vicksburg outwash plain which consists primarily of medium to coarse sand and gravel that decreases in coarseness from northeast to southwest. Isolated blocks of ice were buried by the outwash, forming kettle lakes in a pitted outwash plain. A narrow breach developed in the Kalamazoo Moraine in the area of Paw Paw Lake in southwest Texas Township permitting channelized outwash material to flow out and form what is now the Prairie Ronde Fan. The outwash materials were deposited by a system of braided streams, forming an alluvial fan (Straw, Kehew, Barrese, Kasenow, Steinman, 1990). Outwash materials grade from coarse to fine down fan suggesting a high energy rapidly aggrading, depositional environment. The fan extends from the Kalamazoo Moraine in Texas Township to a chain of wetlands, streams and lakes, which include

Barton and Howard Lakes, located in southeast Schoolcraft Township. Prior to the deposition of the Prairie Ronde Fan, the Saginaw lobe had advanced to the position of the Sturgis Moraine before retreating to the northeast where it stagnated and formed the Tekonsha Moraine in Calhoun and Kalamazoo Counties. As the Lake Michigan lobe pushed southeast, it brought with it a heavy accumulation of supraglacial debris located on the frontal margin of the ice. It is believed that as the ice paused and stagnated, the leading edge of the ice lobe began to slowly melt, contributing this thick layer of insulating material to the formation of a buried part of the Tekonsha Moraine which is thought to be located just southeast of Barton and Howard Lakes. Subsequent surges of water and glacial debris from the Lake Michigan lobe contributed outwash materials to the fan and may have contributed to the process of burying the Lake Michigan lobe of the Tekonsha Moraine. This buried arm may form a ground-water divide for this region (Straw et al., 1990).

CHAPTER II

LITERATURE REVIEW

Hydrogeologic Theory

Ground-water recharge is defined by Freeze and Cherry (1979) as entry into the saturated zone by water that is made available at the water-table surface together with the associated flow away from the water table within the saturated zone. Recharge contributes a downward component of ground-water flow in response to a decreasing hydraulic potential with depth. This decreasing hydraulic gradient results in shallow wells having a higher static water elevation than do nearby deeper wells. A recharge area is defined as that portion of the drainage basin in which the net saturated flow of ground water is directed away from the water table. In a recharge area, the water table is usually found at some depth. The unsaturated zone is therefore thickest in an area of recharge.

Ground-water discharge results in the removal of water from the saturated zone across the water table surface, together with the associated flow toward the water table from within the saturated zone. Ground-water discharge contributes an upward component to the direction of ground-water movement. This upward component is in response to a increasing hydraulic potential with increasing depth. As the hydraulic gradient increases with depth, deeper wells will have a higher static water elevation than in nearby shallower wells. A discharge area can therefore be defined as that portion of the drainage basin in which the net saturated flow of ground water is directed toward the water table. In a discharge area, the water table is usually found at or near the topographic surface. The unsaturated zone is thinnest in a discharge area (Freeze, Cherry, 1979). There is a zone between areas of recharge and discharge where the potential vertical gradient is zero with little or no vertical component to the ground-water flow and the static water elevations for both shallow and deep wells are essentially the same. This area is referred to as a hinge line or transition zone.

In unconfined aquifers there are common characteristics associated with recharge-discharge potential. The broadest characteristic is that the potentiometric surface (water table) of an unconfined aquifer reflects the surface topography. Although more muted in relief than the topographic surface, the elevation of the water table is generally highest under topographic highs and lowest under topographic lows (Mazola, 1966). It is a commonly held belief, supported by both theoretical and field analysis, that regions of topographic highs are recharge areas and regions of topographic lows are discharge areas (Tòth, 1963). A high on the water table results in recharge to ground water at that point and for some distance surrounding that point. The existence of a low on the water table results in discharge of ground water at that point and for some distance surrounding that point. Discharge areas usually occupy a smaller area of a watershed than do recharge areas comstituting 3-40% of the basin. Three dimensional modeling of ground-water flow systems support the distribution of discharge areas at the lower end of that range (Freeze, Witherspoon, 1967).

There are five basic field indicators of recharge and discharge areas. These include: (1) topography, (2) piezometric patterns, (3) hydrochemical trends, (4) environmental isotopes, and (5) soil and land surface features. This study uses topography, land surface features, and substitutes static water elevations of private and public wells for piezometers, to aid in the delineation of recharge-discharge potential. Limitations were placed on well depths in order to select wells screened in the same water table aquifer. By limiting to a single aquifer, static water level data should be sufficient to identify potentiometric surfaces (Freeze et al., 1979).

Geostatistical Theory

Geostatistics encompass a collection of techniques for the solution of estimation problems involving spatial variables. It is described as a systematic approach to making inferences about quantities that vary in space (ASCE I, 1990). Typical ground-water data such as the static water elevations used in this study consist generally of a number of observations gathered from irregularly spaced sampling points over some distance. More often than not the number of observations is insufficient for predicting or estimating additional values at unmeasured sites. Spatial variability in hydrogeolgical environments results in considerable uncertainty in such measurable variables as transmissivity, permeability, storage coefficient and hydraulic head. Even over relatively short distances, spatial variability makes estimation of values at unmeasured sites very difficult and virtually impossible to determine accurately. However, these spatial variables are not necessarily random. Variables that are closer to each other are more likely to be closer in magnitude than variables separated by greater distances. Therefore, there is a correlation with the spatial distribution of these measured observations. Matheron, originator of the kriging technique, named these types of measured and correlatable variables "regionalized variables" which in turn implies that they are typical of a phenomenon developing in space and/or time and possessing a certain structure. The term "structure" refers to the spatial correlation which can vary greatly from one magnitude to the next and from one aquifer to another (Isaaks, Srivastava, 1989).

The science of geostatistics evolved in recognition of the difficulties in producing deterministic estimations of regional variables and provides the statistical tools to (a) calculate the most accurate predictions (according to well-defined criteria) based on measurements and other relevant information; (b) quantify the accuracy of these predictions; and (c) select the parameters to be measured, and where and when to measure them, if there is an opportunity to collect more data (ASCE I, 1990). Rather than use a deterministic approach, which implies the availability of error-free estimations, geostatistics uses the stochastic (random variable) approach. With this approach, geostatistics employs probability theory to improve on predictive assumptions that are based on incomplete data. Input parameters such as hydraulic head are given an associated probability density function at each point in the flow system (Smith, Freeze, 1979). The spatial dependence between measured values can be defined based on the stochastic process model which in turn defines the spatial autocorrelation through the simulation area. The application of the stochastic equation leads to determination of the probability distribution on the output variables. This probability distribution reflects the uncertainty in the predicted values. Mapping these uncertainties can assist in determining where additional data need to be collected if the opportunity arises.

SURFER: Interpolation/Contouring Software Package

In order to evaluate the effectiveness of using computerized water well records for development and validation of a computer technique for mapping recharge, transition and discharge potential, it is necessary to have software programs for manipulating the raw data and for interpolating randomly spaced data to generate a regularly spaced grid of estimated values for contouring as a two dimensional areal map.

SURFER v.4 is a grid-based contouring and three dimensional surface plotting graphics program developed by Golden Software, Inc. and is designed to work in the DOS environment. SURFER contains several subprograms for generation and interpretation of gridded surfaces from those types of measurable quantities as static water elevations or chemical concentrations associated with ground water. SURFER requires raw data to be in an x, y, z format. The subprograms consist of (a) GRID for interpolation of the randomly spaced raw data; (b) TOPO for contouring of the gridded surface; (c) SURF for three dimensional fishnet surfaces; and (d) UTIL which computes certain types of net volumes, cross-section data files, and surface area above a specified level. UTIL also converts a grid into a text file and under Residual, it permits comparison of real data to a gridded surface, computing a mean and a standard deviation of the residuals. All four subprograms were utilized for this study.

The GRID program calculates an interpolated value for each node depending on the interpolation method, search method, search radius, and the number of real data points to be used in the calculation as determined by the user. GRID represents the geostatistical component of the SURFER software program. Proper understanding and use of the options in GRID are critical to decreasing the uncertainty surrounding the interpolated nodal values. Limiting search method, search radius and number of real data points to be used in the search results in several advantages, such as reducing the computational time required for the interpolation of each nodal value and minimizing the impact of more distant data values whose weights will be very small and possibly negative, which in turn could result in negative estimated values.

The interpolation methods available in the DOS based SURFER/GRID include minimum curvature, inverse distance to the power, and kriging. Minimum curvature allows the user to establish the maximum absolute error and the maximum number of iterations. Minimum curvature uses all data in the interpolation process which means that the user cannot limit the search method, radius, or number of nearest neighbor points to be used in the calculation. Of the three interpolation methods, minimum curvature is the method most affected by sparse distribution of the data .

Inverse distance to a power is a weighted average interpolator. The user has the option of establishing the value of the power. GRID limits the choice to > than 0 and ≤ 10. The impact of the power is that it limits the influence of one data point on another. The weight assigned to a particular data point during the calculation of a grid node is proportional to the inverse of the distance (to the power) of the observation from the grid node. This controls the impact of the weighting power as the distance from the estimated node increases. The inverse distance to a power interpolation method is an exact interpolator and attempts to honor the original data. The greatest drawback in using inverse distance to a power is the impact it has on clustered data. Inverse distance weights all data points the same. The weights are a function of the distance between the estimated point and the data point. It is therefore possible to have a cluster of data overly weighted which results in "bullseyes" on a contour map. Inverse distance also does not take into account spatial continuity between sample points (Isaaks et al., 1989) an advantage that is found in the kriging method of interpolation.

Kriging is the third choice for interpolation method in GRID. Kriging is a moving weighted average interpolation method. The SURFER manual describes kriging as an attempt to express trends suggested by the data. There are numerous types of kriging. SURFER v.4 for DOS uses ordinary kriging. Ordinary kriging is often associated with the acronym B.L.U.E. which means "best linear unbiased estimator." Ordinary kriging is linear because its estimates are weighted linear combinations of the available data; it is unbiased since it tries to have the mean residual error equal to zero; and it is best because it aims to minimize the variance of the errors. This last feature distinguishes ordinary kriging from other linear, unbiased estimators (Isaaks et al., 1989). Like inverse distance, kriging is an exact interpolator. It will honor the original data at measured data points. One of the principal components of kriging is the generation of an experimental semivariogram. A semivariogram is a graph of the variance of the regionalized variable vs. the distance *h* between data points. The variance (which kriging seeks to minimize) is a measure of the interdependence of two points separated by a distance *h*. If these two points are highly related, the variance of the distribution of the differences will be low and vice versa. The variance is a measure of the influence of samples over neighboring areas within the entire domain. Therefore, the semivariogram provides some measure of the spatial continuity. The process involves fitting the experimental variogram to one of several theoretical variograms. SURFER describes the function of the semivariogram as to be included in the determination of the local neighborhood of observations to be used in the interpolation of each grid node, and for use in how the weights are applied to the observations during the grid node calculation. With Ordinary kriging, distance is interpreted as a statistical distance rather than geometric distance as is used in inverse distance methods. Distances to various samples and the clustering between samples are incorporated for the determination of statistical distance. Use of statistical distance in the kriging process allows for customizing of the estimation procedure to a particular pattern of spatial continuity. Kriging weights are also tailored to the variability of the samples. When the variables are regular, kriging assigns a higher weight to the closest sample points because continuity would suggest that points closer in distance to each other would be closer in value and exhibit less variance than data points farther apart. If the variables are irregular, the method dampens the weights for the nearest points. This allows for greater flexibility than for those interpolation methods whose weights are defined by geometric distance (inverse distance methods). The two most important considerations when choosing kriging as an interpolation method are; (1) the ability to minimize the effect of clustered data through the use of variable weights, and (2) the determination of the estimation variance, which in turn can be mapped as a spatial picture about the uncertainty of the kriged estimation map. Comparisons of kriged maps to other mapping methods such as distance weighting support kriging as being less sensitive to variability in the data set. Kriged maps are more "robust"and are better at preserving local variations found in measured values (ASCE II, 1990).

Historical Use of the Recharge-Discharge Potential Methodology

Under contract with the Michigan Department of Agriculture, The W.M.U. Institute for Water Sciences conducted a study evaluating the feasibility of using static water levels from computerized drillers' water well records to map the water table and for delineating recharge-discharge potential of the glacial drift (Passero, Chidester, Hughes, 1992). This study utilized water well records available in the Van

Buren County, Michigan, Groundwater Database which consisted of 3,240 well records covering a time period of almost thirty years. The study, conducted at the county level, compared the water table surface generated using unlimited depth of submergence and limited depth of submergence. Depth of submergence is the depth of the well below the static water level. The purpose of this differentiation was to compare a water table map generated by wells of limited depth of submergence (≤ 40 feet depth of submergence) to a water table map that would include all possible depths of submergence including wells possibly screened in lower drift aquifers. In addition, the effect of including surface water elevations with the static water level data sets was examined to determine if this data would affect the water table and recharge-discharge surfaces obtained. The Van Buren County study used the SURFER software program for interpolation of the randomly distributed data and for contouring of the resultant grids. All three interpolation methods available with the SURFER software program were employed. The contoured surfaces were compared for agreement with U.S.G.S. 7.5 minute topographic maps. Statistical comparisons of the interpolated values for each grid to real data values were also conducted. In addition, the study attempted to map recharge-discharge potential for the entire county. Limits placed on the depths of submergence for the recharge-discharge mapping were ≤ 40 feet depth of submergence (DOS) for the shallow grid and ≥ 65 feet DOS and ≤ 100 feet DOS for the deeper grid. This produced a separation distance of 25 feet depth of submergence between the two data sets, established to avoid the influence of long term water table fluctuations.

Visual comparison of the water table and recharge-discharge potential maps resulted in a preference for the minimum curvature interpolation method. This method produced a much smoother grid with fewer isolated highs and lows on the potentiometric surface. All three methods compared reasonably with the topographic surface and with surface drainage patterns with little difference when using different depths of submergence.

Statistical evaluation was carried out using the Residual subroutine of the SURFER subprogram UTIL. This permitted a comparison of real data values (data that had not been used in the determination of the gridded values) to the gridded nodal values. Statistical evaluation of the three interpolation methods showed minimal differences between the three methods with minimum curvature producing the largest area of minimal residual values. In addition, the greatest distribution of residual values (indicating areas with greatest disagreement between estimated values and real values) was generally located along the moraines in Van Buren County. This agrees with the expectation that the greatest uncertainty in the data and in subsequent interpolated values originates with wells located in areas of greatest topographic relief and geologic complexity. The statistical evaluation of the residuals generated under UTIL/residual subroutine resulted in no more than 0.5 foot mean difference with a standard deviation of 14 feet.

The recharge-discharge maps generated for this study were developed by a process of subtracting a gridded surface of estimated static water elevations for deeper depth of submergence wells (estimated values generated through application of the interpolation method) from a gridded surface of estimated static water elevations for shallow depth of submergence wells . The resulting grid consists of positive and negative values representing differences in potential head. These residual values were then contoured. At the time of this study, evaluation of the recharge-discharge potential maps was conducted solely through visual comparison to U.S.G.S. topographic maps. At the county level the recharge-discharge contoured surfaces were found to agree reasonably well with the topographic maps. In addition, the choice of which interpolation method produced the best map was in agreement with the choices made for the water table surfaces. Statistical analysis was not conducted because the UTIL/residual subroutine in SURFER is designed to work with estimated and real values of like magnitude. It was not possible to compare real static water elevations to the residual values generated through the recharge-discharge potential methodology using the residual subroutine.

Conclusions of this study were that (a) computerized drillers' records are statistically reliable sources for static water elevation mapping at the county level, (b) all three interpolation methods compared reasonably well both visually and statistically, (c) at the county level limiting water table maps by depth of submergence gains no significant advantage, (d) inclusion of surface water elevations for the purpose of generating county level maps results in no significant advantage and increases the time and effort required for generating a potentiometric surface map, and (e) recharge-discharge potential can be reasonably mapped at the county level using the previously described method (Passero et al., 1992).

CHAPTER III

DATABASES

Kalamazoo County Groundwater Database

The State of Michigan anticipated the need for ground-water management capabilities at the local and state level in September, 1984, when the Governor's Cabinet Council on Environmental Protection published its "Groundwater Protection Initiatives" in which were listed recommendations for the development of several programs focused on protecting the state's ground-water resources. Recommendation 16 called upon the State to develop and implement a coordinated program to computerize existing and future ground-water data for quick storage, manipulation and retrieval (WELLKEY, 1991). The response to Recommendation 16 was the development of the "Statewide Groundwater Data Base Strategy" in 1986. The Department of Natural Resources was given lead agency status over the implementation of the strategy and the ground-water database project is now an operating function of the Michigan Resource Information System (M.I.R.I.S.) which is a program of the Land and Water Management Division.

Kalamazoo County began development of a county ground-water database in 1988. The County funded the database project through allocation of a portion of the County Cigarette Tax. The Kalamazoo County Environmental Health Division, Human Services Department, has responsibility for entering information from paper well records into the computerized database with the use of the software program WELLKEY, developed through the Michigan Department of Natural Resources. Since 1965, the State of Michigan has required well drillers to complete paper water well records for every well installed and file them with county health departments. Until the development of an automated system such as WELLKEY, the data available on the paper records were difficult and time consuming to access. Kalamazoo County has over 25,000 private water wells (1990 Census Data). Of these 25,000 water wells, only about 8,000 have paper records. To date over 6,000 well records have been entered into the county database. The remaining well records could not be field verified by county staff and therefore were not entered into the database. Although there are over 22,000 water quality results (partial chemistries) entered into the database, only about 4,000 are matched to well records through the well ID numbers (Cousins-Leatherman, personal comment, 1993). Well records for Kalamazoo County primarily cover a time period from 1963 to the present, however, there are a few records from the 1950's. At the time this study was conducted, the county database was completed through 1992. Records will continue to be added until the county is able to maintain the database through entry of new well records.

Kalamazoo County Environmental Health Division followed the state recommended procedure for development of a computerized county-wide database by field verifying every well before it was entered. This required a staff member to confirm every well at its location in the field. Field verification was carried out by using the odometer of an automobile, a U.S.G.S. plot scale 1:24,000 scale ruler, and a copy of the appropriate U.S.G.S. 7.5 minute topographic map. The field staff estimated the distance from the road to the well in question. This required almost a year of field time (Cousins-Leatherman, personal comment, 1993). Field verification ensures that each well is a valid data point before it is entered into WELLKEY. Once field verified, each well location was then transferred to the original U.S.G.S. 7.5 minute topographic map. With the use of a software program called C-MAP, which is a Geographic Information System Work Station developed through Michigan State University, the location of each well was digitized from the quad. This process assigned state plane coordinates (x and y in units of feet) for each well. At the same time a well's location was digitized, the C-MAP operator assigned the well elevation to that well by reading the ground elevation from the topographic map. This was necessary because most well records do not list a well elevation. A well ID number was also assigned to the well at the time the location was digitized. A well ID number allows a particular well record to be readily accessed and the coordination of other data associated with that well ID. Determining the coordinates for each well by digitizing a location "dot" on a topographic map incurs an estimated ± 200 foot error for the size of the dot (Cousins-Leatherman, personal comment, 1993).

The digitized coordinates, the well ID number, all pertinent data from the paper well records as entered by the well driller at the time of installation, plus additional information such as numeric codes for identifying lithologies were then entered into the WELLKEY program by a computer operator. As townships were completed, the WELLKEY operator used the Data Checker option of the program to locate entry errors. In addition, the operator used visual mapping of the data points to make sure that all data points plotted within the political boundaries in question. The Michigan Department of Natural Resources provides support for counties developing computerized water well databases by also performing a check for data entry errors. This includes an automated check of the lithology codes.

M.I.R.I.S. Database

An additional database that was utilized in this study was the M.I.R.I.S. database. This program serves a complementary function with the development of the Statewide Groundwater Data Base Strategy. The purpose of this database is to compile computerized natural resource geographic and hydrologic information for storage, retrieval, and analysis of data that is pertinent to land utilization, management, and resource protection. The data were compiled from 1978 aerial photos. The types of information available include cultural features, land cover, soils, and surface-water and ground-water parameters. This study accessed the surface-water data for mapping of lakes, rivers and streams in Kalamazoo County as a line feature on the maps and cultural features for display of political boundaries such as township lines and section lines.

Additional Data Sources

A surface-water data set was created for this study by digitizing static water elevations for rivers, streams, and large lakes as point data in Kalamazoo County. The purpose of this database was to increase control of the shallow depth of submergence grid by including the static water elevations of surface water bodies in the shallow depth of submergence data sets. This data set consisted of 643 surface-water data points.

Additional well data were added to the already described data by utilizing monitoring wells installed by the Geology Department of Western Michigan University in Texas, Prairie Ronde, and Schoolcraft Townships. Wells were chosen that met the final criteria established through this study for well selection. A total of 13 wells were added.

CHAPTER IV

METHODOLOGY

Recharge- Discharge Potential Methodology

The Recharge-Discharge Potential Methodology is based on the vertical head differences found between wells with shallow depths of submergence and those with deeper depths of submergence. Depth of submergence (DOS) is the difference between the static water level in a well and the total depth of the well or equal to the height of the water column in a well. These differences in vertical head potential are most pronounced in areas of ground-water recharge and in areas of ground-water discharge. In order to normalize the data, wells were selected for depth of submergence rather than total well depth as the criterion for identifying which wells to include for evaluation of the method. This decision was based on the fact that the unsaturated zone is generally thicker in areas of recharge than in areas of discharge. Using depth of submergence (DOS) avoids the effects of differences in thickness of the unsaturated zone. The methodology is based on the premise that when a shallow DOS well and a deeper DOS well are located in close proximity in a recharge area of a water table aquifer, the shallow DOS well would exhibit a higher static water elevation than would the deeper DOS well. If these same wells were located in a ground-water discharge area the reverse would be true; i.e. the shallow depth of submergence well would exhibit a lower static water elevation than the deeper depth of submergence well (Appendix A). If the static water elevation in the deeper depth of submergence well was subtracted from the static water elevation in the nearby shallower depth of submergence well, the residual value would be positive in the recharge area and negative in the discharge area. It follows that in the transition zone where the static water elevations in both shallow and deeper depths of submergence wells would be expected to be comparatively equal, the residual would be zero or a small positive to negative range of values. These residual values can then be contoured as a two dimensional areal map, delineating recharge, transition, and discharge potential. The minimum recharge potential value and the maximum discharge potential value would be set by fixing the transition range.

The recharge-discharge potential methodology was developed to utilize computerized water well records available in county ground-water databases being developed in various counties in the state of Michigan, thus avoiding the time and expense of gathering field data. These water well records include residential, public, commercial, irrigation, monitoring, and test wells. This study used the Kalamazoo County Groundwater Database to provide the static water level elevations and related data needed for determining areas of ground-water recharge-discharge potential at the township and county level.

It is practical, possibly necessary, to employ a computerized geostatistical interpolation method and computerized contouring program to develop and evaluate such a large body of randomly distributed data over regions as large as counties and townships. The interpolation method utilizes geostatistical techniques for generating regularly spaced, gridded, estimated values from randomly distributed data. The software program SURFER, available through Golden, Inc., was chosen for its geostatistical capabilities, contouring program, and because it is relatively user friendly. An important option available through the SURFER software program is the subroutine Modify/Math available in GRID which allows the user to subtract one interpolated grid from another interpolated grid. This is essential to the recharge-discharge potential methodology.

In this study, appropriate water wells were identified by geographic location and depths of submergence, and processed through a selected interpolation method into regularly spaced gridded data. The individual grids, one for shallower depths of submergence wells and one for deeper depth of submergence wells were differenced by subtracting the deeper grid from the shallower grid. The resulting grid of residual values was contoured and evaluated by comparison to U.S.G.S. 7.5 minute topographic maps and local hydrogeologic studies for accuracy in identifying recharge-discharge flow systems. The value of including surface water elevations in the shallow DOS data sets for areas smaller than the county level was also examined.

Determining the capability of the methodology to delineate areas of recharge-discharge potential at the township and county level and evaluating the predictive accuracy of the method depended on the following parameters:

1. Identification of the most appropriate depths of submergence for both shallow and deeper depths of submergence wells.

2. Identification of the appropriate separation distance between wells selected for inclusion in the shallow depths of submergence data set and those selected for inclusion in the deeper depths of submergence data set, ensuring that an individual well would remain in its identified data set regardless of shifts in the water table elevation over time.

3. Identification of the most appropriate interpolation method for generating estimated static water elevations.

4. Identification of errors inherent in both the raw data and stochastically determined data.

5. Determination of possible statistical methods for evaluating reliability of estimated data.

6. Evaluation of the contoured surfaces representing recharge-discharge potential using U.S.G.S. 7.5 minute topographic maps and appropriate locally generated hydrogeologic studies for comparison.

Literature research into the advantages and disadvantages of using minimum curvature, inverse distance or kriging resulted in the selection of kriging as the standard interpolation method. SURFER does not give the error variance. However, the ability of kriging to decouple clustered data is valuable when using a data source based primarily on residential well records. The tendency for humans to live in relative close proximity to each other and for these individual houses and plats to be built along established transportation routes produces clustering of well data in these areas and sparsely distributed well data in the more rural areas. Although kriging was the chosen interpolation method for testing the accuracy of the methodology, the other two methods were tested at the township level and evaluated visually and statistically in order to further our understanding of advantages and disadvantages associated with these three interpolation methods. For this study it was decided to limit the separation distance between nodal points to 1,000 feet, the same separation distance used in a previous study of Van Buren County. In order to maintain some control over the domain of the search, the octant search pattern was chosen with a nearest neighbor of three (total: 8 x 3=24) for calculation of each node. The search radius was set at 20,000 feet (3.8 miles). The program selects the closest well data within the established search parameters. Each township was also tested for the minimum search radius that would result in unbroken contour lines. GRID will blank any node for which the search constraints are not met which results in broken contour lines. A total of 390 grids were generated for this study. Table 1 summarizes the standard study parameters.

Predefined Limits

Prior to well selection, consideration was given to limits placed on both shallow and deeper depth of submergence wells for defining the depth of submergence intervals and the appropriate vertical separation distance between them. In order to ensure that the shallow depth of submergence wells represent wells screened in a water table aquifer in Kalamazoo County, it was decided to use wells with a depth of submergence of $\leq$ 30 feet. The separation distance needed to be wide

Table1

Standard Interpolation Parameters

Interpolation Method	Search Method	Search Radius	Nearest Neighbor
Kriging	Octant	20,000 ft.	3 (3x8=24)

enough to ensure that the wells selected for the shallow or deeper DOS data sets would remain in their identified interval regardless of natural shifts in the water table elevation over time or possibly the effect of pumping wells in a particular area of influence. The Kalamazoo County Groundwater Database included well records dating primarily from 1963 to 1992. A study conducted by the U.S. Geological Survey in Van Buren County recorded fluctuations in water table elevations from 1963 to 1982 (Appendix B). The total range for these fluctuations was about 5 feet, (Cummings,Twenter, Holschlag, 1984). Based on this study, it was decided to use a separation distance of about 20 feet DOS. This study also examined the impact of using a separation distance of 10 feet DOS and one of 30 feet DOS in order to study the effect of the separation distance on recharge-discharge potential mapping. The deeper depth of submergence interval was established for this study by evaluating the impact of using the total range of deeper DOS wells and by limiting that range. The transition interval of ± 5 feet was selected to ensure this interval was outside the limits of the expected changes in the water table over time.

Mapping of the Recharge-Discharge Potential Surface

The process of interpolating the gridded surface in this research study was conducted using SURFER v.4. Since the initiation of this study, the authors of SURFER v.4, Golden, Inc., have developed a Windows version, SURFER v. 5.1. This latest version provides an improved contouring program which allows the use of color, fills, and the addition or subtraction of individual contour lines. SURFER v. 5.1 was used to produce the maps that were developed in this study. Recharge areas will be defined by light gray fill, transition by medium gray fill, and discharge by dark gray fill.

CHAPTER V

ANALYSIS

Texas Township

An initial examination of the Texas Township database revealed that there was a total of 696 well records available with 673 of these records usable for this study. Twenty-three well records were excluded for use in this study as a result of data entry errors at the time the records were completed or errors introduced during data entry into the Kalamazoo County Groundwater Database. Data for the remaining 673 well records is summarized in Table 2.

Table 2

Summary of Texas Township Water Well Records

Variable	Minimum	Maximum	Mean	Range
Well Depth	31 ft.	362 ft.	80 ft.	331 ft.
Depth to Water	3 ft.	150 ft.	38 ft.	147 ft.
DOS	13 ft.	348 ft.	42 ft.	335 ft.
Static Water Elev.	805 ft.	941 ft.	885 ft.	136 ft.
Well Elev.	880 ft.	1030 ft.	923 ft.	150 ft.
Record Dates	1966	1989		23 yrs.

Table 3 shows the distribution of wells in Texas Township by percent of the total data set for selected variables.

Table 3

Summary of Percentile Distributions for Wells in Texas Township

Variable	25%	50%	75%	100%
Total well Depth	≤ 58 ft.	≤ 71 ft.	≤ 88 ft.	≤ 362 ft.
Depth to water	≤ 25 ft.	≤ 32 ft.	≤ 50 ft.	≤150 ft.
DOS	≤ 28 ft.	≤ 35 ft.	≤ 45 ft.	≤ 348 ft.

A map of the topographic surface of Texas Township is found in Appendix C. Figures 8 and 9 for frequency histograms further illustrate the distribution of total well depth and depth of submergence for Texas Township well data. Figure 10 shows the drainage system, well distribution for shallow, middle, and deeper DOS wells used in the study, and section lines for Texas Township.

Table 4 lists the initial parameters used to establish the optimal separation distance and DOS intervals for mapping recharge-discharge potential in Texas

Figure 8. Frequency Histogram for Texas Township Using Total Well Depth.

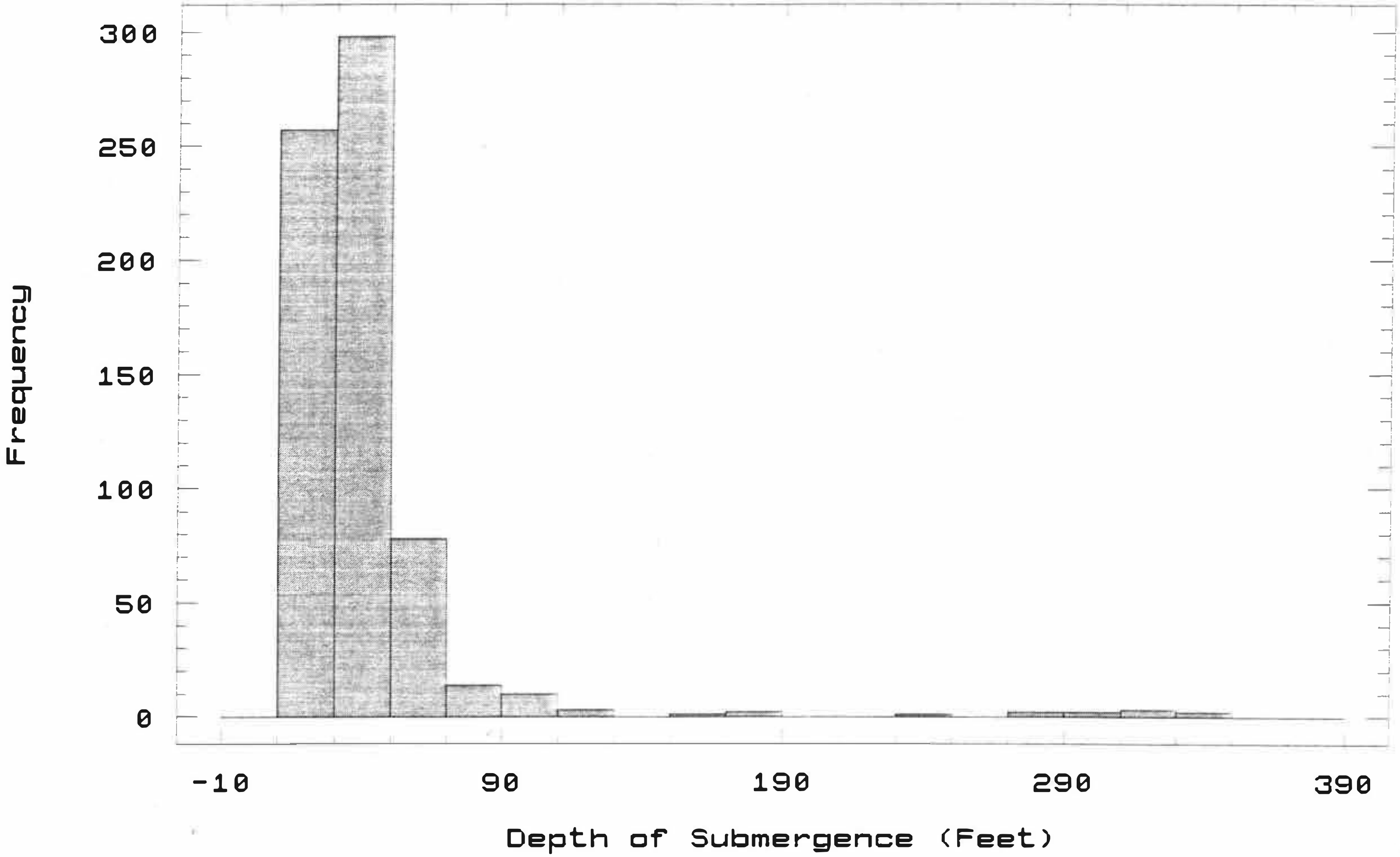


Figure 9. Frequency Histogram for Texas Township Using Depth of Submergence.

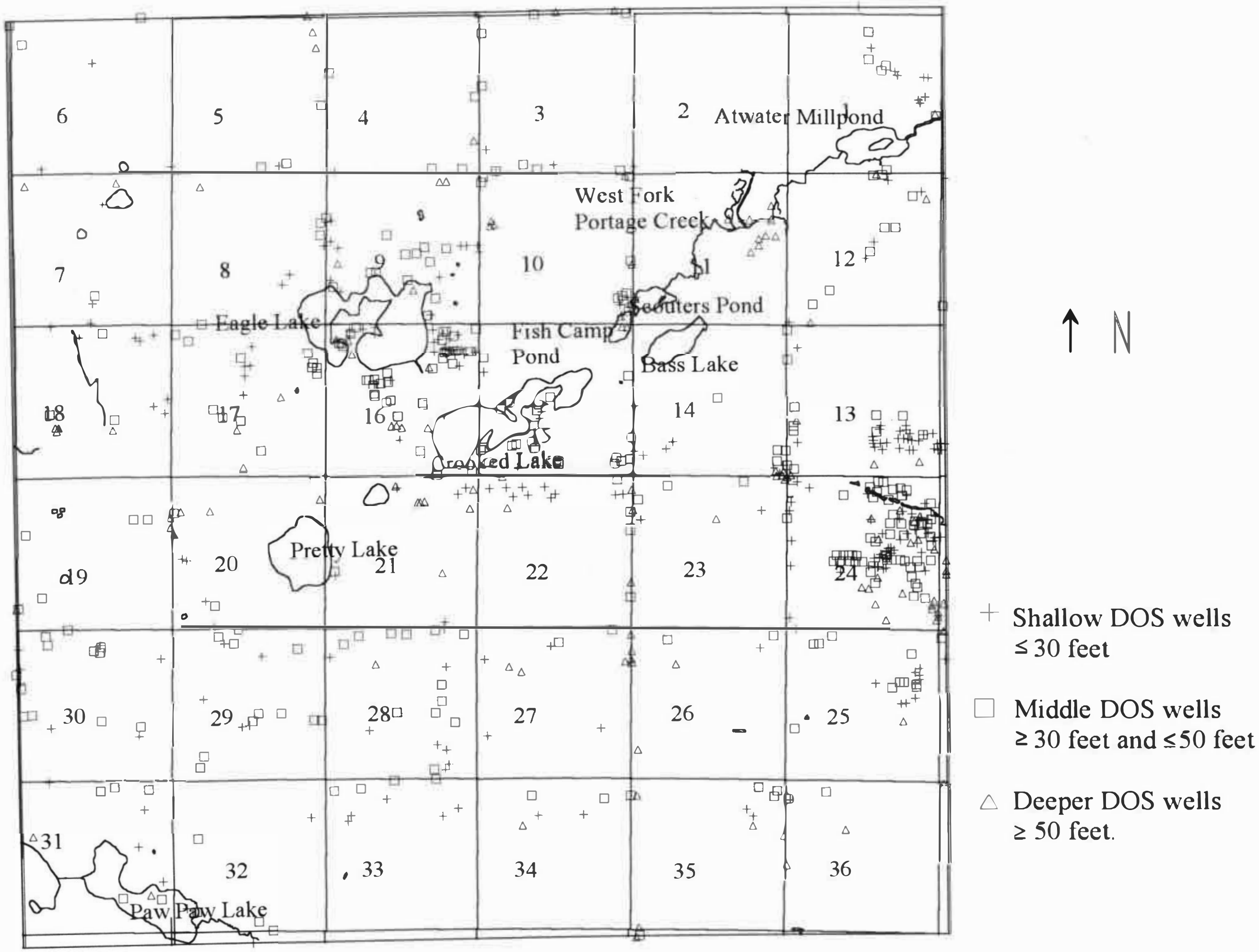


Figure 10. Map of Water Well Distribution and Drainage System (MIRIS Data) for Texas Township.

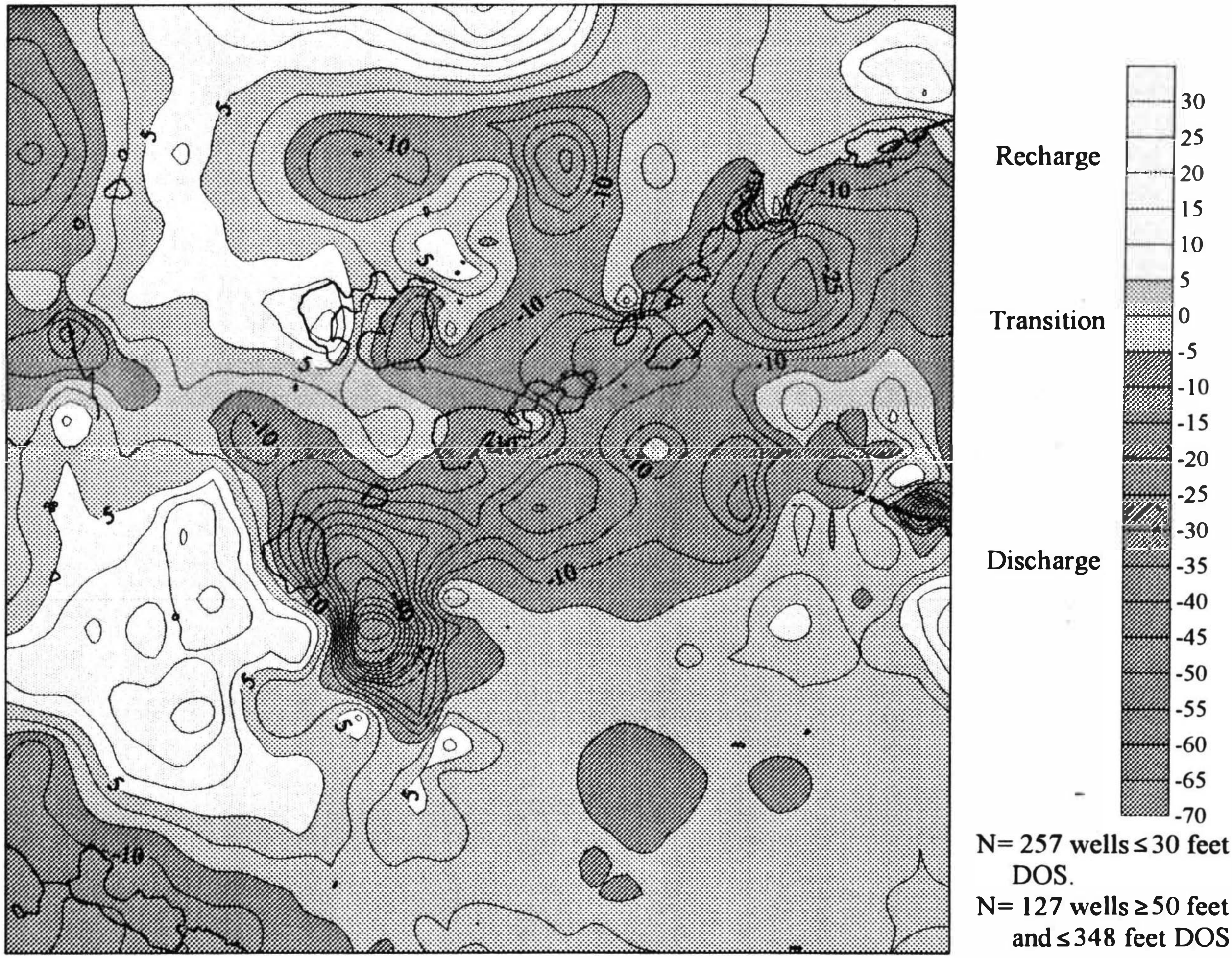
Table 4

Initial Parameters for Determination of Optimal Depth of Submergence Intervals for Texas Township

Shallow DOS	Number of Wells	Separation Distance	Deeper DOS	Number of Wells
≤ 30 ft.	257	10 ft.	≥ 40 ft. to ≤ 100 ft.	238
≤ 30 ft.	257	20 ft.	≥ 50 ft. to ≤ 100 ft.	106
≤ 30 ft.	257	20 ft.	≥ 50 ft. to ≤ 348 ft.	127
≤ 30 ft.	257	30 ft.	≥ 60 ft. to ≤ 348 ft	75

Township. The shallow depth of submergence data set includes 50 surface water data points.

Figure 11was developed using wells with a shallow depth of submergence of ≤ 30 feet and a deeper depth of submergence range of ≥ 50 feet and ≤ 348 feet. Comparison of Figure 11 to the topographic map shows a reasonably good correspondence of the system of lakes, wetlands, and streams that serve as the main drainage system in Texas Township to discharge areas represented by the darkest shade of grey on the recharge-discharge potential map. Recharge areas are depicted as the lightest shade of gray and stand out quite clearly along the Kalamazoo



Surface Water Points
N=50.

C.I. = 5 feet.

N= 257 wells ≤ 30 feet
DOS.
N= 127 wells ≥ 50 feet
and ≤ 348 feet DOS.

Figure 11. Recharge-Discharge Potential Map for Texas Township Using Shallow DOS ≤ 30 Feet and Deeper DOS ≥ 50 Feet.

Kriged, octant, nn=3,
r=20,000 feet.

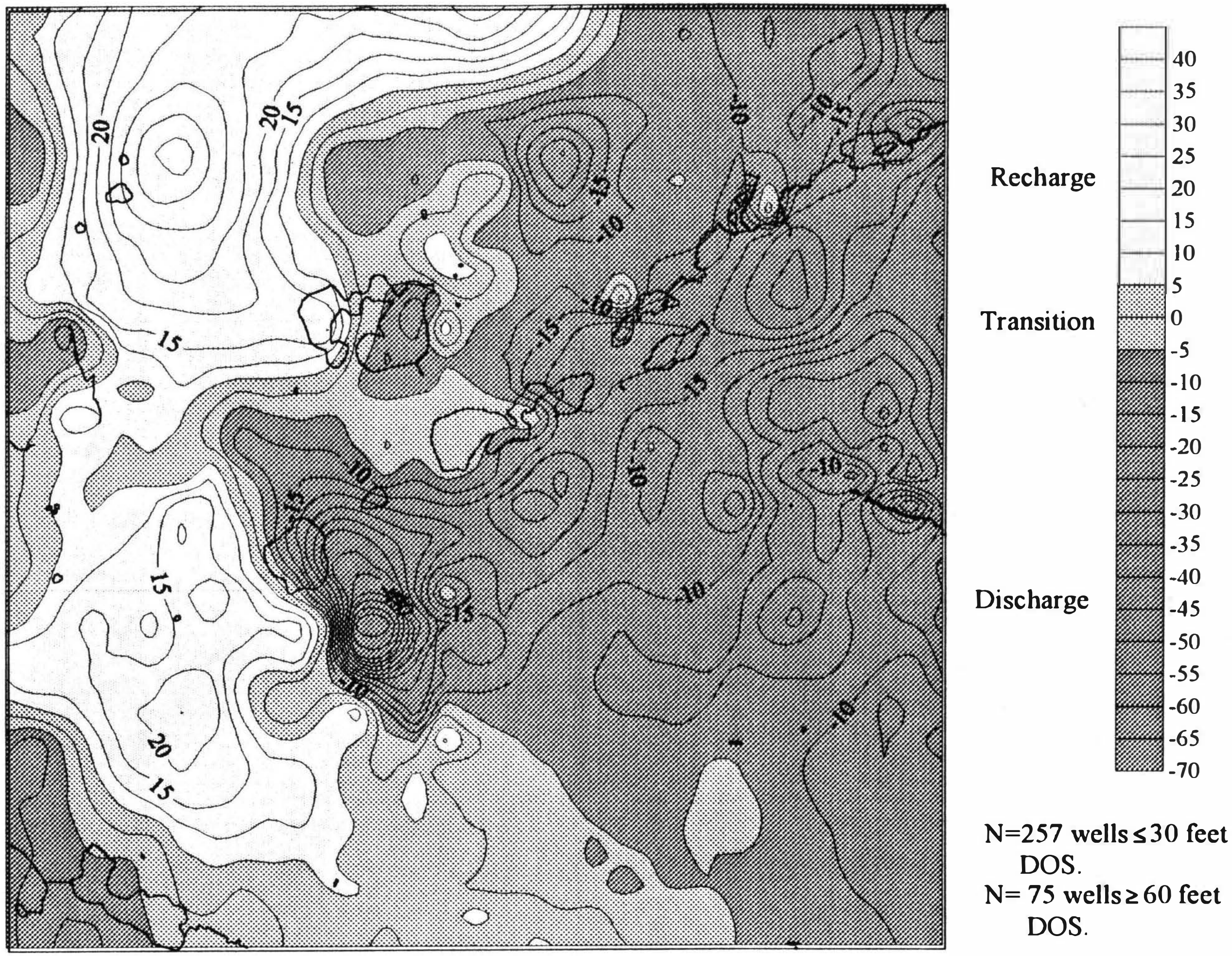
Moraine. It should be noted that there were no deeper DOS wells available in the southwest quarter of the township for computing the nodal values for the deeper depth of submergence grid. Generally speaking, wells in this area have the highest depth to water values and depths of submergence less than 50 feet. This would be expected in an area of high topographic relief (elevations up to 1030 feet) resulting in a much thicker unsaturated zone. Therefore, the interpolation method must use wells with deeper depths of submergence from beyond the morainal highs to compute the nodal values for the deeper depth of submergence grid in this quarter of the township.

This map also corresponds to the surface-water divide separating the Paw Paw River Basin from the St. Joseph River Basin, defining Paw Paw Lake in the southwest corner of the township as a discharge lake (Figure 11). The discharge area shown on the northwest side of the township does not correspond to the topographic map and could in part be an artifact of the boundary effect (boundary effect occurs when there are no data available beyond the limits of the search and the interpolation program computes the nodal value using only data available within the limits of the search). Because there are no data available to the west of the Texas Township boundary shared with Van Buren County, the interpolation program must compute those boundary nodal values from data available within the township. This increases the potential for error in these nodal values.

The southeast corner of the township is an outwash fan and is generally depicted as transition with isolated areas of discharge and recharge. Portions of sections 32 and 33 are marshlands with most of section 34 consisting of Mud Lake, and the northern half of the Balkema Wetlands. Hydrogeologic studies conducted in this area (Fronczek, 1986) concluded that there is an upper and a lower aquifer in this region and that Mud Lake represents the southern-most reach of the upper aquifer and is a discharge point for this aquifer. The same study, using specific conductance as an indication of recharge-discharge potential, concluded that the Balkema wetland is a discharge wetland, with both upper and lower aquifers discharging into this region.

There is nothing on the topographic map or noted in hydrogeologic studies in the area to verify the very steep gradients located in the discharge areas found in sections 21 and 28 and in section 24 of Figure 11. It would be necessary to examine the data set for errors not detected in the initial data evaluation and to search other possible factors (hydrologic or temporal) that could result in unusually high or low static water elevations in the wells found in these sections.

Figure 12 represents a separation interval of 30 feet with deeper DOS wells in the ≥ 60 feet and ≤ 348 feet DOS interval. By decreasing the number of wells (52 wells were removed) that are used in interpolating nodal values in the deeper DOS grid, the recharge-discharge potential shifts significantly. More than half the township now appears as discharge. In order to shift the interpretation of vertical potential to discharge it would be necessary to increase the estimated static water elevations in that area. This was accomplished when the 50 to 59 foot DOS wells were removed from the deeper DOS data set. The effect was to increase the maximum elevation on the deeper DOS surface. Removing the 50 to 59 foot DOS wells raised the elevation on the deeper DOS grid and resulted in a much increased



Surface Water Points
N=50.

C.I. = 5 feet.

N=257 wells ≤ 30 feet DOS.
N= 75 wells ≥ 60 feet DOS.

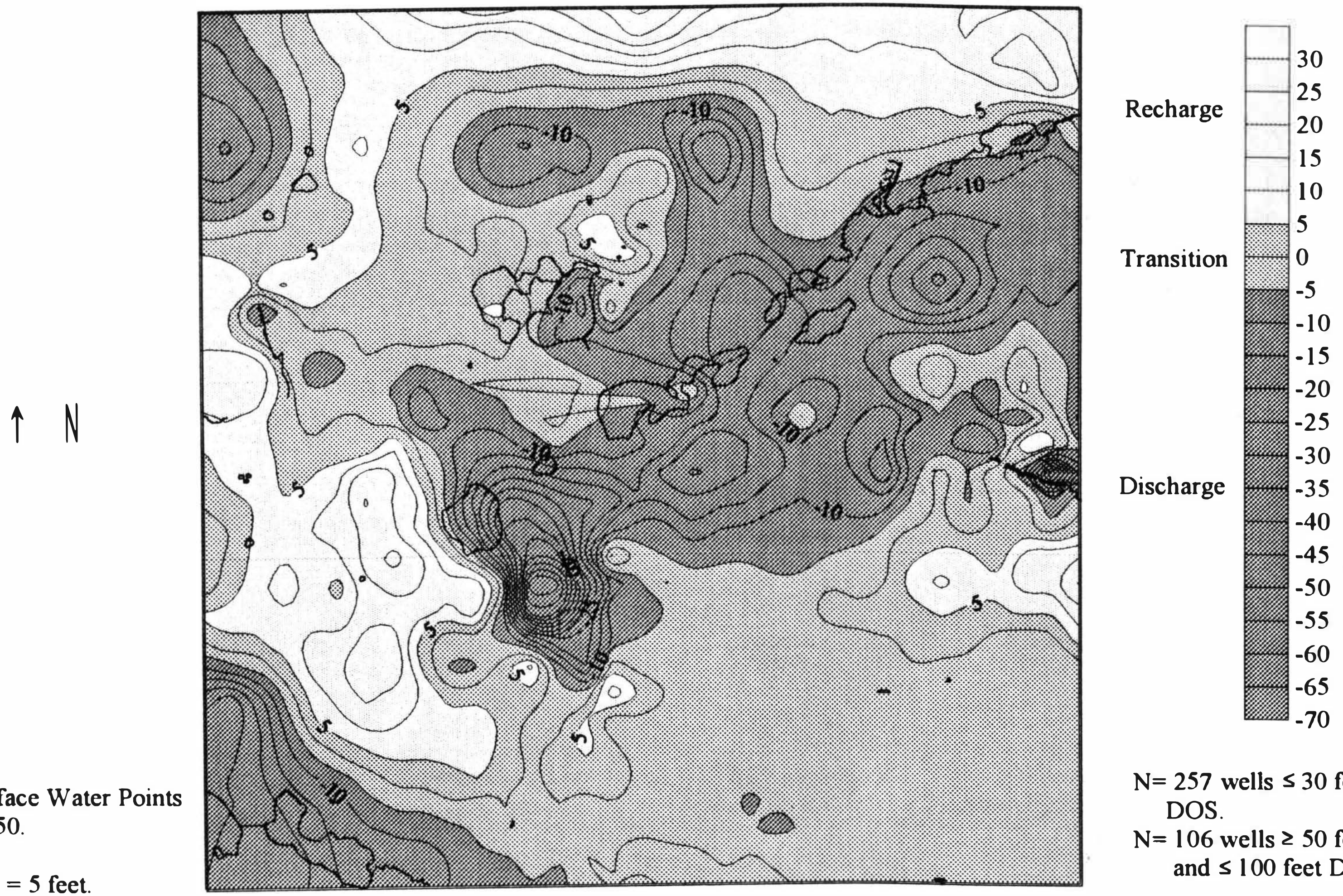
Kriged, octant, nn=3,
r=20,000 feet.

Figure 12. Recharge-Discharge Potential Map for Texas Township Using Shallow DOS ≤ 30 Feet and Deeper DOS ≥ 60 Feet.

interpretation of discharge over most of the eastern half of the township.

Figure 13 represents a separation interval of 20 feet as did Figure 11; however, the deeper DOS wells were limited to a maximum of 100 feet. The deeper DOS grid was interpolated using wells ≥50 feet and ≤ 100 feet. This reduced the number of wells included in this data set to 106 wells, a loss of 21 wells from the total data set used in interpolation of the deeper DOS grid in Figure 11. The effect of reducing the maximum deeper depth of submergence from 348 feet to ≤ 100 feet does not produce major changes in the recharge-discharge potential map. The drainage system is clearly defined as a discharge system with most of the outwash plains to the southeast mapping as transition. Paw Paw Lake still maps clearly as a discharge lake. The recharge area in the northwestern corner of the township extends further south and east on Figure 11 including almost half of Eagle Lake which appears as a flow through lake. On Figure 13 this area of recharge is reduced somewhat but now extends along most of the upper boundary of Texas Township. Eagle Lake maps as a transition/discharge lake.

Figure 14 was generated to evaluate limiting the separation distance between shallow and deeper DOS wells to 10 feet. The deeper depth of submergence wells were held to the 40 to 100 foot range. Inclusion of the wells in the 40-50 foot depth of submergence range resulted in an additional 111 wells being included in the DOS data set. This narrower separation distance produced isolated discharge areas along the drainage system of lakes, wetlands and streams to the northeast and produced an isolated recharge area around Bass Lake. It also resulted in a larger area of recharge



Surface Water Points
N=50.

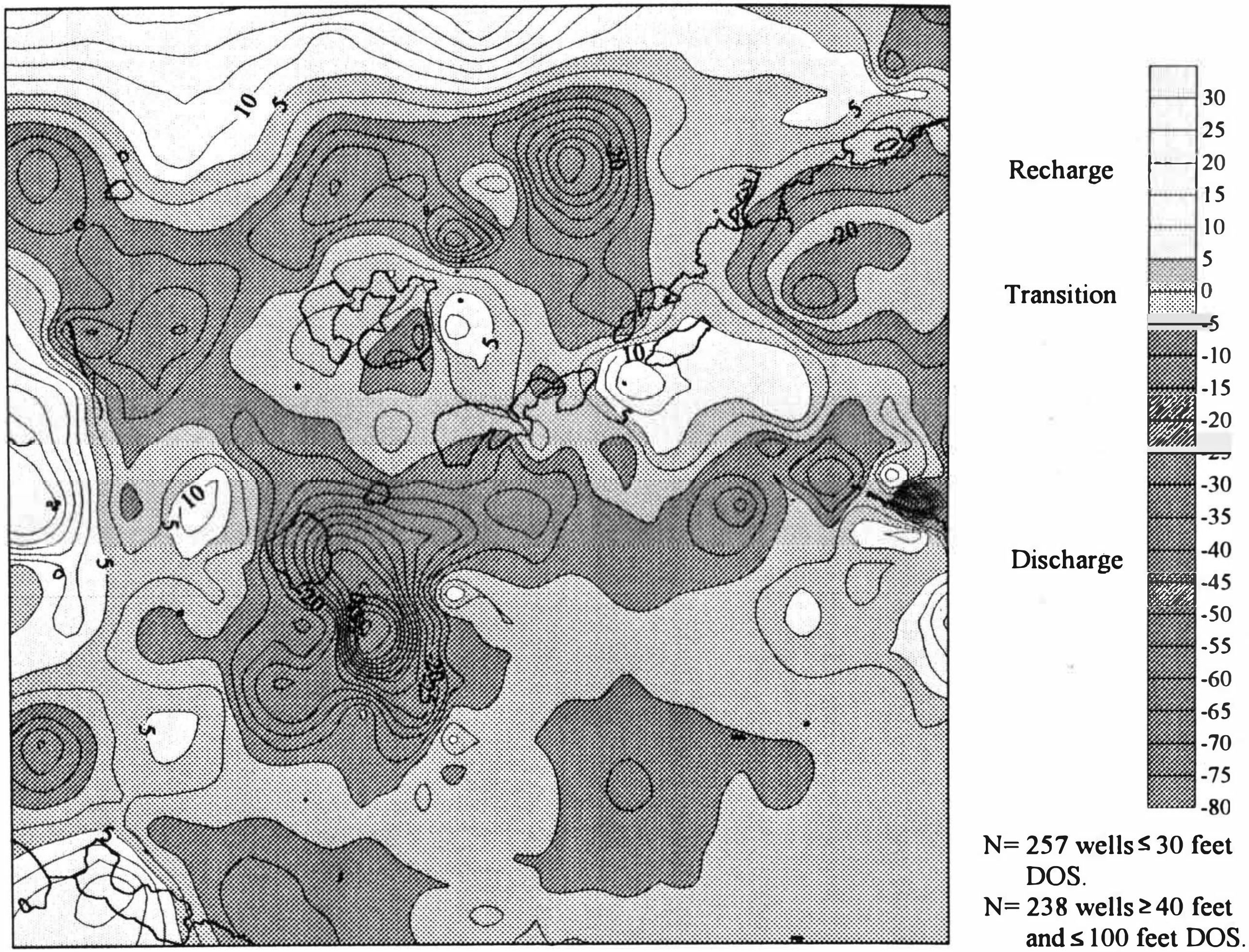
C.I. = 5 feet.

N= 257 wells ≤ 30 feet DOS.
N= 106 wells ≥ 50 feet and ≤ 100 feet DOS.

Figure 13. Recharge-Discharge Potential Map for Texas Township Using Shallow DOS ≤30 Feet and Deeper DOS ≥ 50 ≤ 100 Feet.

Kriged, octant, nn=3,
r= 20,000 feet.

↑ N



Surface Water Points
N= 50.

C.I. = 5 feet.

N= 257 wells ≤ 30 feet DOS.
N= 238 wells ≥ 40 feet and ≤ 100 feet DOS.

Figure 14. Recharge-Discharge Potential Map for Texas Township Using Shallow DOS ≤ 30 Feet and Deeper DOS ≥ 40 ≤ 100 Feet.

Kriged, octant, nn=3,
r=20,000 feet.

along the northern boundary of the township and greatly diminished a large area of recharge in the southwest corner of the township south of Pretty Lake which corresponds to a high on the Kalamazoo moraine which has been described as a kame like structure with an infiltration rate of 6 in./hr. (Straw, personal comment, 1994). In addition, this map depicts Paw Paw Lake as a recharge lake. Reducing the area of the Kalamazoo moraine interpreted as recharge and failing to interpret the drainage system as consistently discharge was sufficient to reject this separation distance. There is also some concern that wells influenced by the presence of nearby pumping wells would be erroneously classified with such a small separation distance.

Comparison of these depth of submergence intervals and separation distances suggested that a depth of submergence separation distance from 30 feet to 50 feet produced the most credible interpretations. The minimum depth of submergence for the deeper depth of submergence interval is 50 feet. Additional factors would be considered before the maximum deeper depth of submergence would be established. To check the extremely high gradients in discharge areas southeast of Pretty Lake and in section 24 a search of the original data set was conducted for possible errors. Wells in this region were isolated and their well elevations were verified on a topographic map. The high relief and hummocky topography found in Texas Township produces steep, convoluted topographic gradients on the topographic map. This is the most likely source for human error in data entry because the well elevations were estimated from the topographic map at the time the well locations were digitized. Comparing the isolated wells to the topographic map detected 20 well elevation errors ranging as high as 96 feet. Correction of these errors greatly reduced the large discharge bullseye located in sections 21 and 28 southeast of Pretty Lake and in section 24.

Other isolated areas of discharge brought into question some of the hydrogeologic assumptions employed in the initial development of the data sets. Texas township is one of the more geologically complex townships in Kalamazoo County. Based on a study in Van Buren County, it was assumed that total well depth might not be a necessary criterion for well selection. It was however, recognized that if wells were selected that were screened in a lower aquifer under confining conditions, the static water elevation for these wells may be higher than the water table surface, even above the land surface as in one area of Van Buren County. Artesian conditions would most likely exist in the relatively low topographic areas. If a well with artesian conditions were included in the deeper depth of submergence data set it would produce an isolated high on the gridded surface that would map as a high gradient discharge depression on the contoured recharge-discharge surface. In order to avoid the influence of artesian wells, it was decided to limit all wells to a total well depth of ≤ 150 feet. This will obviously eliminate more wells in the high topographic areas where the water table may be 200 feet deep and there is a higher percentage of wells deeper than 150 feet. However, only three townships (Cooper, Kalamazoo, and Oshtemo) have greater than 10 percent wells over 150 feet in depth and none exceeds 20 percent. Thirty wells were eliminated from the township data set and represented 4.4 percent of the total number of available wells. Table 5 lists

Table 5

Summary of Data Related to Wells Greater Than 150 Feet Total Depth for Texas Township

Section	Well Elevation feet	Total Depth feet	Depth to Water feet	Depth of Submerg. feet
3	990	172	105	67
3	970	172	70	102
9	949	153	54	99
10	965	230	70	160
10	965	156	70	86
10	950	299	65	234
10	940	260	75	185
11	900	199	15	184
11	921	317	17	300
11	905	358	10	348
11	900	339	21	318
11	890	329	14	315
11	890	306	11	295
11	880	295	8	287
11	910	292	9	283
11	915	362	23	339

Table 5–Continued

Section	Well Elevation feet	Total Depth feet	Depth to Water feet	Depth of Submerg. feet
19	952	158	58	100
21	1020	168	125	43
21	1030	181	149	32
21	1030	205	130	75
21	1020	162	121	41
21	1020	167	27	40
26	915	351	28	323
28	1010	166	136	30
28	1035	156	125	31
28	1048	176	147	29
29	1000	165	126	39
29	1015	165	135	30
29	1030	185	150	35
31	900	151	30	121

those wells that are > 150 feet total well depth along with related data. Figure 15 shows the distribution of those wells that fall into the > 150 feet total depth category.

There is a significant clustering of 11 deep wells in sections 21, 28, and 29 that coincides with topographic highs. Of the 11 wells, only 3 could have been included in the shallow DOS data set and 1 in the deeper DOS data set. The remaining 7 wells would have been excluded because their depths of submergence were between 30 and 50 feet (separation distance between shallow depth of submergence and deeper depth of submergence wells). Removal of these wells greatly reduces the most extreme recharge-discharge potential "bullseyes".

There are 9 wells located in section 11 that were excluded from the study data set structured to represent a water table aquifer. All of these wells are part of the Atwater Well Field (station 24) belonging to the City of Kalamazoo. The well field has 18 wells. Nine of these are included in the Kalamazoo County Groundwater Database and are 199-362 feet in total depth. Their large depths of submergence strongly support the decision to remove all wells that exceed 150 feet total well depth. The Department of Utilities for the City of Kalamazoo confirms that these wells are screened in a lower confined aquifer. The City describes this lower aquifer as a leaky artesian aquifer. Average pumpage on this field was 4,924,920 gpd for 1994 (Paquin, personal comment, 1995). There are two ways in which this well field could influence the recharge-discharge potential mapping in this area. The first would develop from the influence of the pumping on shallow depth of submergence wells screened in the upper aquifer. Due to the leaky confined conditions, static

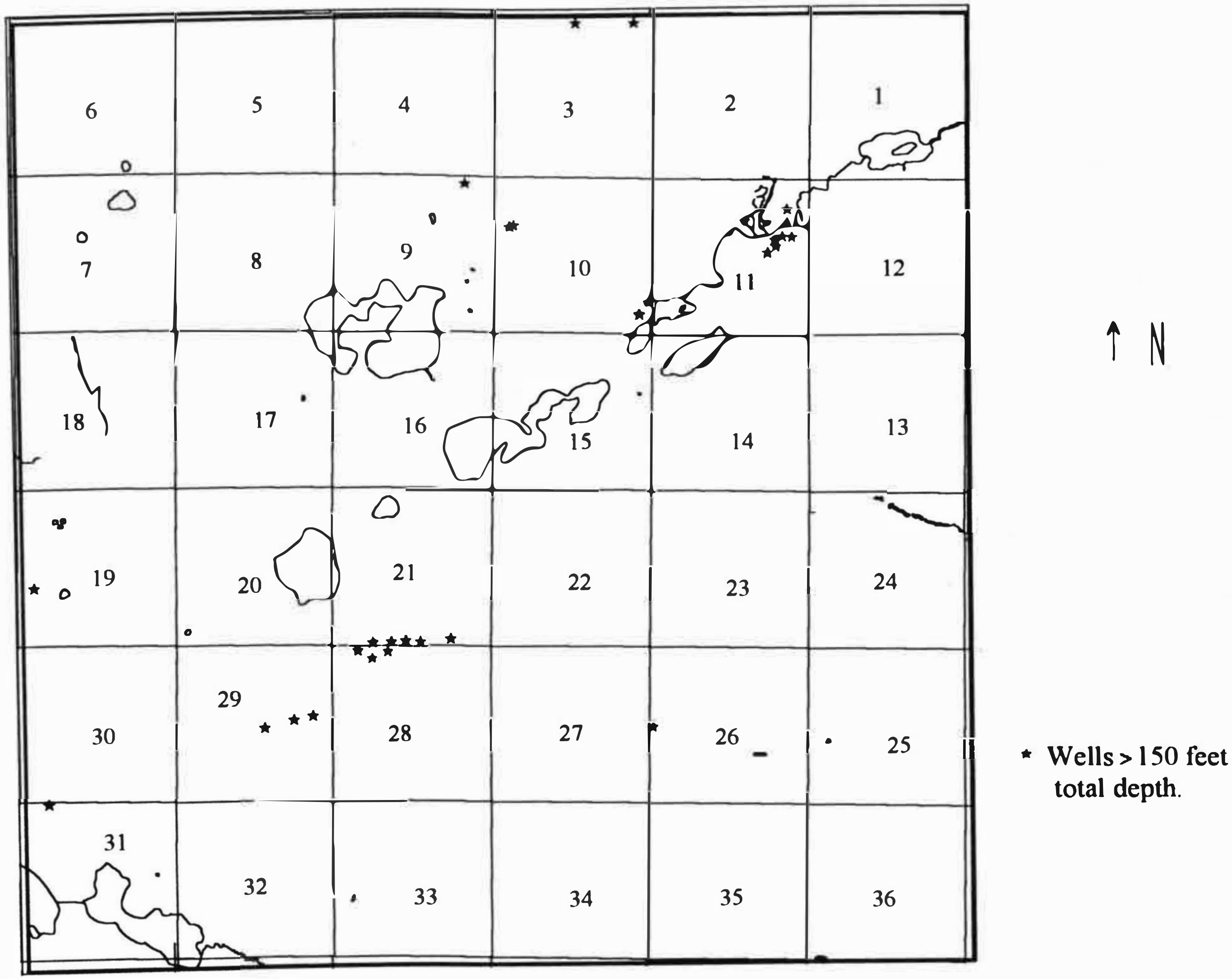


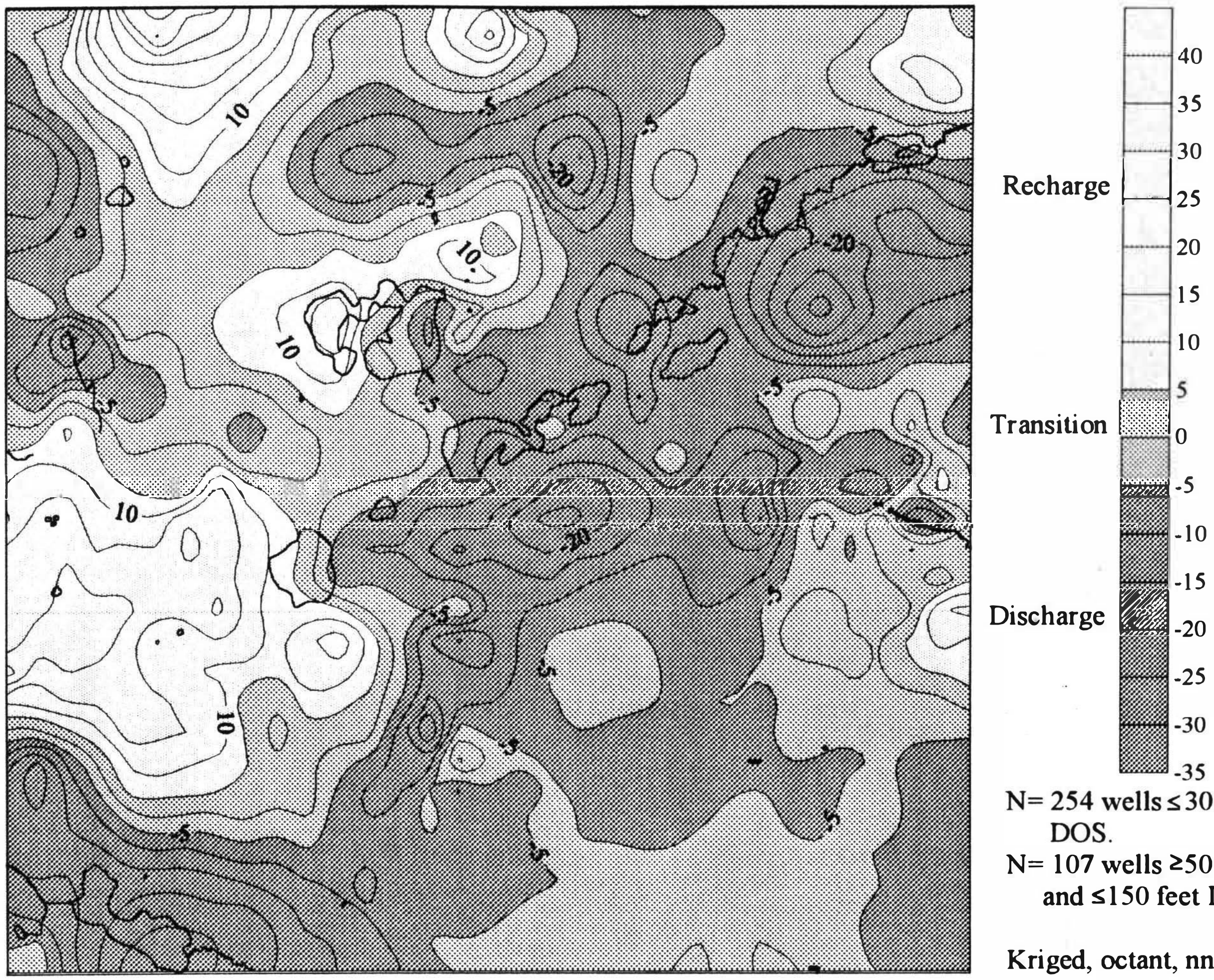
Figure 15. Map of Water Well Distribution for Wells >150 Feet Total Depth for Texas Township.

water elevations on shallow DOS wells would respond to pumping of the lower aquifer, resulting in unusually low static water elevations for these wells. The shallow DOS gridded surface would be lower in this region. This area would therefore map as a discharge area if the deeper depth of submergence grid were higher in this region. The second way in which the Atwater Well Field could influence mapping the recharge-discharge potential in this area is through inclusion of these wells in the deeper depth of submergence data set. The high static water elevations of these 9 wells could produce an isolated high on the deeper DOS grid. Subtraction of this grid from a shallow DOS grid would produce a significant area of discharge with a steep gradient.

Comparison of Figure 11 which includes these 9 wells to Figure 16 from which they have been removed shows little difference in the mapping of recharge-discharge potential for this region of Texas Township. The conclusion is that it is the impact on the shallow depth of submergence wells that is most significant. This area maps as discharge with or without these wells being present in the deeper depth of submergence data set. Analysis of this area of Texas Township underscores the influence of pumping wells on the interpretation of recharge-discharge potential using this methodology.

Finally, the presence of the Atwater Well Field does not negate the choice to exclude wells deeper that 150 feet. The impact of the increased static water elevations for wells screened in confined aquifers can be significant on the estimated nodal values for that region. The final analysis of the previously described figures resulted in the establishment of the default parameters for selecting wells to be included in the mapping of the recharge-discharge potential in Texas Township and for other areas within Kalamazoo County. These parameters include: (a) shallow depth of submergence wells ≤ 30 feet, (b) deeper depth of submergence wells ≥ 50 feet and ≤ 150 feet, (c) a separation interval of 20 feet, and (d) total well depth limited to ≤ 150 feet.

Figure 16 represents the recharge-discharge potential map for Texas Township generated using these final parameters. This map was also generated using surrounding data from Prairie Ronde, Schoolcraft, Portage, and Oshtemo Townships to minimize boundary effect on the southern, eastern, and northern boundaries. Inclusion of data outside the grid limits increases the computational time significantly Therefore, outside data were not used until the final parameters were established. There are still no data available for anchoring the western boundary between Texas Township and Van Buren County therefore this boundary still represents a higher degree of uncertainty. The anomalous discharge depression southeast of Pretty Lake has been minimized and shifted from southeast to directly east. There is a very poor distribution of deeper depth of submergence wells in the southwest quarter of the township (see Figure 10). The nodal values for this section of the deeper DOS grid are interpolated using wells 3 or more miles away. As a result, this quarter of the township recharge-discharge potential map has a higher level of uncertainty. Even with this uncertainty, the highs along the Kalamazoo moraine still map as distinct



Surface Water Points
N= 50.

C.I. = 5 feet.

N= 254 wells ≤ 30 feet DOS.
N= 107 wells ≥50 feet and ≤150 feet DOS.

Kriged, octant, nn=3, r=20,000 feet.

Figure 16. Recharge-Discharge Potential Map for Texas Township Using Shallow DOS ≤ 30 Feet and Deeper Dos ≥ 50 ≤ 150 Feet. Total Well Depth Limited to 150 Ft.

recharge areas. Paw Paw Lake, the Balkema wetlands and Mud Lake are interpreted as discharge as is the drainage system that originates with Pretty Lake and drains to the northeast. There is a new discharge area in sections 25 and 36 which was not previously seen. The addition of data from outside the township (grid limits) for interpolation of the estimated values resulted in the computer program searching in Portage Township to the east, Schoolcraft Township to the southeast, and Prairie Ronde Township to the south for input data in calculating the nodal values for the southeastern portion of the Texas grids. The implication of including data from outside the grid limits becomes apparent when these regions are more closely examined.

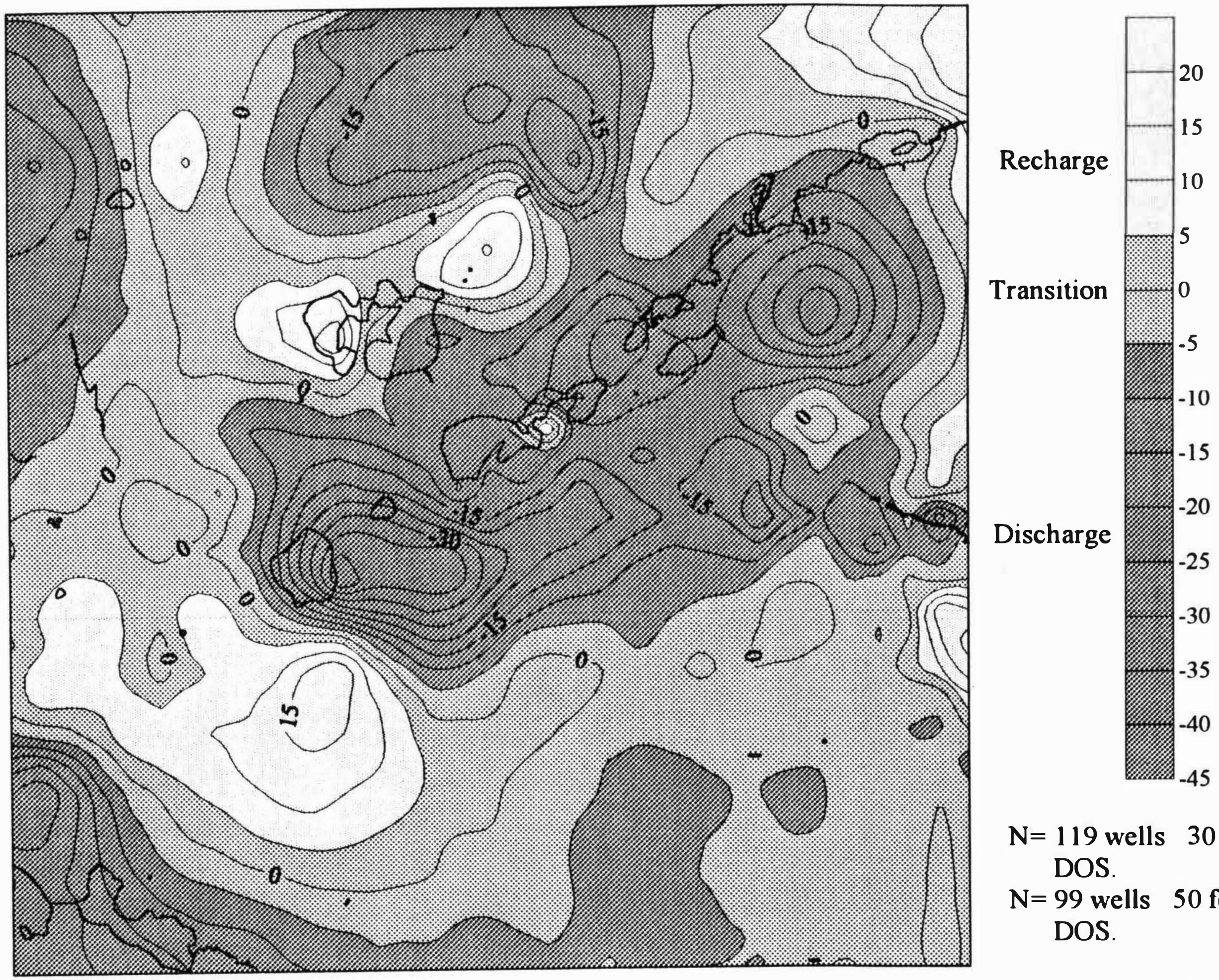
Immediately to the south of section 35 lies Harrison Lake located in Prairie Ronde Township, sections 2 and 3. Hydrogeologic studies conducted on this lake determined that it is a flow through lake with ground water discharging at the northwest limit and recharging to ground water in the southeast portion of the Lake (Fronczek, 1986). Directly to the east of Texas Township lie a series of wetlands, Hampton Lake, and Portage Creek which drains to the northeast. To the east-southeast lie Little Sugarloaf and Sugarloaf Lakes and Gourdneck Creek with contiguous wetlands draining to the east-southeast. The presence of a large number of wetlands, lakes, and streams suggests discharge potential in these regions. The inclusion of data from these regions (which comprises 270 degrees of the total search) may influence the estimated nodal values such that the southeastern quarter of Texas Township is now mapped as more strongly discharge than in Figure 11 in which outside data was not used. In addition, the influence of the data beyond the township boundaries is increased by the lack of any well data in section 36 of Texas Township. There are 50 well records available for sections 25, 26, 27, 34, 35. Of these wells, 20 (40% of total) were removed from consideration because their depths of submergence were ≥ 30 and ≤ 50 feet. There were only 11 deeper depth of submergence wells available in these sections with none available in sections 34 and 36 (Figure 10). The remaining 19 wells are shallow depth of submergence wells. The interpretation of sections 25 and 36 as discharge underscores the influence of data outside the mapped area influencing the computer generated grids. The inclusion of this data may help anchor the boundaries, however it may also have the potential for unduly influencing the estimated values.

The only other significant change on Figure 16 is an increase in gradient north of Paw Paw Lake. The topographic drop in elevation in this area is about 100 feet. The recharge-discharge potential shifts from + 20 feet to -30 feet, a total change of 50 feet potential. Earlier maps show a change of 35 feet or less. Figure 16 may represent a greater resemblance of the recharge-discharge potential surface to the topographic surface.

Temporal Analysis of Texas Township Data

The temporal influence on the potentiometric surface is one of the more obvious sources for error in recharge-discharge potential mapping when using residential well records collected over almost thirty years. Selection of a separation distance sufficient to minimize overlap of different depth of submergence data sets was an effort to minimize the temporal effect. To further analyze the effect of data gathered over an extended period of time, the well records for Texas Township were limited to a ten year interval and subsequently analyzed using the default grid parameters. The data were limited to a time period of 1979 to 1989. This reduced the shallow data set from 257 to 118 well records. The deeper data set was reduced from 127 to 99 well records. As with previous analyses, 50 surface water data points were added to the shallow data set resulting in 168 total data points. Figure 17 illustrates the effect of limiting the time span of the original data set as compared to Figure 16. The most obvious effect is that the recharge areas are substantially reduced in areal extent. Recharge areas in sections 5 and 6 are lost and the recharge areas in sections 8 and 9 that were west and north of Eagle Lake were reduced. The recharge area south and west of Pretty Lake that corresponds to the topographic highs (sections 19, 20, 28, 29, 30) in that region of the township now map in sections 28 and 29, a significant decrease. Section 28 lost 7 wells and section 29 lost 5 wells. All of the lost wells are from the shallow DOS data set. It is apparent that these wells were significant to mapping the areal extent of recharge in this region. The range of recharge-discharge residual values was -32 to +40 feet in the original recharge-discharge map (Figure 16). The range of residual values was -44 to +23 feet in the ten year time limited map (Figure 17). The decrease in maximum residual values and the subsequent increase in negative residual values reflects the loss of control on the shallow gridded surface.

↑ N



Surface Water Points
N= 50.

C.I.= 5 feet.

N= 119 wells 30 feet
DOS.
N= 99 wells 50 feet
DOS.

Kriged, octant, nn=3,
r=20,000.

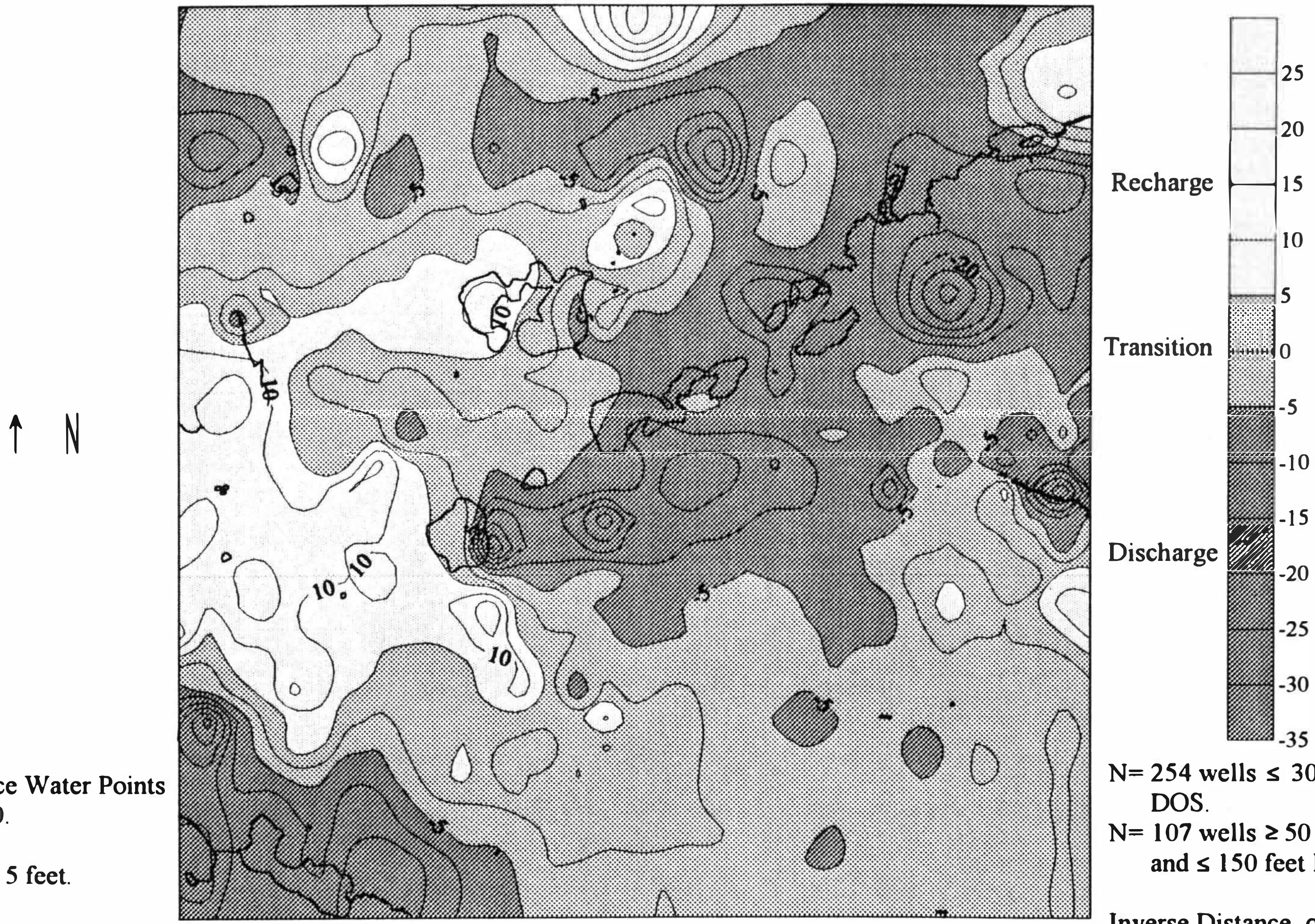
Figure 17. Recharge-Discharge Potential Map for Texas Township Using Wells Limited to Installation Dates of 1979 to 1989.

The major discharge area south of the main drainage system is smaller and does not extend down into the southeast. This appears to be a better interpretation of the discharge extent than found in Figure 16. However, this map was not generated using data from outside the township and this has already been shown to influence the southeast quarter of Texas Township. Overall, comparison of the 30 year map (Figure 16) to the 10 year map (Figure 17) shows reasonable agreement and suggests that longer time intervals are not a major factor in mapping recharge-discharge potential at the township level.

Analysis of Interpolation Methods for Texas Township Data

As in the Van Buren County study, an attempt was made to compare the three interpolation methods available in SURFER using the Texas Township data. Figure 18 represents the inverse distance to the second power with an octant search pattern, a radius of 20,000 feet and a maximum of three data points per octant. There is a reasonably close agreement on recharge-discharge potential between this method and the Figure 16, which is a kriged map. There appears to be a greater number of small isolated highs and lows. This is more common with inverse distance than kriging. Unlike kriging, inverse distance does not attempt to decouple clustered data and therefore characteristically produces isolated bullseyes.

Figure 19 was developed using the minimum curvature method of interpolation. Minimum curvature uses all the data in the data set for the



Surface Water Points
N= 50.

C.I. = 5 feet.

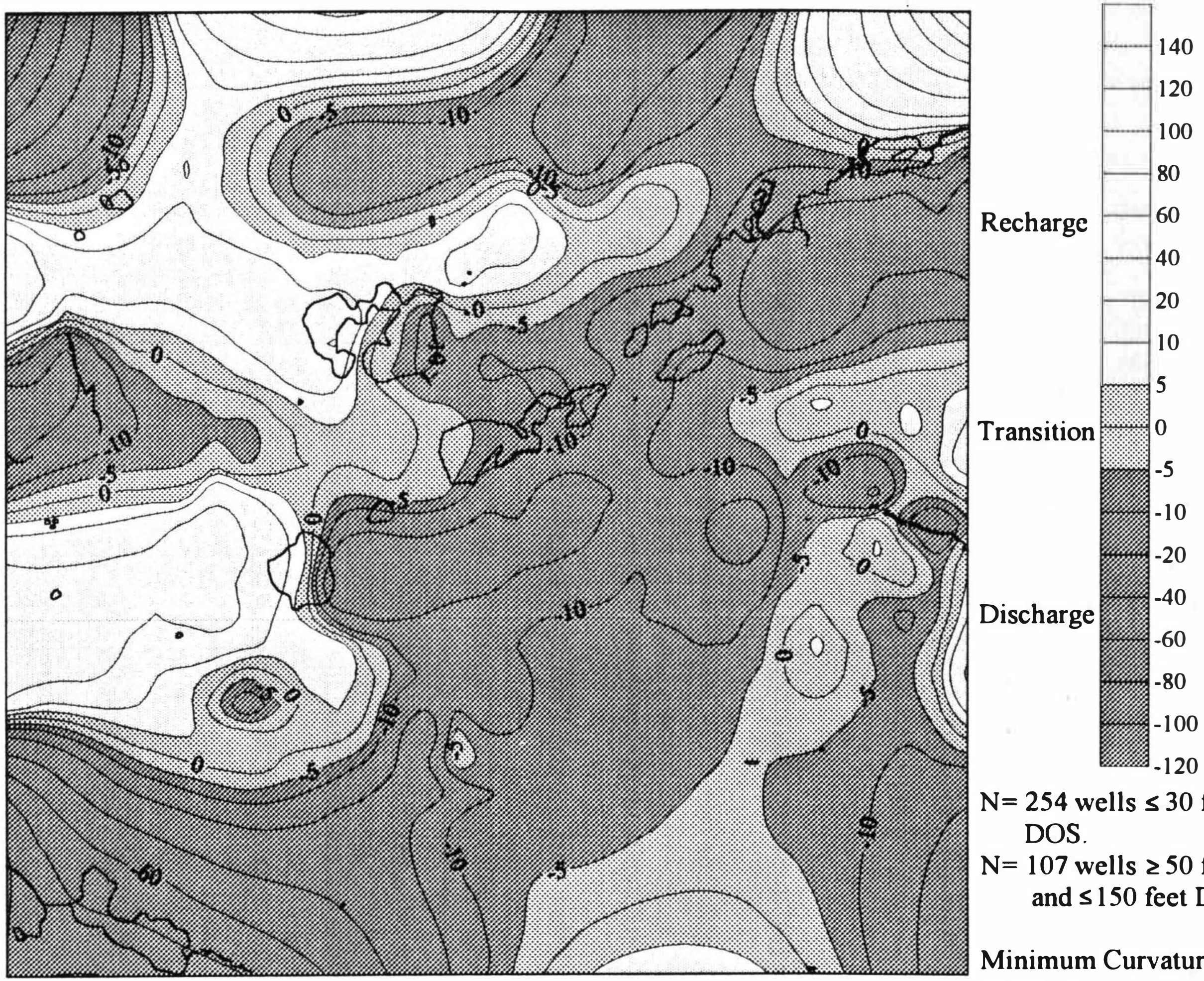
N= 254 wells ≤ 30 feet. DOS.
N= 107 wells ≥ 50 feet and ≤ 150 feet DOS.

Inverse Distance, octant
nn=3, r=20,000 feet.
Total Well Depth >150 Feet.

Figure 18. Recharge-Discharge Potential Map for Texas Township Using Inverse Distance Squared Method of Interpolation.

Surface Water Points
N= 50.

C.I. = 5 feet.



N= 254 wells ≤ 30 feet DOS.
N= 107 wells ≥ 50 feet and ≤ 150 feet DOS.

Minimum Curvature, all wells.

Total Well Depth > 150 feet.

Figure 19. Recharge-Discharge Potential Map for Texas Township Using Minimum Curvature Method of Interpolation.

interpolation of each individual node, generates the smoothest possible surface and is not considered to be an exact interpolator. Therefore, it will not always honor the data exactly. It is apparent that minimum curvature introduces extremely steep gradients into the recharge-discharge potential map. These extreme gradients are sufficient to reject minimum curvature as a reliable interpolation method for this set of data.

Statistical Analysis of Texas Township Data

Regression analysis was used evaluate the agreement between: (a) non-gridded topographic elevations and non-gridded static water elevations for the shallow depth of submergence data set; (b) gridded topographic elevations and gridded static water elevations for the shallow depth of submergence wells; (c) gridded topographic elevations and recharge-discharge potential residuals for shallow depth of submergence wells (calculated from gridded data); and (d) gridded static water table elevations and recharge discharge potential residuals for the shallow depth of submergence wells. Topographic values were assigned to each well from a topographic map at the time the well location was digitized and entered into WELLKEY. Gridded data were obtained through the use of the SURFER subroutine Convert, which is part of the SURFER subprogram UTIL. Convert uses a grid file and converts it to an ASCI text file. The output file consists of the x and y coordinates for each grid node and the estimated variable for that node. The gridded and non-gridded data for the shallow depth of submergence wells were used because these data are most representative of the water table surface. Theoretically, the water table surface would be expected to show reasonable agreement with the topographic surface, reflecting the tendency of the water table surface to mimic changes in relief on the topographic surface, although in a more muted manner. The recharge-discharge potential surface was compared to both the topographic surface and the water table surface in order to determine where the agreement was closest.

Table 6 lists the results of the regression analysis. There is moderate correlation between the shallow water table surface and the topographic surface. The gridded data correlates more closely than the non-gridded data because the interpolation process produces an averaging of the estimated values, which results in

Table 6

Regression Analysis of Non-Gridded and Gridded Data for Texas Township

Type of Data	Order of Analysis	N	Surface Water	R
Non-gridded	Topo. vs Shallow Water Table	257	0	0.4998
Gridded	Same	1089	50	0.5839
Gridded	R/D vs Topo.	1089	50	0.3471
Gridded	R/D vs Shallow Water Table	1089	50	0.5601

a small reduction of the maximum and minimum values. As expected, the gridded recharge-discharge (R/D) potential surface correlates more closely with the shallow water table surface than it does with the topographic surface. If the water table surface represents a more muted reflection of the topographic surface, it follows that the recharge-discharge potential surface would represent an even more muted reflection of the topography and a closer reflection of the shallow water table surface.

Correlation coefficients (coefficient of correlation (R) varies between -1 and +1 representing negative linear correlation and positive correlation respectively) of R=0.6 or less may be due to the higher relief and more complex geology found in Texas Township. Hummocky relief can produce numerous subbasins within the major drainage basin. These subbasins can exhibit discrete local flow systems. Well data representative of these local flow systems are used to estimate the recharge-discharge potential for areas where well data is sparse. Consequently, the nodal values for areas outside the subbasins are estimated based on the data within the subbasins. In addition, SURFER v.4 does not allow input to the interpolation process to take into account anisotropy which can also be interfering with the interpretation of a township sized area. Correlation coefficients of about 0.6 are considered reasonable given the nature of the data.

Regression analysis was also used to correlate each of the three interpolation methods with the other two methods. This analysis used gridded data. Table 7 shows the correlations of the gridded shallow water table for the three pairs of interpolation methods. Inverse distance and kriging have a high positive correlation and show

Table 7

Correlation of Interpolation Methods Using Shallow Water Table Grid for Texas Township

Interpolation Methods	R	Maximum and Minimum Static Water Elev. in Feet for Gridded Surface		
			Max.	Min.
Inverse Distance vs. Kriging	0.939	I.D. M.C.	924 953	859 821
Inverse Distance vs. Minimum Curvature	0.756	K.	924	855
Kriging vs. Minimum Curvature	0.848			

good agreement between maximum and minimum gridded static water elevation. Minimum curvature exhibits the lowest correlation with either of the other two methods and generates the widest range of maximum and minimum static water elevations.

The same regression analysis was also performed on recharge-discharge potential residuals for comparison of interpolation methods. Table 8 summarizes the regression analysis for these data. The R values for recharge-discharge potential are lower than the R values for the shallow water table surface correlations. However,

Table 8

Correlation of Interpolation Methods Using Recharge-Discharge Potential Values for Texas Township

Interpolation Methods	R	Maximum and Minimum Residual in Feet.		
			Max.	Min.
Inverse Distance vs. Kriging	0.797	I.D. M.C.	1.4 140	-15.5 -98.8
Inverse Distance vs. Minimum Curvature	0.546	K.	9.5	-6.80
Kriging vs. Minimum Curvature	0.534			

the highest correlation (0.797) is still between inverse distance and kriging. Because inverse distance does not handle clustered data well it is therefore not surprising that there is less agreement between the maximum and minimum static water elevations for both methods. What is most interesting is the extreme maximum and minimum generated by the minimum curvature method of interpolation. Minimum curvature is obviously the least suitable interpolation method for generating the gridded surfaces used in this analysis.

Schoolcraft Township

There were 238 well records listed in the Kalamazoo County Groundwater

Database. Fourteen records were discarded for this study because they were incomplete. Data from the 224 well records is summarized in Table 9.

Table 9

Summary of Schoolcraft Township Water Well Records

Variable	Minimum	Maximum	Mean	Range
Well Depth	22 ft.	275 ft.	63 ft.	253 ft.
Depth to Water	2 ft.	45 ft.	16 ft.	43 ft.
DOS	7 ft.	265 ft.	47 ft.	258 ft.
Static Water Elev.	797 ft.	879 ft.	846 ft.	82 ft.
Well Elev.	835 ft.	889 ft.	862 ft.	54 ft.
Record Dates	1966	1989		23 yrs.

A map of the topographic surface for Schoolcraft Township is found in Appendix D. Figure 20 represents the frequency distribution for total well depth with Figure 21 describing the frequency distribution for depth of submergence. Table 10 shows the percentile distribution of well data for Schoolcraft Township (n=224 records). For comparison, the same data are listed in parenthesis for Texas Township.

Wells are deeper in Texas Township. The maximum relief in Texas Township is 150 feet reflecting the difference between the Kalamazoo Moraine and the outwash fan. Schoolcraft relief is only 54 feet reflecting a gradual decrease in elevation from

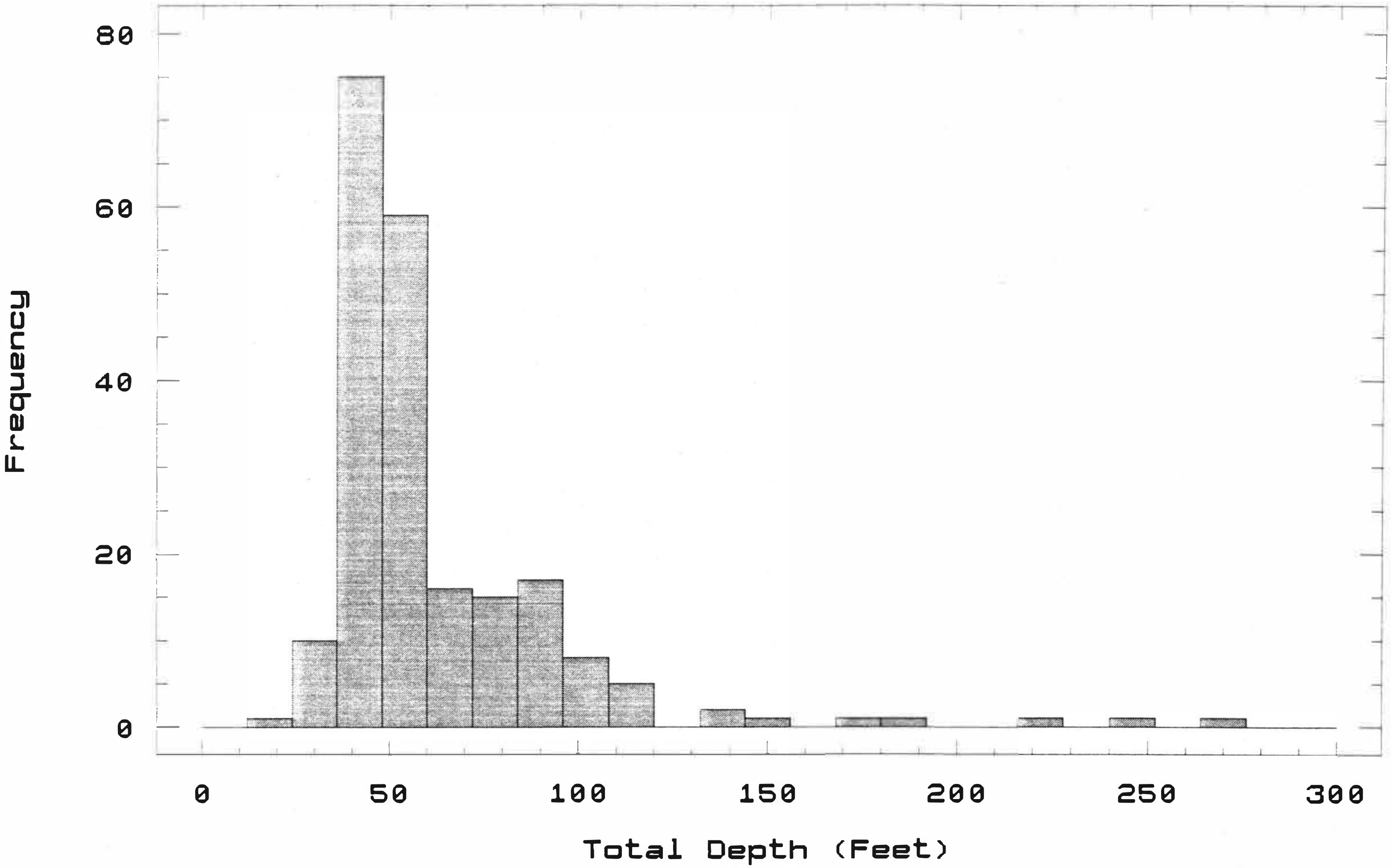


Figure 20. Frequency Histogram for Schoolcraft Township Using Total Well Depth.

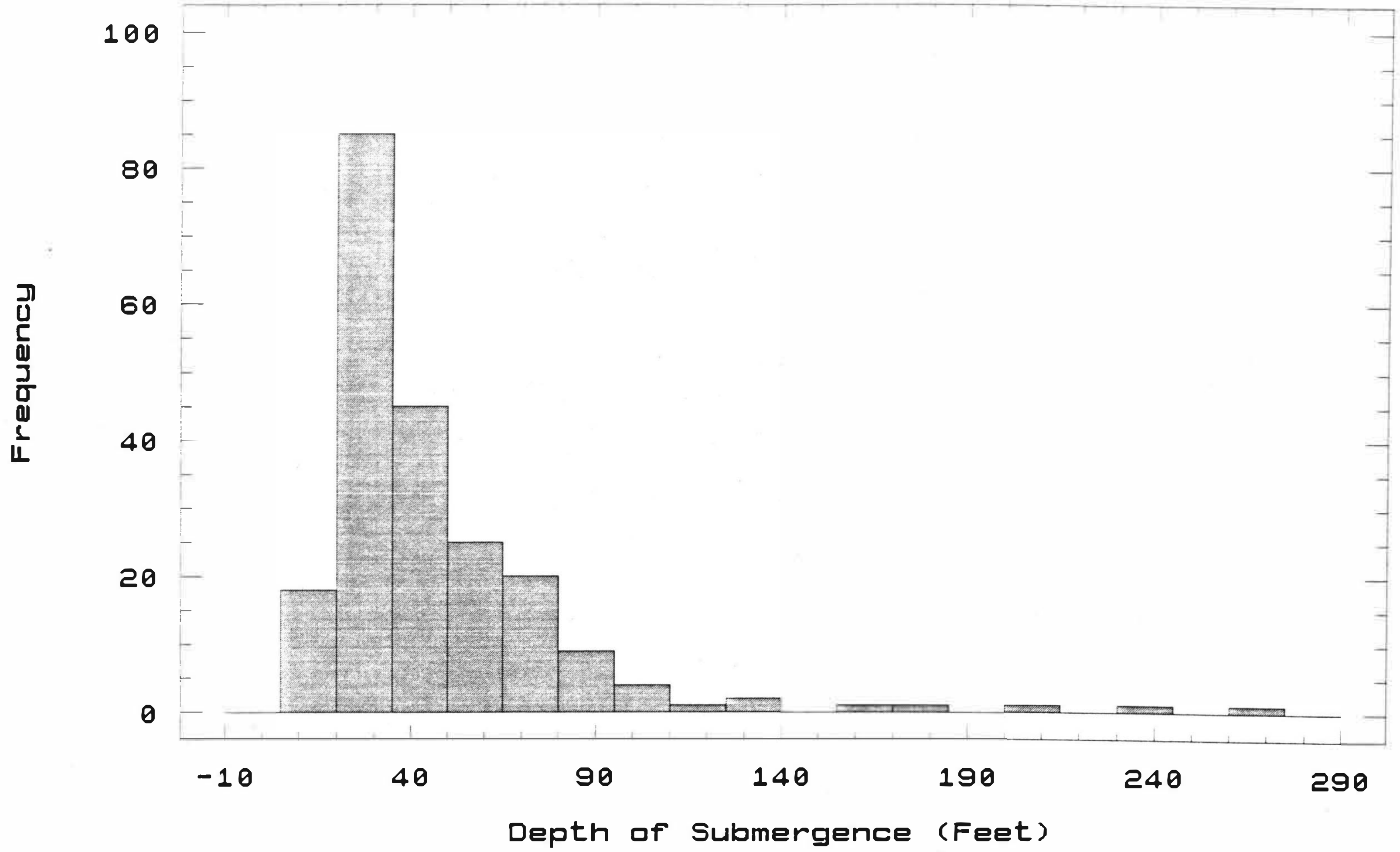


Figure 21. Frequency Histogram for Schoolcraft Township Using Depth of Submergence.

Table 10

Summary of Percentile Distributions for Well Data
in Schoolcraft Township

Variable	25%	50%	75%	100%
Total well depth	≤43 ft.(58)	≤56 ft.(71)	≤72 ft.(88)	≤275 ft. (362)
Depth to water	≤12 ft.(25)	≤17 ft.(32)	≤20 ft.(50)	≤45 ft. (150)
Depth of submerg.	≤27 ft.(28)	≤36 ft.(35)	≤56 ft.(45)	≤265 ft. (348)

(Texas Township Data)

the northwest to the southeast. This low gradient is also reflected by the fact that 75 % of the wells in Schoolcraft Township have lower depths to water than 25 % of the wells in Texas Township. The average hydraulic gradient is 0.001 to 0.002 foot/foot (Straw et al., 1990). Schoolcraft Township recharge-discharge potential was evaluated using the same parameters as for Texas Township with the exception of using a separation distance of 10 feet between the shallow DOS wells and the deeper DOS wells. The initial interpolation constraints were also the same (kriging, radius =20,000 ft., octant search method, nearest neighbor = 3). Initially 55 surface water points were added to the shallow depth of submergence data set. After an initial analysis, 190 more surface water data points were added for additional control on the shallow depth of submergence surface, a total of 245 surface water points. As with Texas Township, data from outside the township were not included in the initial evaluations to save computation time. Figure 22 shows the drainage system and the distribution of shallow, middle, and deeper DOS of the Schoolcraft data set.

Figure 23 is based on a shallow DOS data set of ≤ 30 feet. The deeper depth of submergence data set is based on a DOS interval of ≥ 50 feet and ≤ 265 feet. No limit was placed on total depth. Sections 1- 6 represent an area of discharge along the chain of lakes, streams and contiguous wetlands including Little Sugarloaf, Sugarloaf, Hogset, and Gourdneck Lakes, and Gourdneck Creek that drain to the southeast. Sections 7, 8, 17, and 18, which includes the Village of Schoolcraft, map as an area of discharge. Although there are some discreet wetlands indicated on the topographic maps, it seems unlikely that this area should map as a discharge area, especially with a residual value as high as 14 feet (difference between shallow and deeper DOS grids). The discharge area may reflect the influence of pumping at the village well field located near the center of the Village of Schoolcraft in section 18 and several commercial wells in the immediate area. The southern most tier of sections map as discharge, reflecting the influence of Spring Creek and contiguous wetlands. The area most difficult to interpret is the large drainage system in the southeast portion of the township containing Howard Lake, Black Lake, Tub Lake, Barton Lake, Kimble Lake, and Portage Creek. This is a major perennial drainage system which flows to the east. It would be expected to map as a discharge area. Hydrogeologic studies on the Prairie Ronde Fan (Figure 24) concluded that the chain of lakes including Howard and Barton Lakes are most likely to be discharge lakes

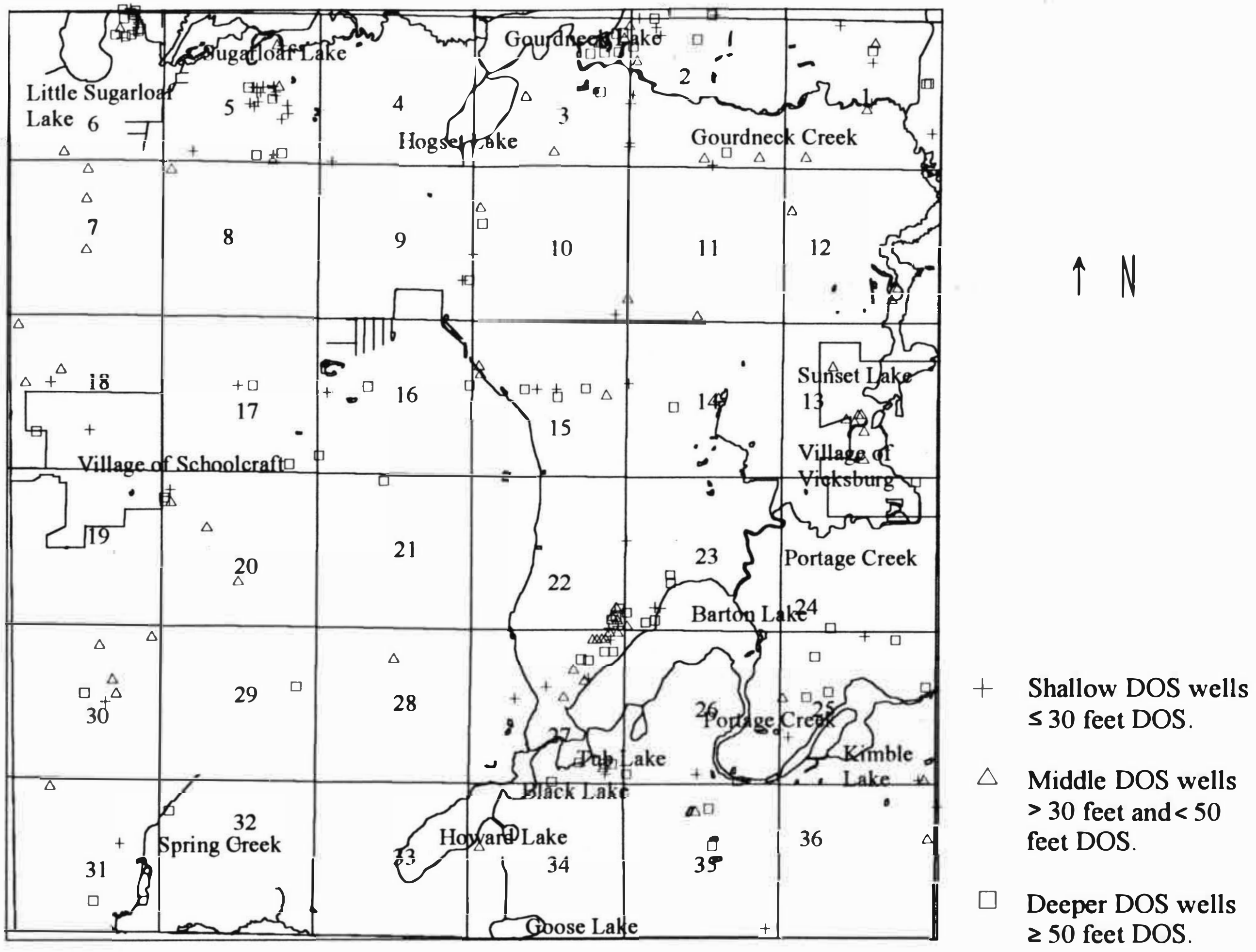
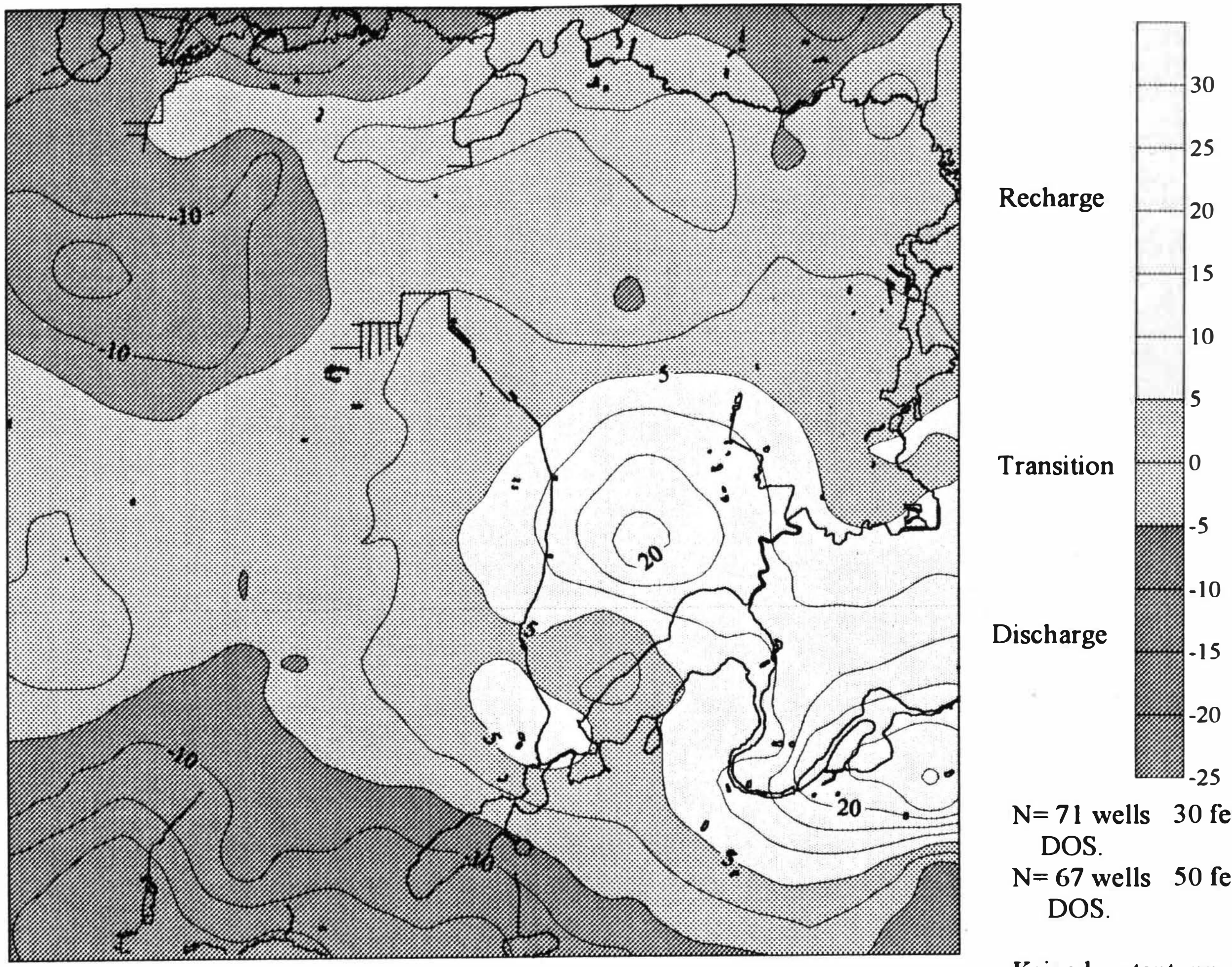


Figure 22. Map of Water Well Distribution and Drainage System (MIRIS Data) for Schoolcraft Township.



Surface Water Points
N= 245.

C.I. = 5 feet.

N= 71 wells 30 feet DOS.
N= 67 wells 50 feet DOS.

Kriged, octant, nn=3, r=20,000 feet.

Figure 23. Recharge-Discharge Potential Map for Schoolcraft Township Using Shallow DOS ≤ 30 feet and Deeper DOS ≥ 50 feet.

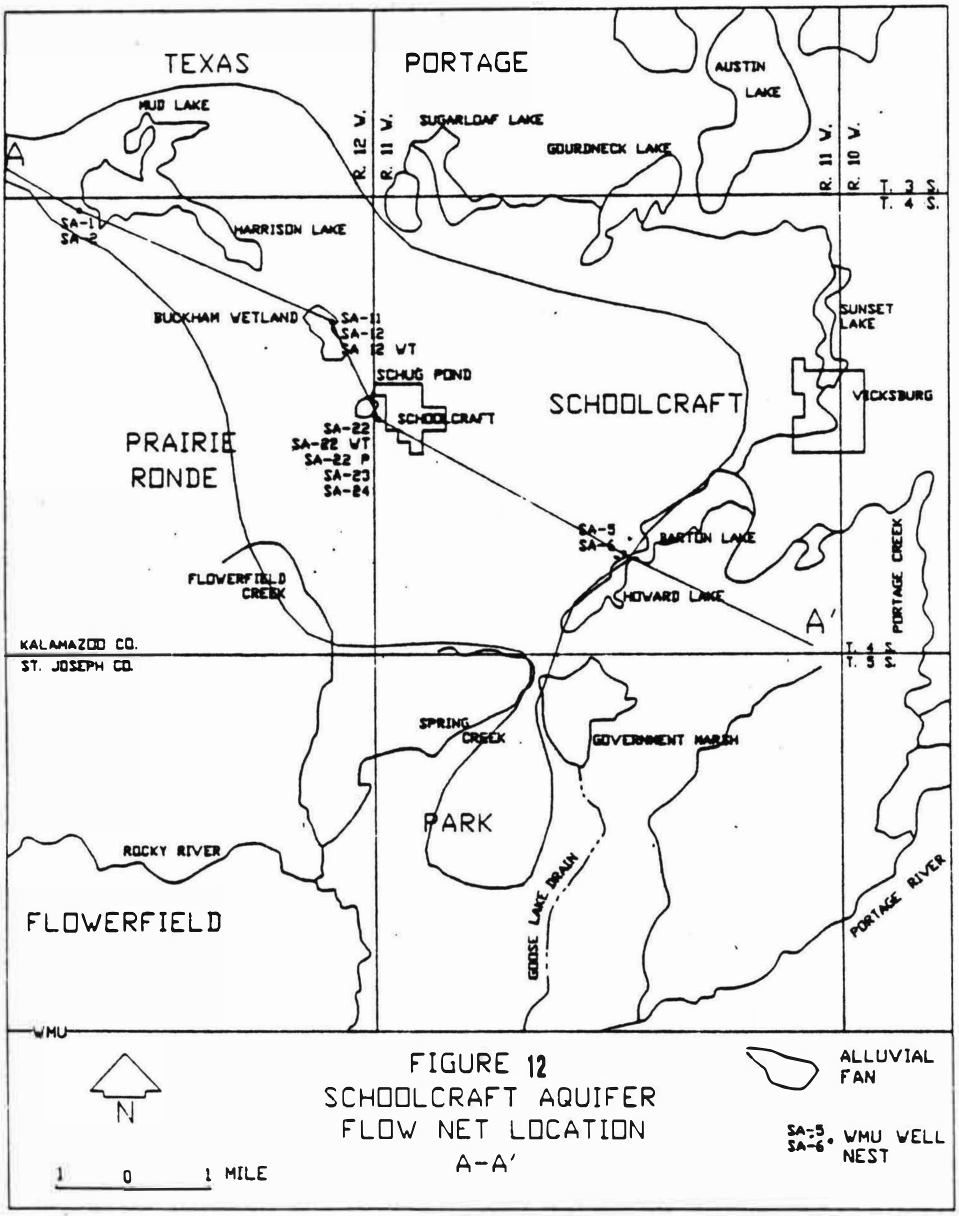


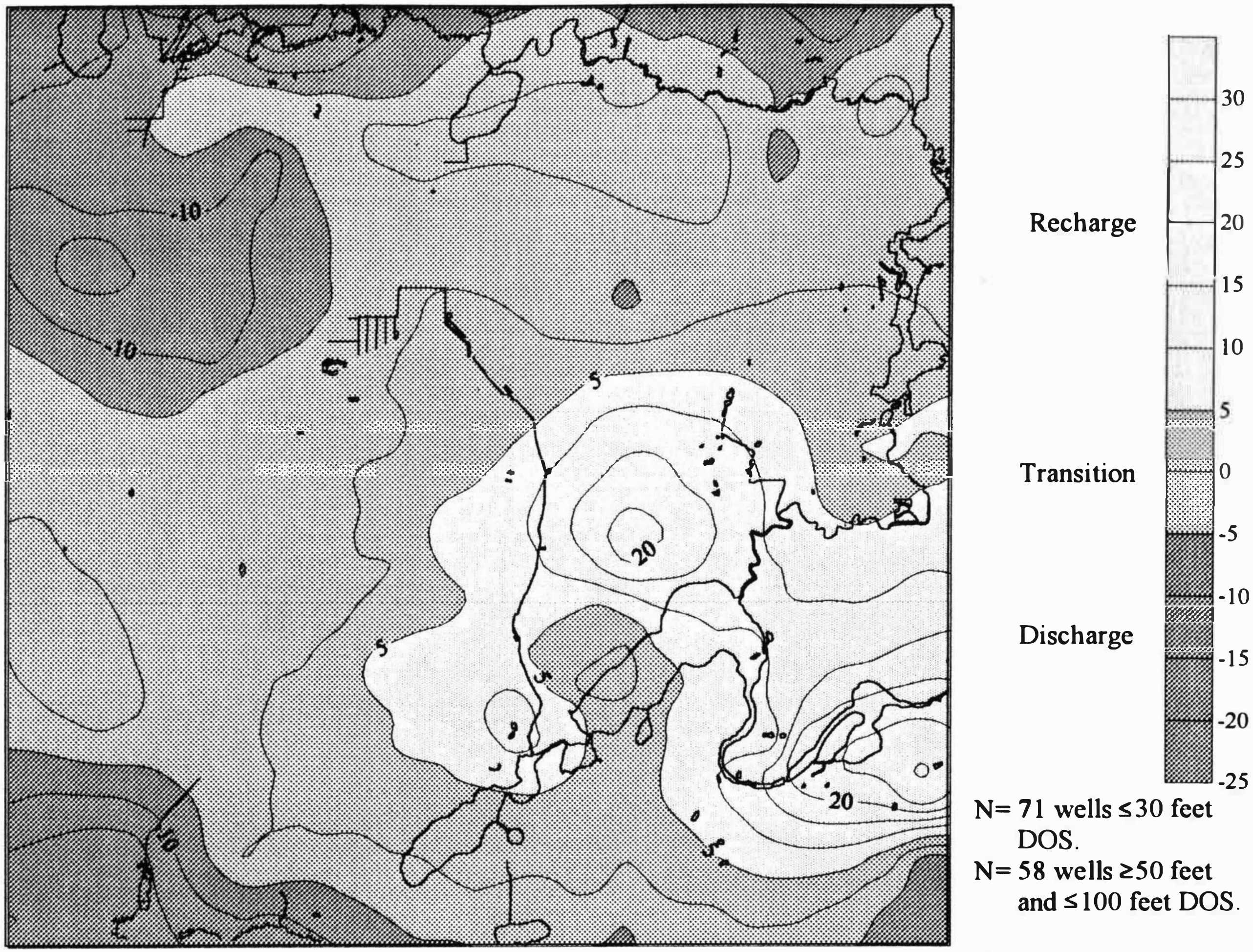
Figure 24. Map Showing Placement of Well Nests for Hydrogeologic and Hydrochemical Study Conducted on the Prairie Ronde Fan.

Source: Straw, W.T. et al. (1990), Hydrogeological and hydrogeochemical characterizations and implications for consumptive ground water use of a large glacial-drift aquifer system in southwest Michigan.

(Straw et al., 1990). It is thought that southeast of these lakes, beyond the distal end of the fan, lies the buried arm of the Tekonsha Moraine which functions as a ground-water divide. Regional movement of ground water down the long axis of the fan would discharge into this chain of lakes. Efforts to remove those wells with extremes in elevations produced little change in the interpretation of recharge potential. In an effort to enhance the shallow DOS data set, 190 additional surface water points were added to that data set, but this did not produce a significant change to the recharge interpretation. It should also be noted that monitoring well nests SA-5 and SA-6 installed close to the northern most end of Howard Lake for the hydrogeologic study conducted on the fan, indicated that area as recharge. Monitoring well SA-5 had a well depth of 162 feet with a static water elevation of 834.24 feet. SA-6 had a total well depth of 72 feet and a static water elevation of 835.53 feet, a difference in recharge potential of +1.29 feet. Geochemical characterization of this study site for upward or downward vertical hydraulic gradient using projected variation of carbonate chemical parameters supported the interpretation that these wells were installed in an area of recharge potential (downward hydraulic gradient). In addition, analysis of redox chemistry also strongly supported this interpretation while residence time indices analysis was inconclusive (Straw et al., 1990). Sections 34 and 35 consist largely of wetlands. There is a peat bog called Government Marsh located south of Goose Lake and outside the study area. Studies on the ground-water flow systems in the bog suggest that this is a recharge marsh (Kasenow, personal comment, 1994). Well data showed 74 wells installed in this area of lakes and streams for sections 14, 15, 22-27, 34, 35, and 36 . Of these 74 wells, 31 were removed because their depths of submergence was between 30 and 50 feet. Of the remaining 43 wells, few were questionable. Examination of paper records showed greater incidence of clay in this region than in wells to the northwest, but it was generally in the deeper wells. If these wells were screened under confining conditions and the static water elevations were higher, it would increase the chances that the recharge-discharge potential would be discharge. As this is not the case, it would appear that, if there were wells screened in a lower confined aquifer, they are not influencing the interpretation of this area. The Kalamazoo County Soil Survey lists the soils most closely associated with the Barton Lake - Portage Creek area as Houghton and Sebewa soils which are poorly drained. Northeast of this system the soils are the Kalamazoo loam, Oshtemo sandy loam, and Schoolcraft loam. These soils exhibit better drainage characteristics. Southeast of this same area are more isolated areas of Kalamazoo loam and Oshtemo loam surrounded by Houghton and Sebewa soils. The presence of significant areas of very poorly drained soils in close association with the Howard Lake-Barton Lake-Portage Creek drainage system, would suggest that this area should map as a discharge area. This is also the area of lowest topographic elevation in Schoolcraft Township. Efforts made to map this area at a 500 foot nodal separation distance, or to remove wells that may be questionable failed to change the overall interpretation as recharge. It is possible that the very low gradient in this area makes it very difficult for the interpolation process to distinguish any significant change from recharge to transition and discharge. This area would probably merit a detailed examination of the individual well records.

Figure 25 was developed using data selected at the same DOS interval and the same separation distance of 20 feet, but limited the deeper depth of submergence interval to ≥ 50 feet and ≤ 100 feet by removing 16 wells from the deeper DOS data set. As can be seen when comparing Figure 23 to Figure 25, the removal of the deepest depth of submergence wells from the data set produced very little change in the recharge-discharge potential map. The most significant change was to shift Howard Lake from a discharge lake to a transition lake. In addition, the area of discharge in the southwest corner of the township was reduced in areal extent to produce a better match with the drainage in this area. This moderate change in the recharge-discharge potential for Schoolcraft Township was comparable to the moderate changes in Texas Township when wells with a depth of submergence > 100 feet were also removed .

Figure 26 utilized the deepest DOS wells and increased the separation distance between the shallow and deeper depth of submergence data sets to 30 feet. This resulted in a loss of 20 wells from the 50 to 59 feet depth of submergence interval. Although the discharge area north of the Village of Schoolcraft was reduced in magnitude, the most significant change was in the southeast quarter of the township. The major area of recharge found in both Figures 23 and 25 has been reduced to a recharge area north of Howard Lake and an isolated and less pronounced recharge area along Portage Creek to the southeast of Howard Lake. The



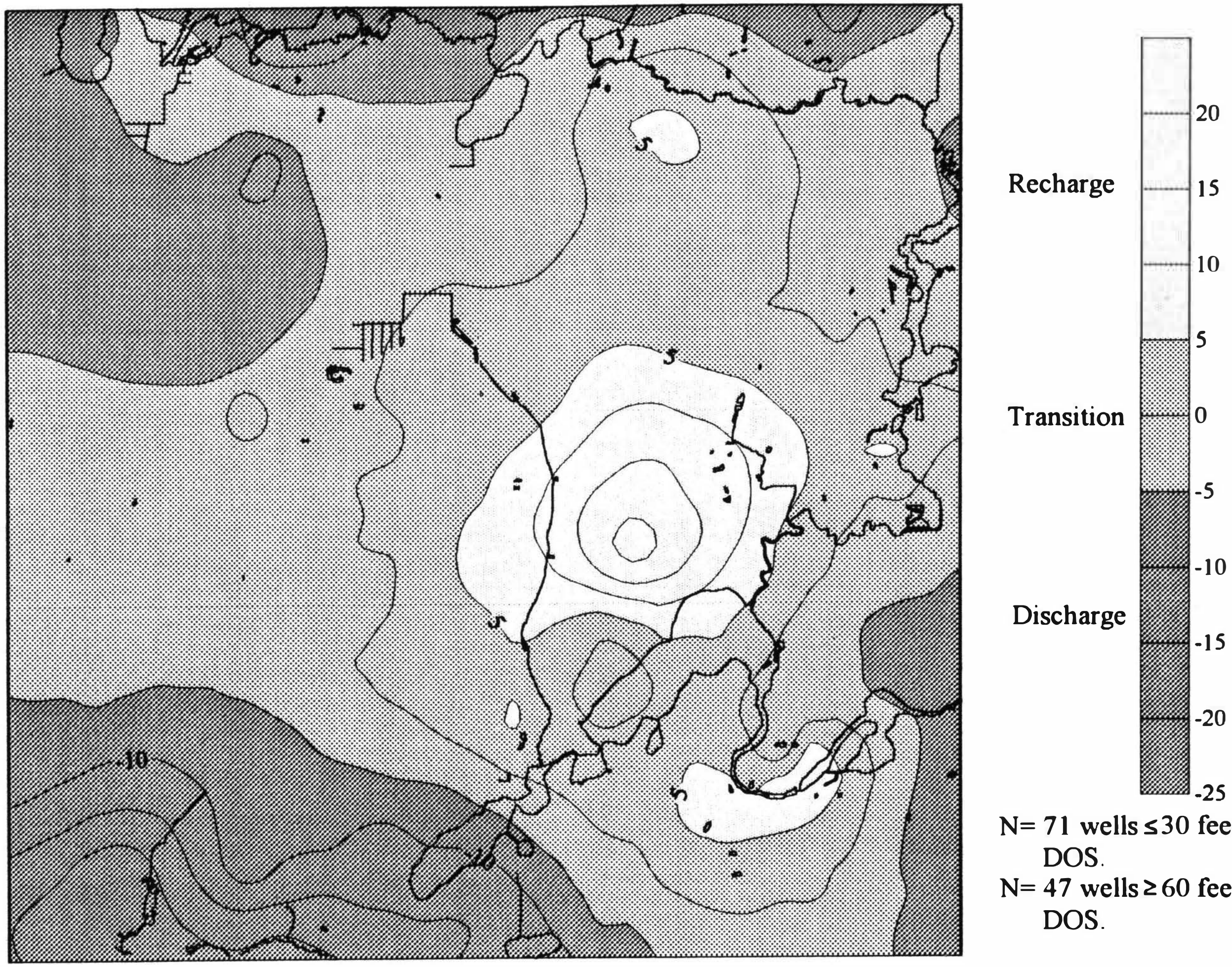
Surface Water Points
N=245.

C.I. = 5 feet.

N= 71 wells ≤30 feet
DOS.
N= 58 wells ≥50 feet
and ≤100 feet DOS.

Kriged, octant, nn=3,
r=20,000 feet.

Figure 25. Recharge-Discharge Potential Map for Schoolcraft Township Using Shallow DOS ≤ 30 Feet and Deeper DOS ≥ 50 ≤ 100 Feet.



Surface Water Points
N=245.

C.I. = 5 feet.

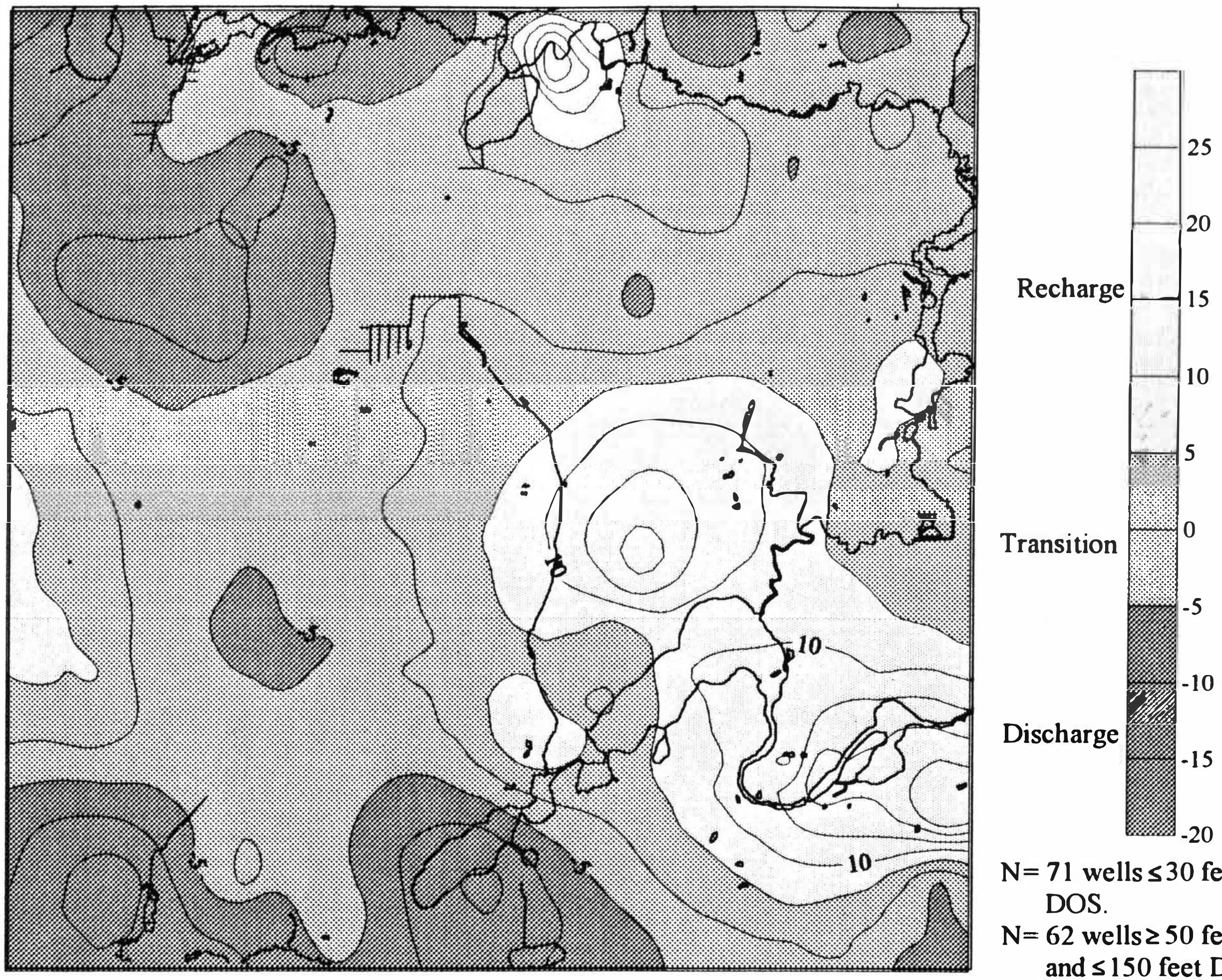
N= 71 wells ≤ 30 feet
DOS.
N= 47 wells ≥ 60 feet
DOS.

Kriged, octant, nn=3,
r= 20,000 feet.

Figure 26. Recharge-Discharge Potential Map for Schoolcraft Township Using Shallow DOS ≤ 30 Feet and Deeper DOS ≥ 60 Feet.

western half of sections 24, 25, and 36 now map as discharge areas. In general, wells with a depth of submergence between 50 and 60 feet are randomly distributed in the township; however, removal of wells in this interval had its most significant influence around Schoolcraft Township's drainage system in the southeast quarter. In order to produce a shift away from recharge and into transition and discharge it is necessary for the nodal values in this area of the deeper depth of submergence grid to become higher, reflecting an increase of static water elevations in this region. Examination of the static water elevations for wells in this region of the township confirm that those wells whose depths of submergence were between 50 and 59 feet had slightly higher static water elevations than those wells with depths of submergence ≥ 60 feet.

Figure 27 was generated using shallow and deeper DOS data sets restricted to a total depth of 150 feet. There were no wells removed from the shallow DOS data set with this restriction. However, 5 wells were sacrificed from the deeper DOS data set. Separation distance was maintained at 20 feet. Figure 27 was generated using the full Kalamazoo County Database to anchor the township borders and reduce boundary effect. The effect of limiting total depth was to generally increase the area of transition although not to a large degree. In addition, the area of recharge in the southeast quarter of the township was reduced due to the expansion of transitional flow in the area between Howard Lake and the lower half of Barton Lake. The continuous area of discharge in the northern most sections has now been broken into discreet areas of discharge with one isolated area of recharge over the southern most part of Gourdneck Lake and south of that lake. An additional recharge site is now



Surface Water Points
N=245.

C.I. = 5 feet.

Total Well Depth
≤ 150 feet.

Figure 27. Recharge-Discharge Potential Map for Schoolcraft Township Using Shallow DOS ≤ 30 Feet and Deeper DOS ≥ 50 ≤ 150 Feet.

N= 71 wells ≤ 30 feet
DOS.
N= 62 wells ≥ 50 feet
and ≤ 150 feet DOS.

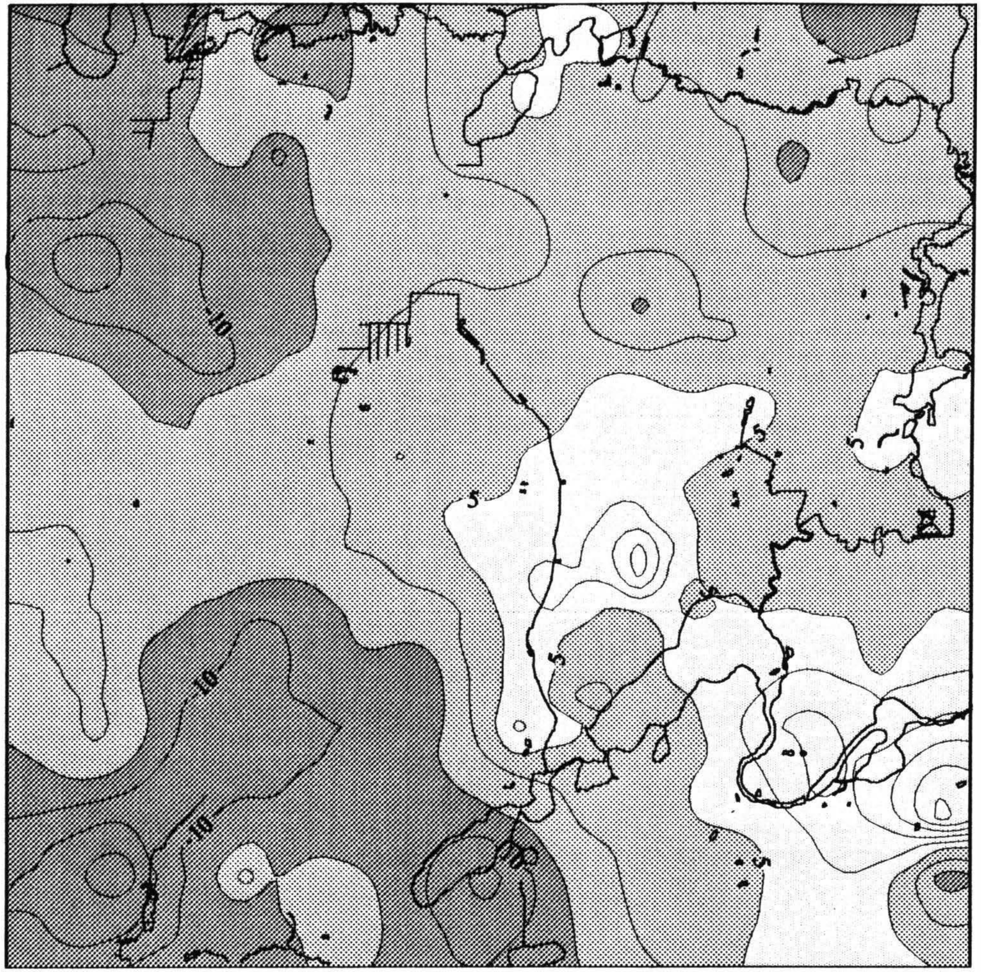
Kriged, octant, nn=3,
r=20,000 feet.

located in section 19 on the western border of the township. As several of the changes on this map are at or near the borders, it can also be assumed that the data located outside the township boundaries also influenced the interpolated values for grid nodes at and near the boundaries, thus affecting the interpretation of the recharge-discharge potential at these sites. Use of the full Kalamazoo County Database and a search radius of 3.8 miles appears to be overly influential in the interpolation of boundary nodes. It is possible that better results would be obtained if the data set was limited to one section beyond the township boundaries or to a smaller search radius.

Analysis of Interpolation Methods for Schoolcraft Township Data

Figure 28 is a recharge-discharge potential map using the inverse distance squared interpolation method and the same constraints on the data as was used for Figure 27. The most significant effect was to expand the discharge area in the southwestern portion of the township. This does not agree with the study conducted on the fan which suggests that there is intermittent local discharge along the long axis of the fan in flow-through wetlands, but that the major discharge for regional flow is the Howard and Barton Lake chain. Figure 27, which uses kriging, appears to be more consistent with this interpretation.

Figure 29 was constructed using the standard constraints with the minimum curvature method of interpolation. This map loses the small discharge region on the fan and also has very steep gradients, particularly on the corners of the map. The



Surface Water Points
N=245.

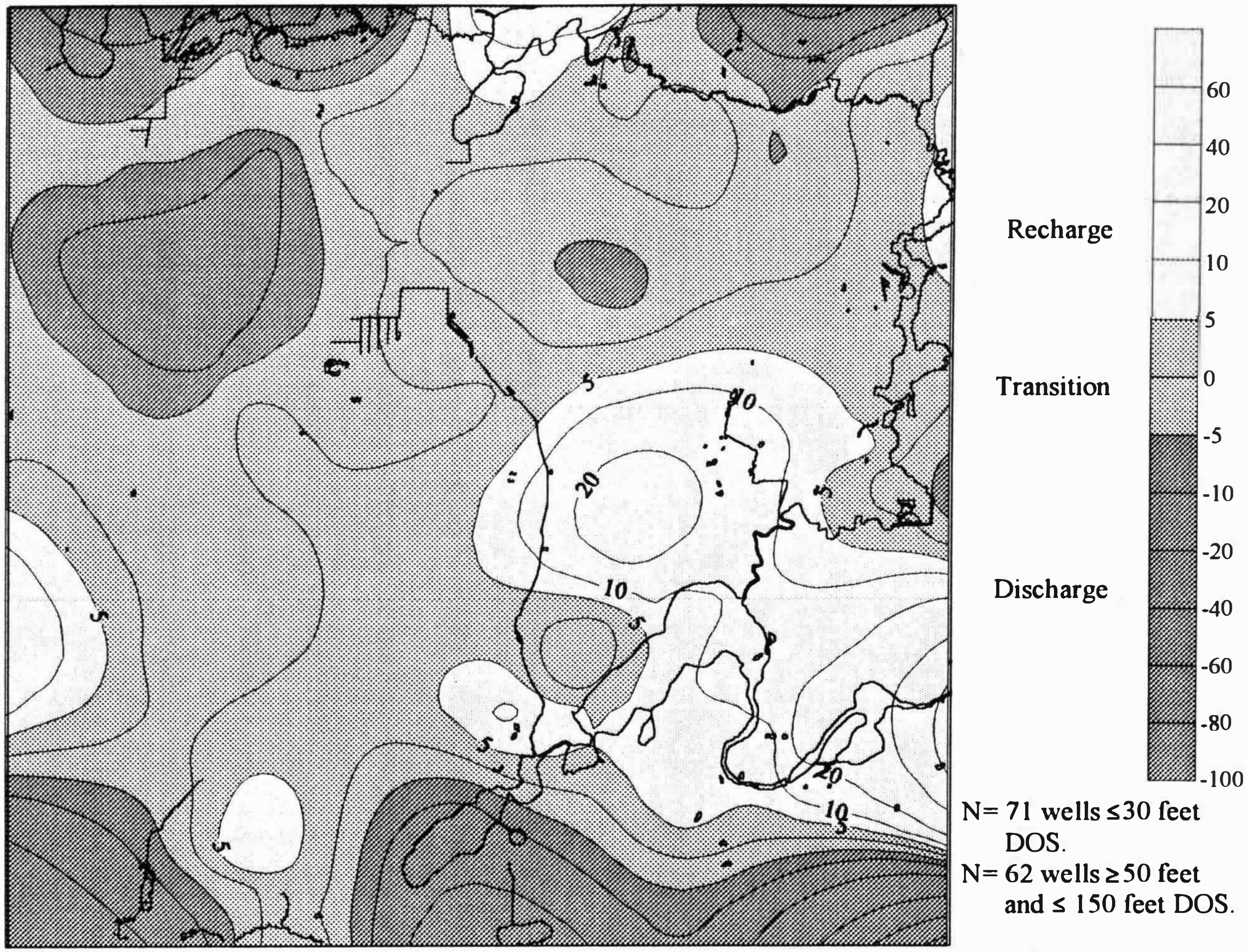
C.I. = 5 feet.

Total Well Depth
≤ 150 feet.

N= 71 wells ≤ 30 feet
DOS.
N= 62 wells ≥ 50 feet
and ≤ 150 feet DOS.

Inverse Distance Squared,
octant, nn=3, r=20,000 feet.

Figure 28. Recharge-Discharge Potential Map for Schoolcraft Township Using Inverse Distance Squared Method of Interpolation.



Surface Water Points
N= 245.

C.I. = 5 feet.

N= 71 wells ≤30 feet DOS.
N= 62 wells ≥50 feet and ≤ 150 feet DOS.

Minimum Curvature, all wells.

Figure 29. Recharge-Discharge Potential Map for Schoolcraft Township Using Minimum Curvature Method of Interpolation.

other maps are generally in the ± 20 feet range for recharge-discharge residual values. Minimum curvature produces a range of +30 to -90 feet. Again, this method is not suitable for the distribution and variability of the data found in water well records.

Statistical Analysis of Schoolcraft Township Data

As with the Texas Township data, non-gridded topographic data were compared to non-gridded static water elevation data. Gridded topographic elevations and gridded static water elevations from shallow depths of submergence wells were compared. Gridded topographic data and recharge-discharge residuals from shallow DOS wells were compared, and gridded static water elevations and recharge-discharge residuals from shallow DOS wells were compared using regression analysis. The results are shown in Table 11. There is good correlation between the non-gridded topographic and static water elevations and between the gridded topographic and static water elevations. This agreement is probably due to the more homogenous nature of the Schoolcraft aquifer. However, there is very poor correlation between the shallow water table (static water elevations for shallow depth of submergence wells) and the recharge-discharge potential residuals. To determine why the correlation of the recharge-discharge surface to the shallow water table surface was so low for Schoolcraft Township (R=0.1), the data was further analyzed using the STATGRAPHICS software program. The gridded topographic elevations for the shallow depth of submergence wells were plotted against the recharge-discharge potential residuals using simple regression analysis. There is an inverse

Table 11

Regression Analysis of Non-Gridded and Gridded Data for Schoolcraft Township

Type of Data	Order of Analysis	N	Surface Water	R
Non Gridded	Topo. vs Shallow Water Table	214	0	0.8791
Gridded	Same	1089	245	0.8243
Gridded	Shallow Water Table vs R/D	1089	245	0.1362

correlation between the two variables shown in Figure 30. Recharge potential is associated with lower topographic relief and discharge potential is associated with higher topographic relief. This is the opposite of what should have shown. After plotting the distribution of the residual values on the topographic map, it became apparent that the large discharge area in sections 7 and 18 was largely the cause for the inverse correlation. This area is one of the highest relief areas in the township. Figure 31 gives a 3-dimensional fishnet view of the topographic surface, water table, and recharge-discharge potential surface. There is a clear depression on the water table surface on the western boundary that correlates with the area just north of the Village of Schoolcraft. It is probably because of the effect of the pumping wells (municipal and commercial) that this area plots as a discharge area. The highs on the

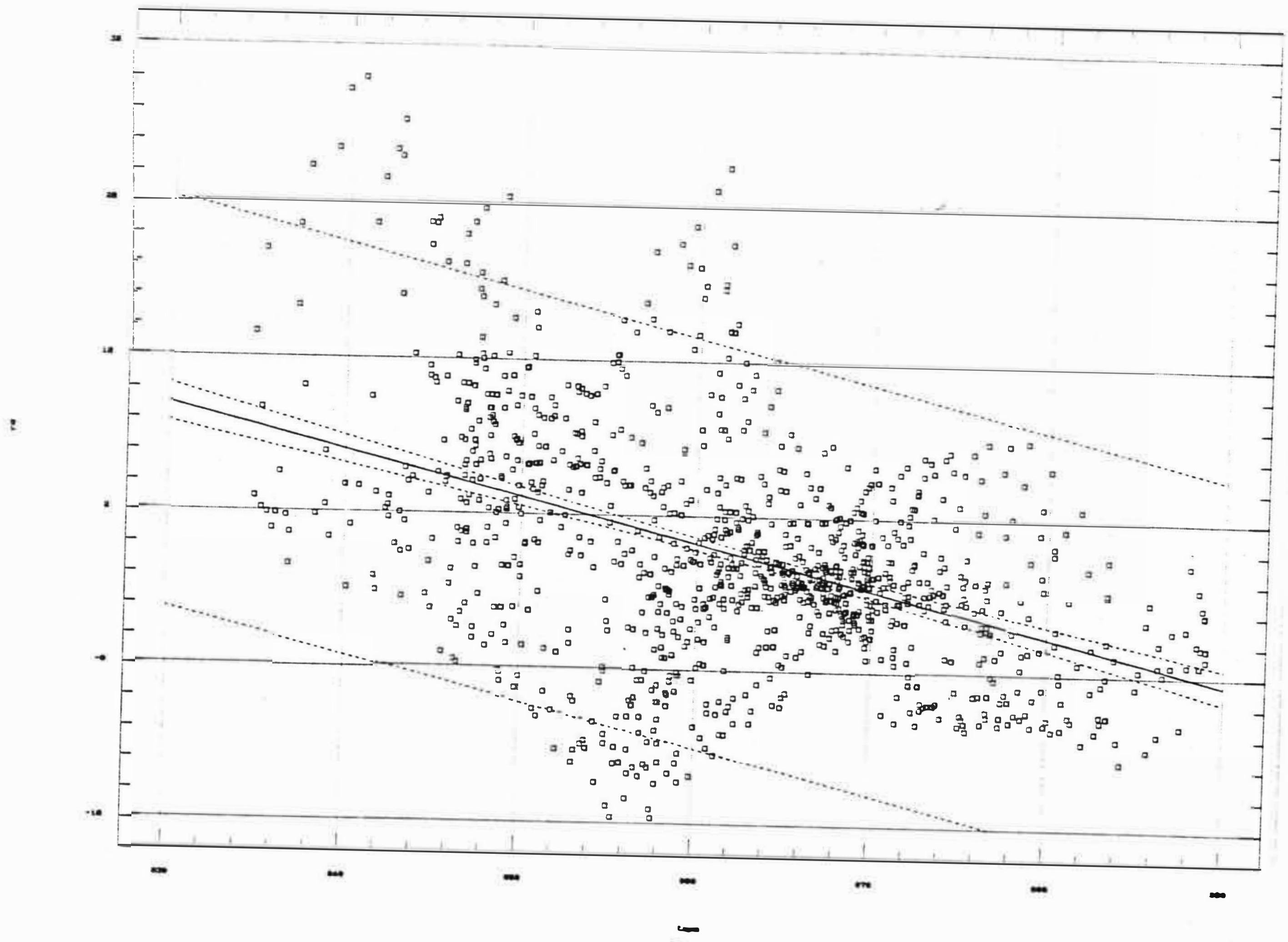


Figure 30. Linear Regression Plot of Recharge-Discharge Potential Residual Values vs. Topographic Elevations for Schoolcraft Township.

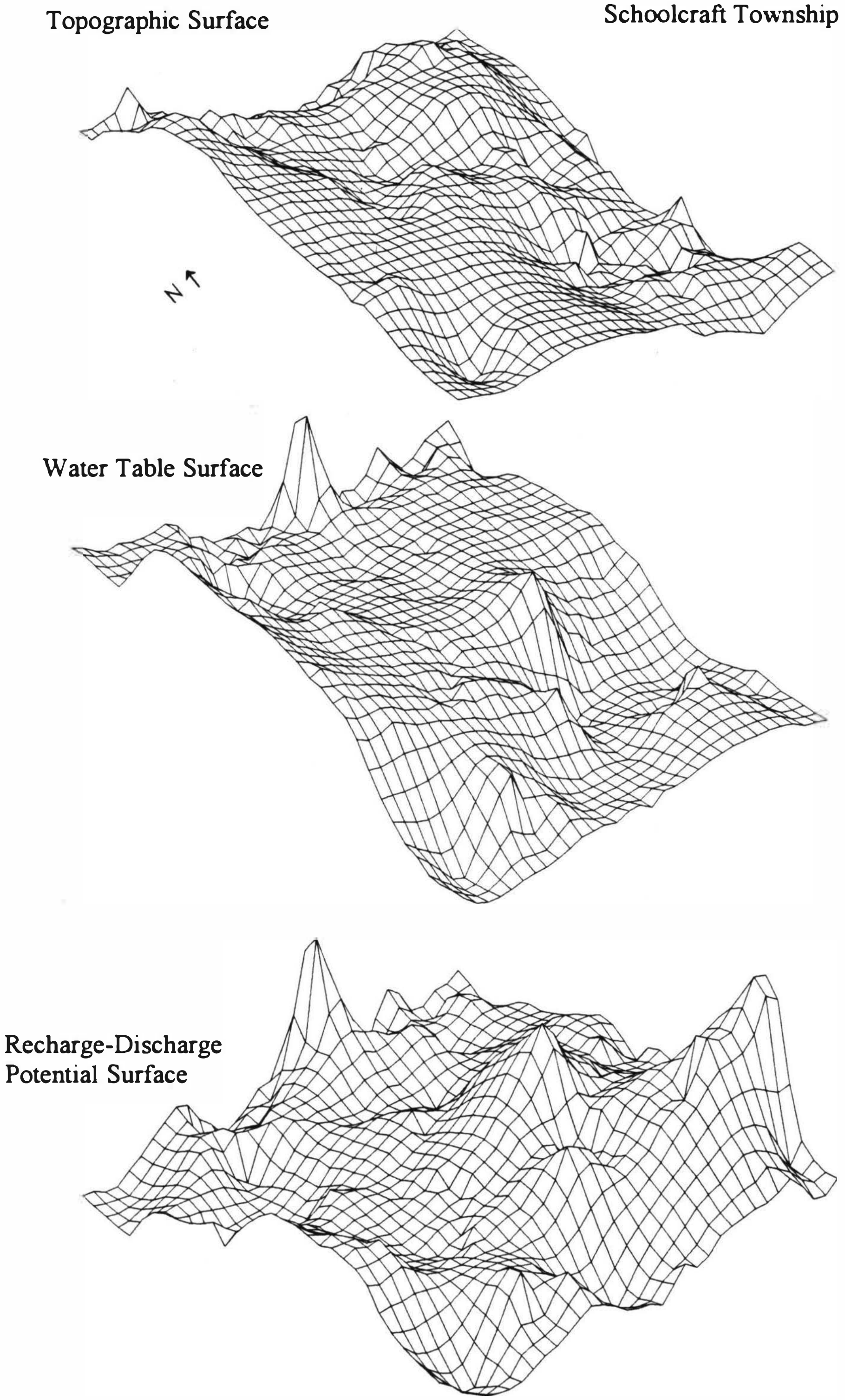


Figure 31. Stacked Fishnet Surfaces Illustrating Relationship of Topographic Surface to Water Table Surface to Recharge-Discharge Potential Surface.

water table that are northwest and southeast of the Barton Lake area are also clearly apparent and are very likely what are responsible for the recharge interpretation surrounding that area.

Evaluation of the different interpolation methods for Schoolcraft Township was conducted in the same manner as was Texas Township. Table 12 summarizes the correlation between interpolation methods (using the nodal values for the shallow depth of submergence grids as representative of the water table). As can be seen, the correlations between interpolation methods are relatively high for all three methods. This is generally higher than was found in Texas Township. The maximum and minimum static water elevations for minimum curvature are more extreme than the other two methods and removed this method from consideration as a potential interpolation method for this data. There is very little difference between kriging and inverse distance in terms of generating a shallow depth of submergence surface. The closer agreement between methods most likely results from the more homogenous nature of the Schoolcraft aquifer and the lower relief on the topographic and water table surface for Schoolcraft Township.

Regression analysis was also used to evaluate the correlation between methods as they relate to the generation of the recharge-discharge potential gridded surface. Table 13 summarizes this data. Again, the agreement between the three different interpolation methods was much closer in Schoolcraft Township than they were in Texas Township. Kriging shows the least extreme maximum and minimum values and minimum curvature shows the most extreme. However, in Schoolcraft

Table 12

Correlation of Interpolation Methods Using Simple Regression Analysis of the Schoolcraft Township Shallow Water Table Surface

Interpolation Methods	R For Shallow DOS Grids	Maximum & Minimum Static Water Elevations for Gridded Surfaces in Units of Feet		
			Min.	Max.
Inverse Distance vs Kriging	0.993	I.D. M.C.	866 872	826 798
Inverse Distance vs Minimum Curvature	0.964	K.	866	823
Kriging vs Minimum Curvature	0.974			

Township these maximum and minimum values for inverse distance and kriging show a much wider range of values than was shown in Texas Township. The high positive values are located in the southeast corner of the township and are associated with the area of recharge around Howard and Barton Lakes and Portage Creek. This recharge interpretation is questionable and therefore the high positive residuals are in question also. The higher negative values are located in the discharge area north of the Village of Schoolcraft and are probably associated with the municipal and commercial wells located in the general area. The range of values for minimum

Table 13

Correlation of Interpolation Methods Using Simple Regression Analysis of the Schoolcraft Township Recharge-Discharge Potential Surface

Interpolation Methods	R For Recharge-Discharge Potential	Maximum & Minimum Residual Values using Units of Feet		
			Min.	Max.
Inverse Distance vs Kriging	0.989	I.D.	31.3	-22.4
		M.C.	67.6	-90.2
Inverse Distance vs Minimum Curvature	0.952	K.	30.6	-18.5
Kriging vs Minimum Curvature	0.940			

curvature is narrower in Schoolcraft Township than in Texas Township suggesting that this method has less difficulty if there is more uniformity to the data.

Donnell Lake Project Area: Cass County

The Donnell Lake Project Area was chosen as a validation site for the recharge-discharge potential mapping methodology because it is instrumented with multilevel nests of monitoring wells and has carefully measured static water level data. Figure 32 shows the study area and the sites where 23 monitoring wells have been installed in 11 well nests. The Donnell Lake research area provides numerous advantages as a validation site. These include (a) 11 well nests consisting of 2-3 wells completed at different depths and depths of submergence, (b) static water elevations which were measured within a time span of two weeks, (c) well installation and sampling methods were known, (d) data collected at this site has been carefully analyzed , and (e) recharge, transition and discharge areas have already been determined through careful evaluation of the static water elevations at each well nest. Table 18 (Appendix E) lists the well data relevant to application of the recharge-discharge potential methodology.

Some of the constraints placed on the data were the same as were used in Texas and Schoolcraft Township. The shallow depth of submergence wells were selected for ≤ 30 feet. The deeper depth of submergence wells were limited to ≥ 50 feet DOS and ≤ 150 feet DOS. Separation distance between the shallow and deeper depth of submergence intervals was approximately 20 feet. Total well depth was limited to 150 feet. The transition interval was reduced to better represent data collected over a shorter period of time and a significantly reduced total area. In order to delineate transition flow, additional contour lines were added at the transition interval. All three interpolation methods were used initially. In an effort to force the SURFER contouring package (TOPO) to honor the surface water present in the study site, 563 surface water data points were added to the shallow depth of submergence data set. The lowest search radius was chosen which would provide unbroken contour lines. After evaluating different radii, the final choice was 8,000 feet. The

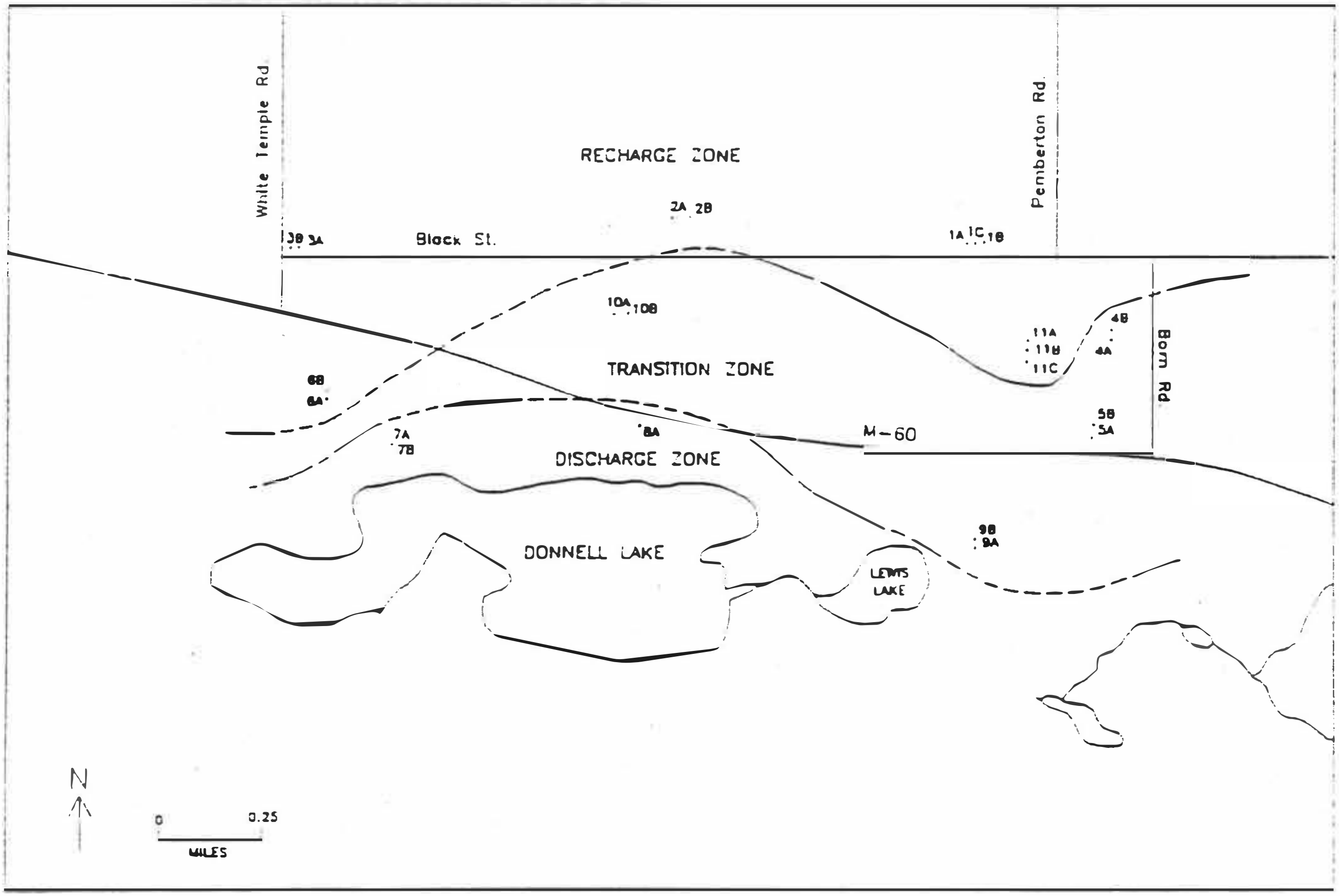
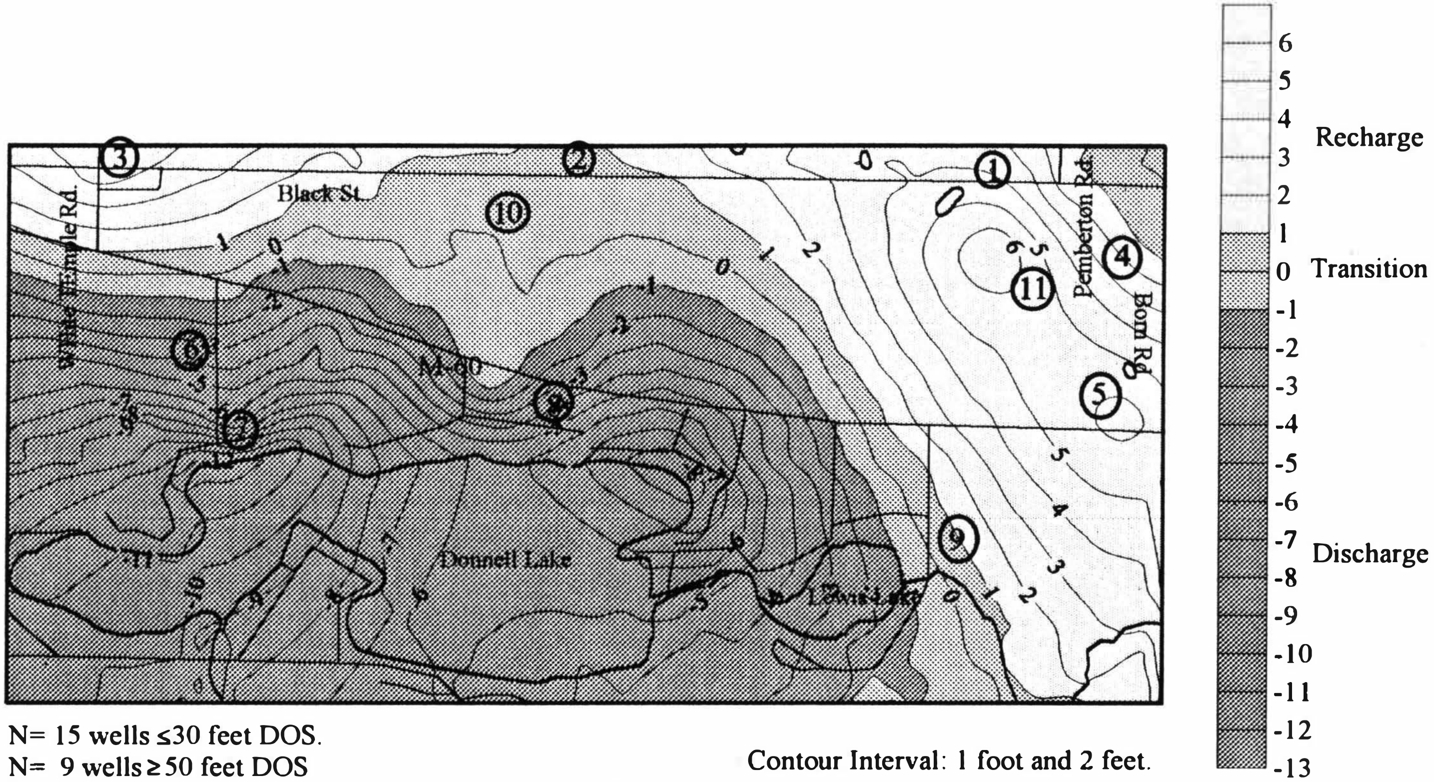


Figure 32. Ground-water Flow Zones as Determined by Manual Interpretation of Monitoring Well Static Water Level Elevations for the Donnell Lake Project Area.

Source: Stuk, M. A., (1992), Master's Thesis, Western Michigan University.

search method was Octant and the number of nearest neighbor data points were 3 (total of 24: 8x3=24). Initially only six wells were available for inclusion in the deeper depth of submergence wells. After considering well nests 4 and 9, both of which had been evaluated as transition wells, it was decided to add one well from each well nest to the deep depth of submergence data set. This decision was based on the premise that if these well nests did represent a transition flow then the deep depth of submergence wells would have the same static water elevations as the shallower DOS wells. It was also decided to add well nest 8 to the deep DOS data set as there was some question as to whether it was transition or discharge and control was needed in the location of well nest 8. This made a total of 9 wells selected for the deeper DOS data set. The shallow DOS data set contained 15 well elevations. Although there are only 11 well nests, 6 intermediate depth wells fit the ≤ 30 DOS criteria for the shallow DOS data set and were added to increase the size of that data set.

Figure 33 is the recharge-discharge potential map using just the monitoring well data. The transition interval is set to ± 1 foot because the monitoring well data was collected over a shorter time interval and the area being mapped is much smaller than a township. Figure 33 shows agreement with the previous interpretation of recharge potential that includes well nests 1 and 3. There is a 4 to 5 foot downward vertical head differential at these well nests indicating a strong area of recharge. The vertical potential for well nest 2 suggests that it too is recharge; however, there is less than a foot of head differential (+0.88 feet) at this well nest. The recharge-discharge



N= 15 wells ≤30 feet DOS.
N= 9 wells ≥50 feet DOS
and ≤ 150 feet DOS.
Total Depth: ≤150 feet.

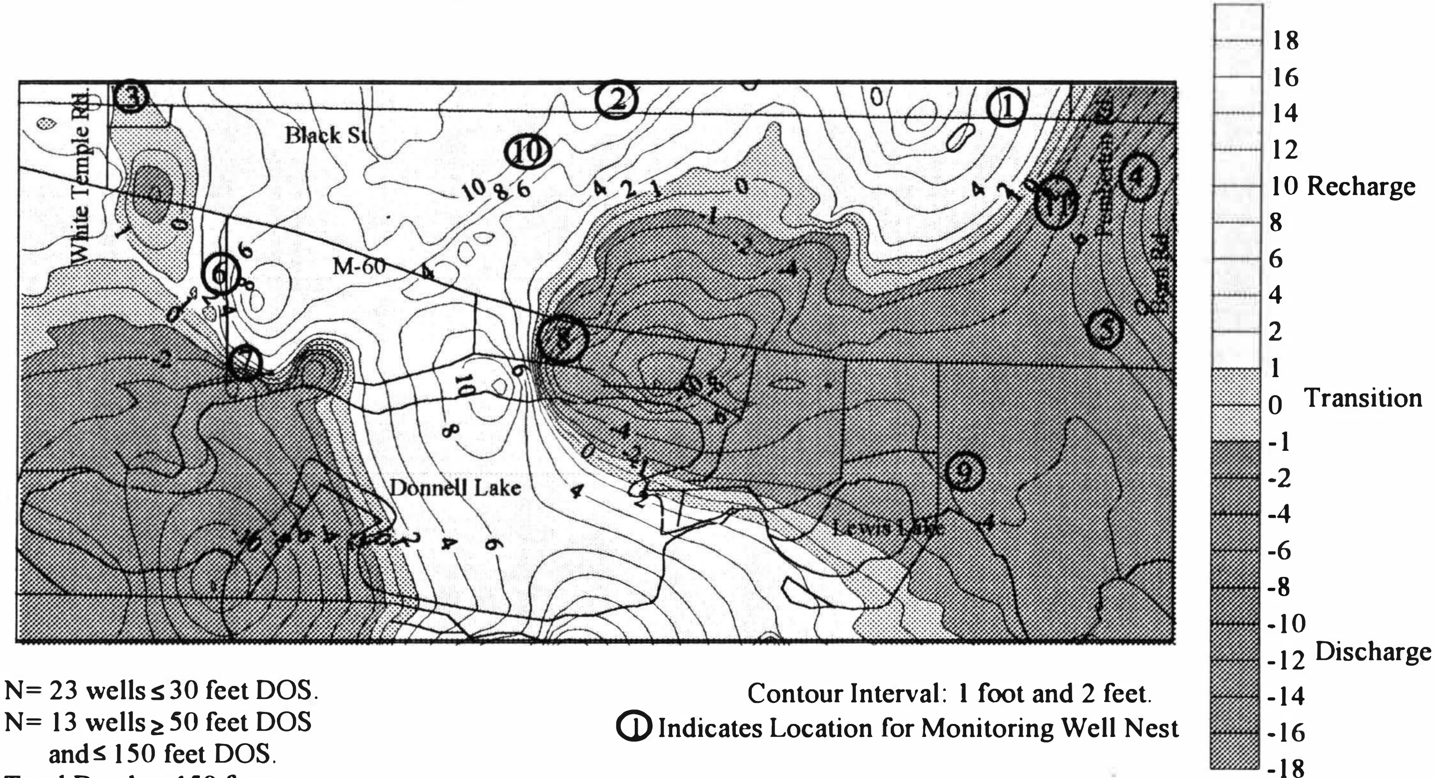
Contour Interval: 1 foot and 2 feet.

① Indicates Location of Monitoring Well Nests

Figure 33. Donnell Lake Recharge-Discharge Potential Map Using Monitoring Well Data.

methodology interprets this well nest as transition flow; i.e. with the ± 1 foot transition interval. The reasons for this well nest not exhibiting a stronger vertical potential as is found in well nests 1 and 3 are not yet understood. The effect of well nest 2 is such that the transition and discharge flow regimes are pulled up to the north. Well nests 9 and 10 map very close to the line between transition and discharge. The influence of the discharge area surrounding Donnell Lake causes well nest 6 to map as discharge when it is actually recharge. The range of residual values in the project area is -13 to +6. The high negative values are outside the project area of control.

Using only residential wells (Figure 34) produces a significant change in the interpretation of the Donnell Lake area. The transition interval is set at ± 2 feet. This is larger than the ± 1 foot used for the monitoring well data because the residential well data was collected over 27 years. However, the area being analyzed is still much smaller than a township therefore the transition interval is kept lower than ± 5 feet as was chosen for the township level. The range of residual values has expanded to ± 18 feet. There were 22 wells selected for the shallow DOS data set and 13 for the deeper DOS data set. The farther reaching eastern residential well records expand the eastern area of discharge considerably. Research suggests the wetland is recharge (well nest 11). The recharge flow regime extends across Donnell Lake, even with the addition of 563 surface water points. This is an unlikely interpretation of the area. Figure 34 suggests that the time span over which data is collected when using residential well records to delineate small geographic



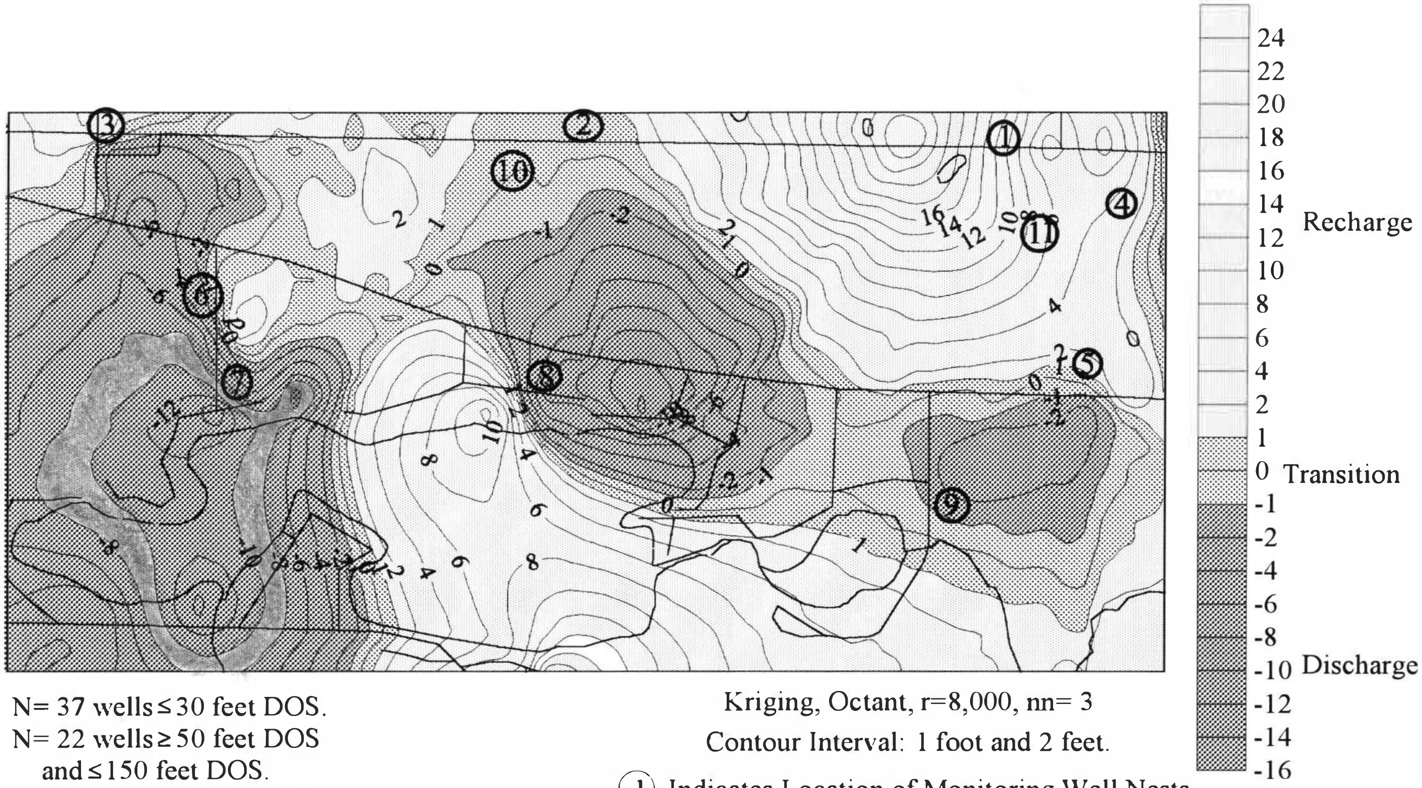
N= 23 wells ≤ 30 feet DOS.
N= 13 wells ≥ 50 feet DOS
and ≤ 150 feet DOS.
Total Depth: ≤ 150 feet.

Contour Interval: 1 foot and 2 feet.
① Indicates Location for Monitoring Well Nest

Figure 34. Donnell Lake Recharge-Discharge Potential Map Using Residential Well Data.

areas can distort the interpretation of the flow regime significantly in those areas.

Figure 35 was developed using both monitoring wells and residential wells combined to test whether the combination of reliable data and more questionable data in small regions can improve the interpretative process. This interpretation still demonstrates questionable interpretation of the recharge-discharge potential. The transition interval was kept at +2 to -2 feet. The isolated area of discharge just south of well nest 10 and including well nest 8 is an unlikely interpretation for this area. Real data gives no support to this interpretation. Well nest 3 maintains a recharge potential interpretation. However, it is very near to transition and discharge potential, an improbable interpretation given the strong downward potential at this well nest. Monitoring wells in this area are strongly influencing the discharge interpretation that is being pulled north to well nest 3. Again, the large area of transition and recharge through the middle of Donnell Lake is difficult to support. As with Figure 34, Donnell Lake is mapped as discharge at the east and west ends of the lake and recharging to some extent in the middle. Well nest 11 is being interpreted as recharge which is in agreement with Figure 33. Well nests 4 and 5, which are identified as transition wells, also map as recharge, suggesting that well nest 11 is strongly influencing the interpolation process. This is supported by the increase in recharge potential (+24 feet) for this area of the map. The combination data for monitoring and residential wells honors the manual interpretation better than residential wells alone. However, the monitoring well data alone does agree the most with the manual interpretation of the recharge-discharge potential for this study site.



N= 37 wells ≤ 30 feet DOS.
N= 22 wells ≥ 50 feet DOS
and ≤ 150 feet DOS.
Total Well Depth: ≤ 150 feet.

Kriging, Octant, r=8,000, nn= 3
Contour Interval: 1 foot and 2 feet.

① Indicates Location of Monitoring Well Nests

Figure 35. Donnel Lake Recharge-Discharge Potential Map Using Monitoring and Residential Well Data.

Statistical Analysis of the Donnell Lake Project Area Data

Simple regression analysis was performed on the gridded data for the Donnell Lake project area as was done for the township studies. Table 14 shows the correlation of the gridded recharge-discharge potential surface to the shallow water table surface. Surface water data were not included in the regression analysis because of the high ratio of surface water points (563 points) to real data points. Analyzing real data alone permits evaluation of the quality of the real data. Gridded surfaces for monitoring wells exhibit a much better correlation than do the gridded surfaces for residential wells. This is most likely due to the shorter time interval over which the monitoring well data were collected and the care with which the data were gathered. Residential wells have not been examined for error and there may be some incorrect data contributing to such a low level of correlation. Addition of the monitoring well data to the residential well data increases the correlation coefficient (R= 0.4459) for the combined data set. Questions raised by the low magnitude of recharge potential found in well nest 2, given the strong vertical gradient in well nests 1 and 3, suggest a more complex flow system for the Donnell Lake study area, and are probably why the correlation coefficient for the monitoring wells data is equal to 0.6363.

Tables 15 and 16 list the correlation coefficients for shallow water table surfaces and recharge-discharge potential surfaces for monitoring well data in terms of the interpolation methods. These figures were derived without using the additional surface water data. There is a very close correlation between all three methods when

Table 14

Correlation of Recharge-Discharge Potential Surface
to Shallow Water Table Surface for Donnell Lake

Well Type	Number of Wells	R
Residential Wells	Shallow DOS =22 Deeper DOS= 13	0.1378
Monitoring Wells	Shallow DOS=15 Deeper DOS=9	0.6363
Residential Wells and Monitoring Wells	Shallow DOS = 37 Deeper DOS=22	0.4459

generating a shallow water table surface. This probably reflects the quality of the monitoring well data and that the area is small enough to have fewer local flow systems interfering with the broader interpretation. Table 16 compares the correlation between recharge-discharge potential surfaces for the three interpolation methods. The correlation between methods is as high for the Donnell Lake study site as it was for Schoolcraft Township. Given that there is very little data available from which the nodal values can be estimated , it is probably the quality of the monitoring well data which raises this correlation. The maximum and minimum values are again high for minimum curvature making it a poor choice for interpolating gridded surfaces with data of this type.

Table 15

Correlation of Interpolation Methods Using Shallow Water Table Surfaces for Donnell Lake

Interpolation Method	R	Maximum and Minimum Static Water Elev. in Feet for Gridded Surface		
			Max.	Min.
Inverse Distance	0.977	I.D.	882	846
vs.				
Kriging		M.C.	953	821
Inverse Distance	0.977	K.	824	855
vs.				
Minimum Curvature				
Kriging	0.955			
vs.				
Minimum Curvature				

Kalamazoo County

The final phase in evaluating the recharge-discharge potential mapping methodology was to develop a regional map for Kalamazoo County. The map was created using the same constraints for interpolation and data selection as were used for Texas and Schoolcraft Townships. A total of 5,754 well records were available for analysis of the county. A total of 643 surface water points were added to the shallow depth of submergence data set. It is important to note that only 37% of the county has been examined for errors in the well data. Of this 37 % only 12.5 % of the

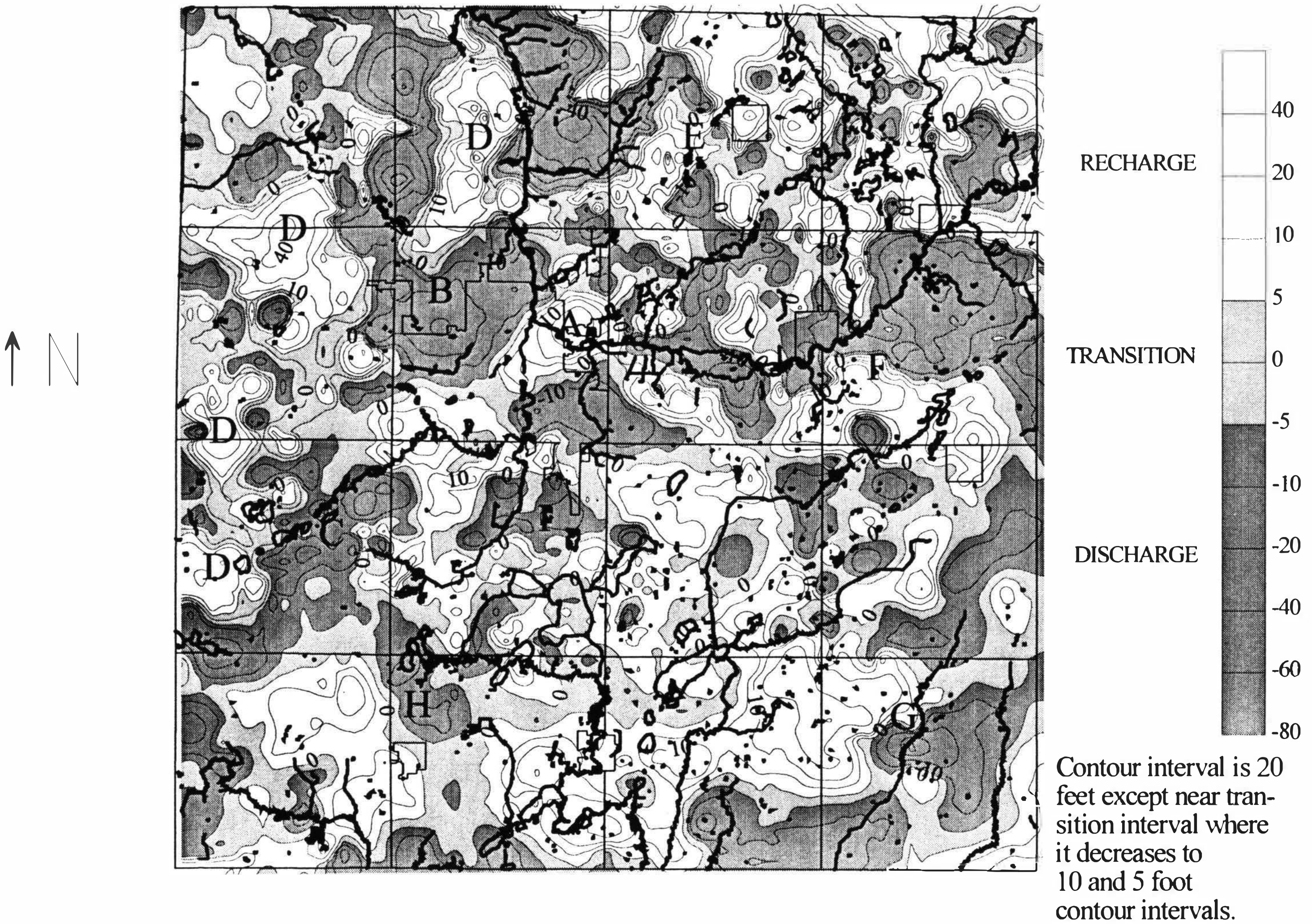
Table 16

Correlation of Interpolation Methods Using Recharge-Discharge Potential Surfaces for Donnell Lake

Interpolation Methods	R	Maximum and Minimum Residual in Feet		
			Max.	Min.
Inverse Distance vs. Kriging	0.933	I.D.	19.4	-20.4
		M.C.	142	-73.3
Inverse Distance vs. Minimum Curvature	0.947	K.	19.7	-17.8
Kriging vs. Minimum Curvature	0.915			

area (Texas and Schoolcraft townships) has been closely examined. It is therefore not possible to determine the cause of every questionable area of interpretation. However, because the contour interval used for the Kalamazoo County recharge-discharge potential map is 20 feet, many of the errors resulting from incorrect elevations will not significantly affect the interpretation. Contour intervals for ± 5 feet were added to Figure 36 to define the transition interval.

What is most apparent on Figure 36 is the clear depiction of the Kalamazoo River watershed as a discharge area. The only significant area of recharge on the river is located in Kalamazoo Township where the river turns north (A on map).



Contour interval is 20 feet except near transition interval where it decreases to 10 and 5 foot contour intervals.

Figure 36. Kalamazoo County Recharge-Discharge Potential Map.

This is an area of waste treatment lagoons no longer in use by the local paper companies. In addition, this area is a localized area of topographic high near Schippers Creek. The large discharge area to the northwest (B on map) has no obvious drainage system, however the water table is close to the surface and, more importantly, the City of Kalamazoo maintains two well fields in the immediate area, Station 11 just west of Howard St. and Western Michigan University and Station 12 which is located just west of the intersection of Howard St. and Stadium Drive. Both stations have been pumping since the late 1950's and may have had a significant impact on static water elevations with their zones of influence. This area appears as an area of culturally induced discharge as was found in Schoolcraft Township. However, Kalamazoo Township has only 16 well records in the shallow DOS data set and 27 well records in the deeper DOS data set. This is a very small data set from which to derive a recharge-discharge potential map for a township.

Even with a 20 foot contour interval, the Texas Township drainage system is clearly defined as a discharge area (C on map) and the Kalamazoo Moraine (D on map) trending northeast-southwest in the township is dominantly recharge (Figure 7, page 10). To the northeast in the county, the Richland morainal area maps clearly as a recharge area (E on map). The Tekonsha Moraine however maps as recharge and discharge (F on map). Research has shown this to be a recharge area as is the Climax Scotts outwash plain, the northern portion of which maps as discharge. The Wakeshma Till Plain (G on map) also maps as a complex recharge and discharge area. Recharge is dominantly to the west and the discharge to the east, although to a lesser extent. The discharge area across Wakeshma Township probably reflects the shallow water table and extensive surface water drainage. The average mean depth to static water level is 22 feet in the Wakeshma till plain, which is the lowest mean depth in the county. The mean depth of submergence is 53 feet which is the highest mean DOS in the county . The till plain has a mean clay thickness of 16.3 feet and a mean partial clay thickness of 20 feet (Chidester, 1993). The presence of clay layers near the surface forces well drillers to drill below the clay to locate sufficient water supply. These wells are more likely to exhibit increased head due to confining conditions and therefore will exhibit higher static water elevations for these deeper wells, which would lead the recharge-discharge methodology to interpret this area of the till plain as discharge.

The lower relief outwash plains in Schoolcraft and Prairie Ronde Townships are readily identifiable by larger areas of transition. As previously noted, the discharge area just north of the Village of Schoolcraft (H on map) is probably indicative of the wetlands in this area and perhaps the influence by the village well field and the commercial wells located in this area on the potentiometric surface. To the northeast in Portage Township the distinct discharge depression indicating the influence of the Upjohn Company (I on map) well field is apparent.

Statistical Analysis of Kalamazoo County Data

Figure 37 presents a frequency distribution of the total well depths for all the wells in the Kalamazoo County Database. Figure 38 is a frequency distribution of residual values generated by the recharge-discharge methodology. Analysis of the data base shows that 92 % of the wells in the database (5754 well records) have a total depth of ≤ 150 feet. Of these same wells, 54% have a depth to water of 35 feet or less. The well depth histogram in Figure 37 illustrates a predominance of shallower wells due to the availability of a shallow, largely unconfined aquifer system in Kalamzoo County. The frequency histogram for recharge-discharge potential residuals (over 17,000 nodes) indicates that a large number of values are clustered around a very narrow range. The majority of the nodes are between -13 and +8 feet of vertical head differential. This narrow range of vertical head differential would be expected in a region consisting of largely unconfined sand and gravel aquifers.

Correlation of the topographic surface, shallow water table surface, and recharge discharge surface was analyzed using gridded and non-gridded data as appropriate. Table 17 summarizes this analysis. Both non-gridded and gridded data show reasonably high correlation (0.7882 - 0.9105) when comparing the water table to the topographic surface. However, recharge-discharge surfaces show a much lower level of correlation to both the water table surface (0.2317 - 0.3118) and the topographic surface (0.1783 - 0.2285). Lower correlation of these surfaces probably reflect possible data errors, local subbasins, and the influence of pumping wells not identified for the entire county.

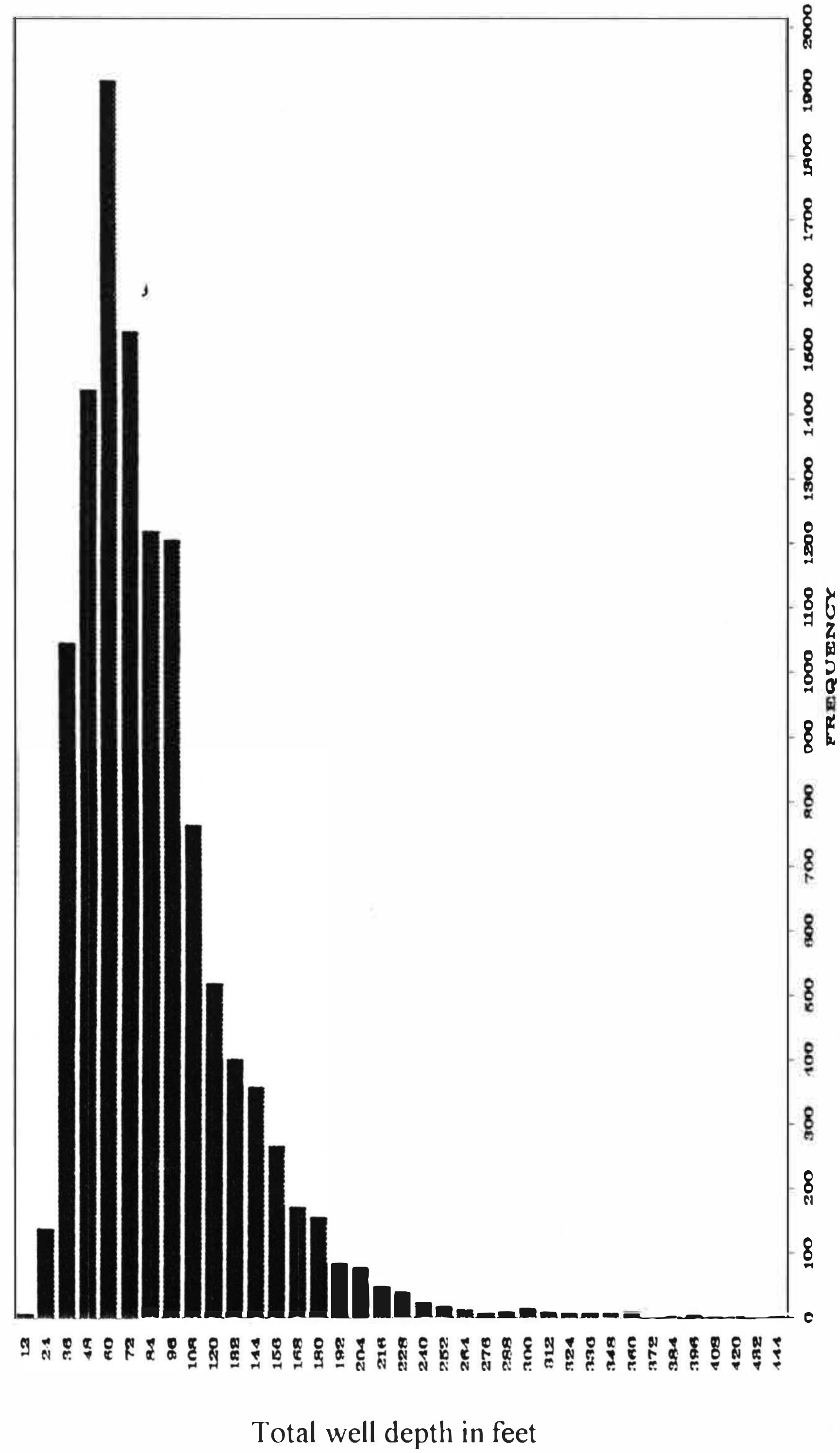


Figure 37. Frequency Histogram of Total Well Depth for Water Wells in Kalamazoo County.

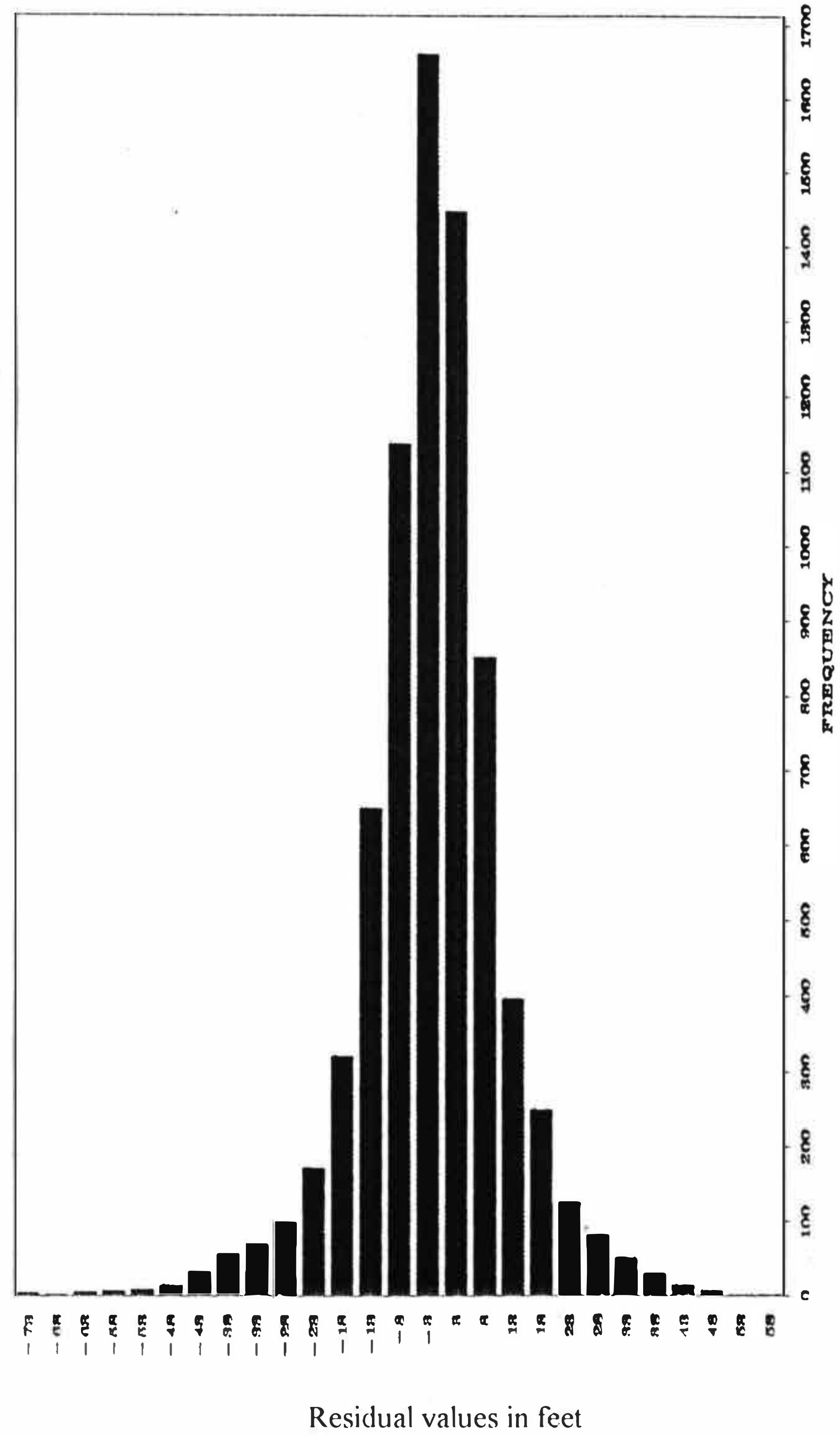


Figure 38. Frequency Histogram of Residual Values for Recharge, Transition, and Discharge Potential in Kalamazoo County.

Table 17

Regression Analysis of County Level Topographic, Shallow Water Table, and Recharge-Discharge Potential Surfaces

Data Type	N	R	Township
Non Gridded Topographic vs Water Table: Shallow DOS Wells	2153	0.8668	0.4998 (Texas) 0.8791(Schoolcraft)
Non Gridded Topographic vs Water Table: All Wells	5,754	0.7882	
Gridded Topographic vs Water Table: Shallow DOS Wells	17,424	0.9105	0.5839 (Texas) 0.8243(Schoolcraft)
Gridded Topographic vs Water Table: All Wells	17,424	0.8849	
Gridded Topographic vs Recharge-Discharge: Shallow DOS Wells	17,424	0.1783	0.3471 (Texas)
Gridded Topographic vs Recharge-Discharge: All Wells	17,424	0.2285	
Gridded Water Table vs Recharge-Discharge Shallow DOS Wells	17,424	0.2317	0.5601 (Texas) 0.1362(Schoolcraft)
Gridded Water Table vs Recharge-Discharge: All Wells	17,424	0.3114	

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

The effectiveness of the recharge-discharge potential methodology was evaluated through computer manipulation of the input data in order to determine: (a) the limits to be placed on the selection of well data, (b) the best interpolation method for mapping of the recharge-discharge potential, and (c) errors inherent in both the raw data and the interpolated data. Statistical evaluation of the raw data and the computer generated gridded data was accomplished through application of a simple regression model. This permitted analysis of the relationship between the water table and the topography, as well as the relationship between the recharge-discharge potential surface and both the water table and the topography. Error identification was accomplished through visual comparison of the interpolated surfaces to U.S.G.S. 7.5 minute topographic maps and through application of regression analysis.

Two townships, Texas Township and Schoolcraft Township, were chosen to test the effectiveness of the methodology because they exhibited the extremes in topographic relief and gradient on the water table in Kalamazoo County. Texas Township exhibits the more complex hydrogeology of the Kalamazoo Moraine and the outwash fan complex to the southeast. Schoolcraft Township exhibits the more homogenous hydrogeology of an outwash plain consisting mainly of well-stratified outwash sands and gravel. Texas Township had a lower correlation between the topography and the water table than did Schoolcraft Township, which can be attributed to its higher relief, more complex geology, and possibly more complex recharge-discharge conditions due to subbasins within the major drainage basins. Anomalous discharge potentials in Schoolcraft Township may reflect the effect of cultural influences on the potentiometric surface. Pumping wells can produce a reversal of the natural flow system over a significant distance.

As a final test of the recharge-discharge potential methodology, two additional sites were studied. The Donnell Lake area provided an opportunity for mapping recharge-discharge potential on a smaller research site that had already been carefully characterized and which had accurate data available. This site permitted comparison of the methodology using both research data and drillers' residential well data. Application of the recharge-discharge methodology at the county level allowed for evaluation of the methodology in a larger geographic region with considerable geologic complexity and a very large database, most of which had not been thoroughly examined for data entry errors.

Conclusions

This study investigated the use of computerized differencing of the gridded surfaces generated from shallow depth of submergence wells and deeper depth of submergence wells for rapidly producing maps of areas of recharge-discharge potential. Of the three interpolation methods available for this study for the interpolation of regularly spaced estimated values from randomly spaced real values (static water elevations derived from computerized water well records), there is a reasonable correlation between all three in regions of low topographic relief.

In Schoolcraft Township water table and recharge-discharge-potential surfaces, produced through application of the three interpolation methods (minimum curvature, kriging, and inverse distance squared), correlated well with R > 0.940. In Texas Township, an area of higher topographic relief, kriging and inverse distance squared produced the best correlation for the water table surface (R=0.939) and recharge-discharge potential (R=0.797). However, for both regions of low relief and regions of higher relief, the range of maximum and minimum elevations in estimated nodal values suggests that inverse distance squared and kriging are most appropriate. Minimum curvature produced extreme values and is considered unacceptable. These extreme values were greater for the recharge-discharge potential grids. For this study, the preferred method for generating topographic, potentiometric, and recharge-discharge potential grids is kriging. Kriging possesses several advantages over inverse distance squared, especially in regions of greater geologic complexity. These advantages include:

1. Kriging attempts to minimize the error of the variance such that the kriged average error is approximately zero.

2. Kriging "decouples" clustered data making the kriged map less sensitive to variability in the data. Inverse distance to the power tends to overemphasize

clustered data by weighting every data point in the cluster equally. Over weighting results in the generation of "bullseyes" on the mapped surface.

3. Kriging uses statistical distance which allows for a customizing of the estimation procedure to a particular pattern of spatial continuity.

Although there was reasonable agreement between surfaces generated with inverse distance and kriged interpolation methods, these additional advantages made kriging the preferred method for generating topographic, potentiometric, and recharge-discharge potential grids.

A recharge-discharge potential map reflects the quality of both the shallow depth of submergence grid and deeper depth of submergence grid. These grids are dependent upon the accuracy of the input data, and the density and distribution of that data over the area to be mapped. It was determined that several additional factors affected the interpretation of recharge-discharge potential. These factors include:

1. Hydrogeology: This method assumes a homogeneous, water-table aquifer that does not significantly affect the model. This assumption was supported in Schoolcraft Township with its higher correlation factor (R) reflecting the more homogeneous nature of the Prairie Ronde Fan. Texas Township, with the more heterogeneous geology of the Kalamazoo Moraine, demonstrated a lower correlation factor (R). Higher topographic relief and more complex geologies result in localized areas of recharge-discharge potential that may interfere with the interpretation of a regionalized map of ground-water flow. Poorly distributed well data may force the interpolation program to include data that are representative of local recharge-

discharge potential and use them to estimate static water elevations that are outside that subbasin. In addition, wells sited in more heterogenous material may not have recovered sufficiently after being developed by the well driller before the static water elevations were taken. This would introduce erroneous data into the ground-water database.

2. The time interval over which the data has been collected may reflect fluctuations in the water table over time, although records show that the natural water levels in wells in southwest Michigan do not fluctuate more than about 5 feet. Reducing the time interval from 30 to 10 years in Texas township did not alter the general recharge-discharge potential interpretation for that township. However, the recharge-discharge potential map for Donnell Lake, which relied on residential water well records collected over 27 years, demonstrated reasonably poor agreement with the recharge-discharge potential map that was based on research data collected within a two week time span. This suggests that the time interval may become increasingly important as the size of the mapped area is decreased. It may also be possible to decrease the range of values for the transition zone as the time interval over which the data is collected is reduced, particularly if the area being mapped is also smaller. A transition zone of ± 1 foot worked well for the recharge-discharge potential map of the Donnell Lake monitoring well data.

3. The magnitude of the area over which the recharge-discharge potential is to be mapped can be very influential in the interpretive quality of the map. The time interval, local heterogeneities, and density and distribution of the well data become

increasingly influential as the mapped area decreases. Narrower contour intervals emphasize anomalous areas of recharge-discharge potential. In contrast, county level maps exhibit a reasonable interpretation of recharge-discharge potential even when the database has not been evaluated for data errors. The larger contour interval overrides smaller anomalous interpretations. Major drainage systems are clearly delineated on the Kalamazoo County recharge-discharge map. Regions of higher topographic relief are clearly defined as recharge. Therefore, the time interval over which the well data has been collected is far less influential at the county level than at the level of a research site.

4. Water wells screened in confined aquifers may exhibit significantly increased hydrostatic pressures, even flowing wells. If these wells were selected for the deeper depth of submergence data set, they could produce an anomalous high on the gridded surface. When subtracted from the shallow depth of submergence surface, there could be an erroneous interpretation of discharge potential in an area that may be correctly interpreted as transition or recharge potential. It may be necessary to limit the total depth of the wells chosen for mapping to avoid the inclusion of wells screened under confining conditions. Identification of confined conditions could, of course, be an advantage of the methodology.

5. Pumping wells potentially lower the static water elevation in nearby wells with shallow depths of submergence, which can result in the area being interpreted as discharge when the natural flow is recharge. This would not be an incorrect interpretation, as the well is in fact creating a point of discharge. The presence of a

pumping well represents a cultural influence on the ground-water flow for that area, and may result in a reversal of the natural flow for that region. Identification of ground-water discharge in a pumping well field is another advantage of the methodology.

6. Recharge basins may produce a local high on the potentiometric surface, thus increasing the static water elevations in nearby shallow depth of submergence wells. This could result in a local recharge area masking regional discharge as along streams. The overall influence of recharge basins on the interpretation of recharge-discharge potential may be less significant than that of pumping wells. Most recharge basins are used to capture stormwater runoff and therefore are intermittent in their affect on the potentiometric surface. Their influence would be greatest when mapping a small study site. Waste treatment lagoons may have a stronger affect on the potentiometric surface as the surface area can be larger and infiltration from the lagoon would be continuous rather than periodic.

This study suggests that application of the recharge-discharge potential methodology utilizing drillers' records can be reasonably effective, but has very definite limitations. The smaller the area being delineated the more important is the quality of the data and the time span over which it was collected. Application to a research site showed that the method produced recharge-discharge potential maps very similar to the manually interpreted research maps if only the research wells were used and these were supplemented with surface water data. Localized heterogeneities will influence the potentiometric surface maps and the recharge-discharge potential maps more if the area is geographically smaller. Therefore, the smaller the study area the more important becomes the evaluation of the input data. When possible, and especially for smaller study areas, individual well records may need to be evaluated with limits established through analysis of the lithologies on each well record. Assuming the surface water is hydraulically connected to the ground water, the addition of surface water data becomes increasingly important as well density and the size of the area being mapped decreases. Addition of large numbers of surface water data points may be included to optimize the accuracy of the contouring routine in the software program and to facilitate recognition of the surface water bodies during the interpolation process. Careful analysis must be given of the resulting surface to avoid the effect of over weighting larger water bodies. Inverse distance to the power would be less effective with the addition of large numbers of surface water points because it does not "decouple" the clustered surface water data.

The use of computerized drillers' records for delineation of recharge-discharge potential is most effective over larger geographic regions underlain by homogeneous aquifers. As the geographic area decreases and/or the heterogeneity of the aquifer increases, there must be more careful selection of the data and the interpolation method to be used in generating the gridded surfaces and the recharge-discharge potential map.

Appendix A

Conceptual Model for Recharge-Discharge Potential

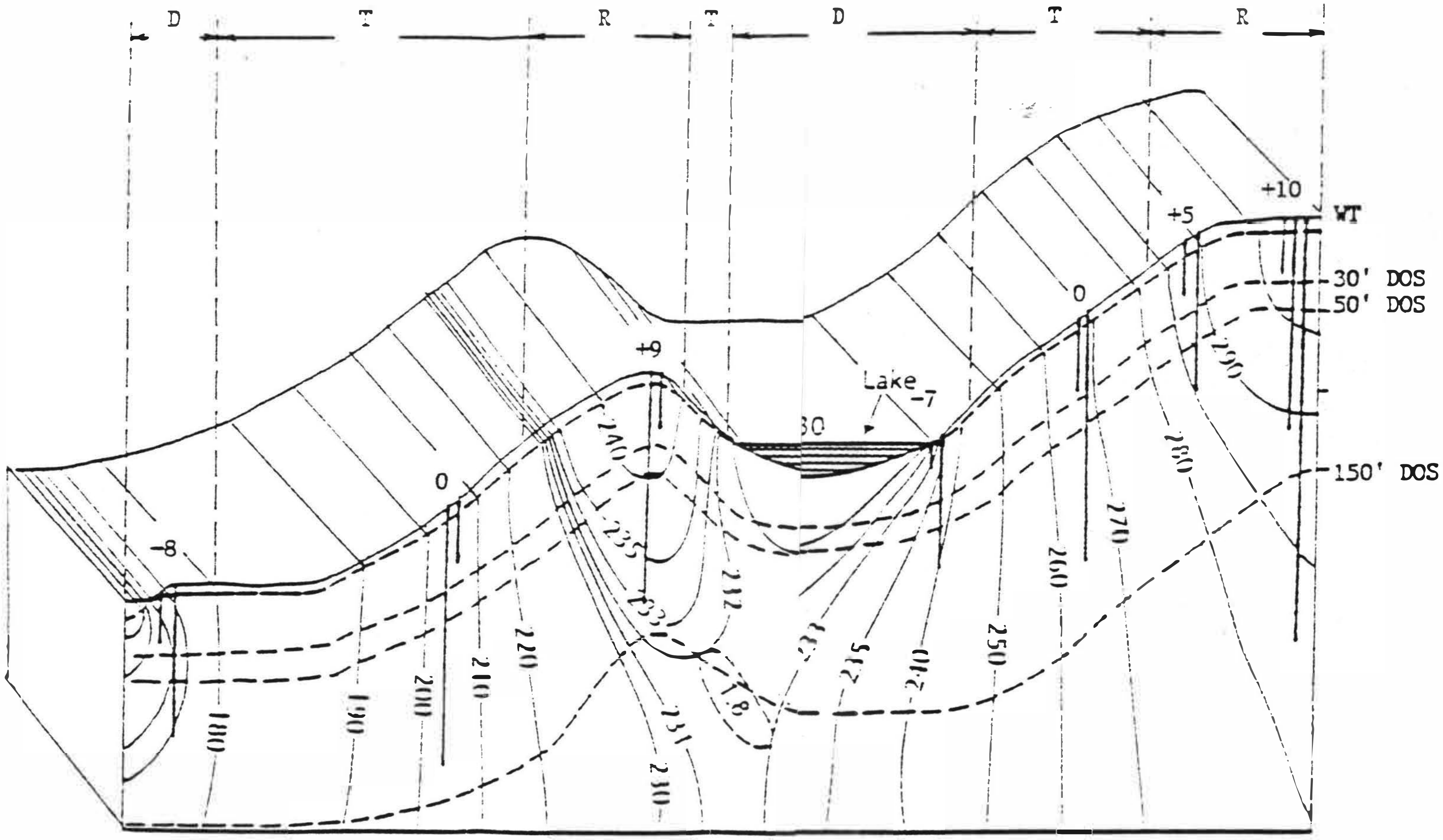
R = Recharge
T = Transition
D = Discharge
+ = Downward Potential
\- = Upward Potential
DOS = Depth of Submergence

EXPLANATION

╌╌╌╌╌╌╌╌ Water Table

230 ———— Line of equal hydraulic potential (ft.) above a standard datum

Interval is variable

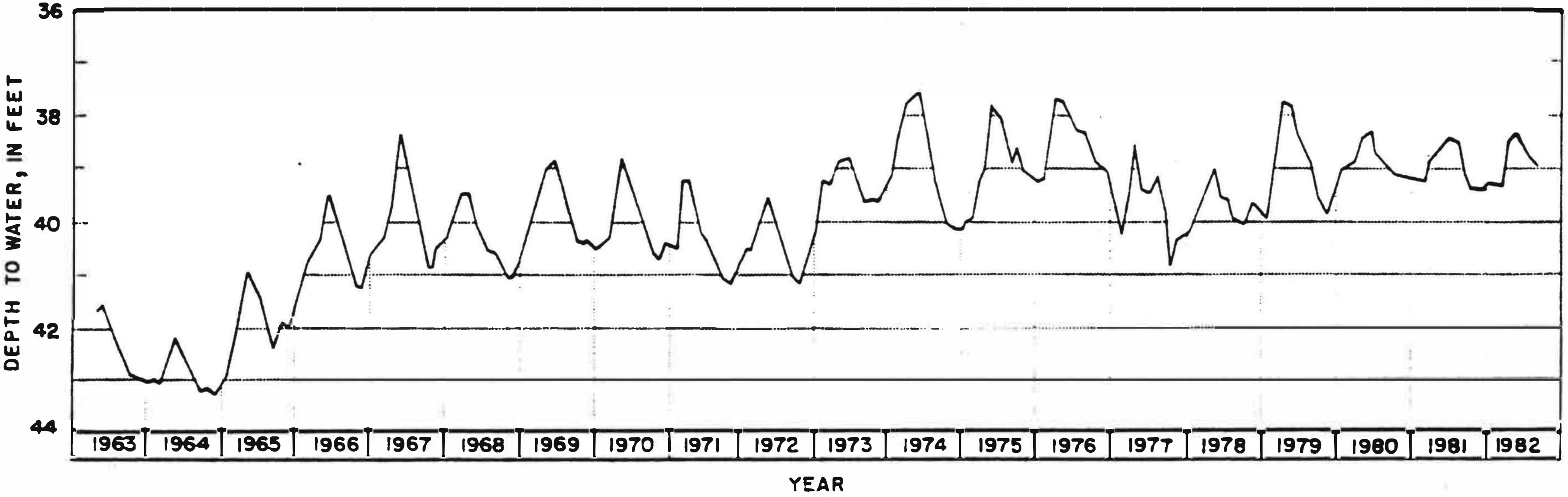


Conceptual Model for arge-Discharge Potential

Adapted from Winter (1976)
R. Passero (1994)

Appendix B

Hydrograph for U.S.G.S. Monitoring Well # 16, Van Buren County

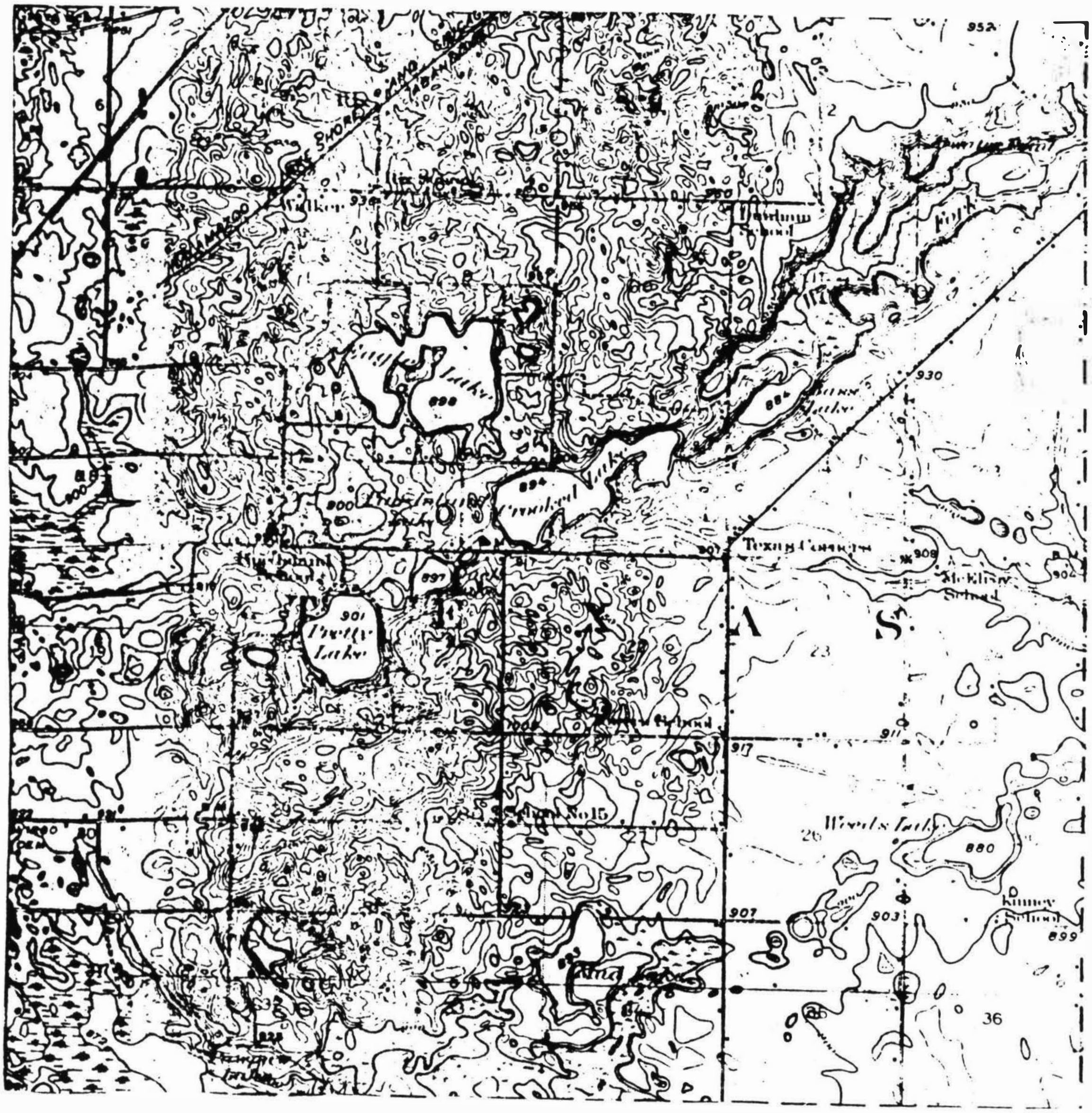


Hydrograph Showing Static Water Level in Well # 16, Van Buren County.

Source: Cummings, T. R., (1984), Hydrology and land use in Van Buren County, Michigan, U.S. Geological Survey: Water-Resources Investigations Report 84-4112.

Appendix C

Topographic Map for Texas Township

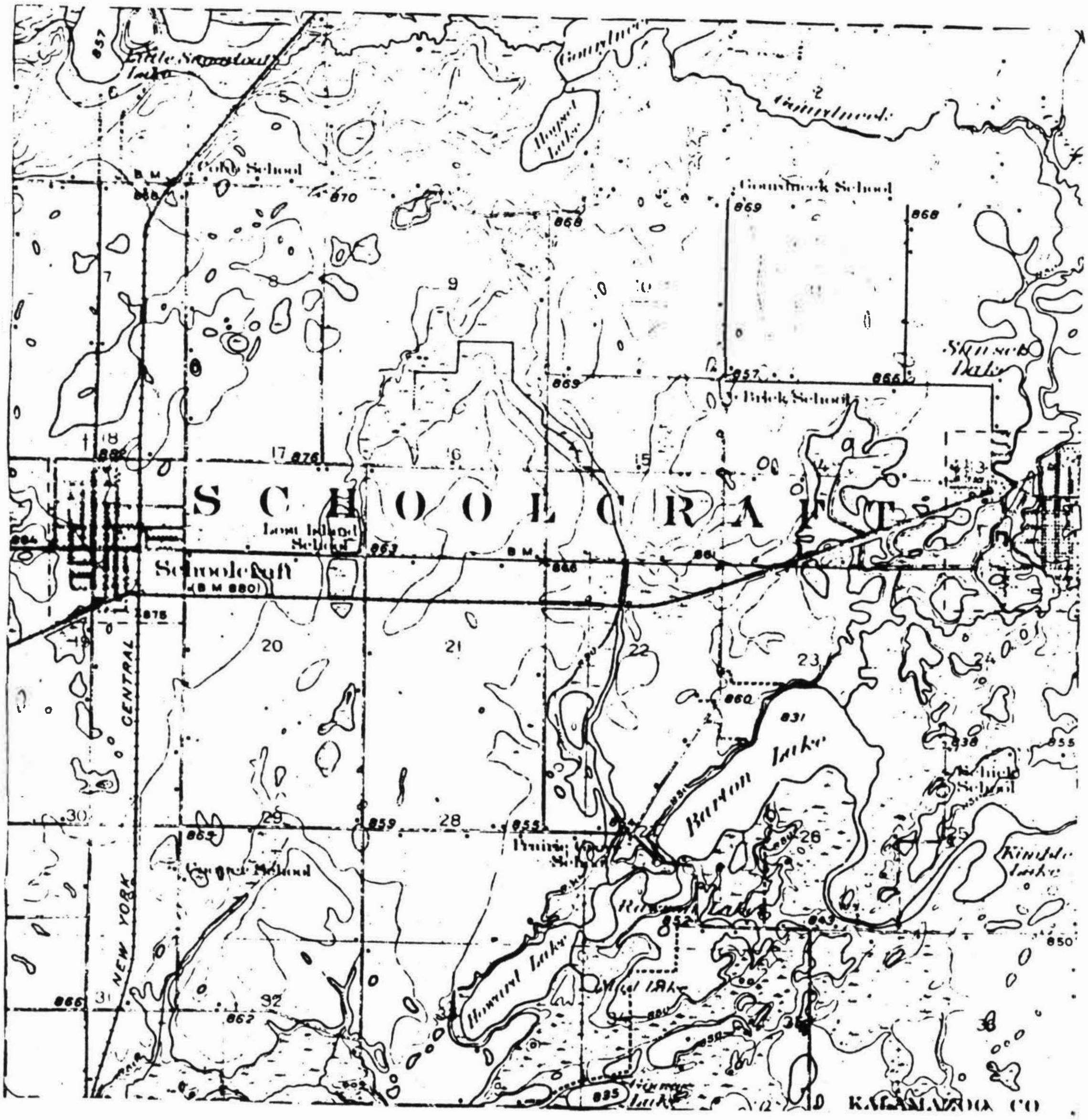


Topographic Map for Texas Township

Source: U.S.G.S. 7.5 Minute Topographic Map

Appendix D

Topographic Map for Schoolcraft Township



Topographic Map for Schoolcraft Township

Source: U.S.G.S. 7.5 Minute Topographic Map

Appendix E

Table 18: Donnell Lake Study Monitoring Well Data

Table 18

Donnell Lake Monitoring Well Data

Well	Depth	Ground Elevation	Static Water Depth From Ground	Depth of Submerg.	Static Water Elevation	Recharge-Discharge Potential
1A	71	897.23	9.05	61.95	888.18	Recharge +3.93 ft.
1B	39	896.90	8.74	30.26	888.16	
1C	14	897.04	4.93	9.07	892.11	
2A	28	901.52	17.74	10.26	883.78	Recharge +0.88 ft.
2B	78	901.48	18.58	59.42	882.90	
3A	28	881.61	11.84	16.16	869.77	Recharge +4.9 ft.
3B	77	881.47	16.60	6.04	864.87	
4A	33	911.48	20.17	12.83	891.31	Transi. -0.02 ft.
4B	44	911.84	20.51	23.49	891.33	
5A	43	921.11	36.73	6.27	884.38	Transi. -0.02 ft.
5B	62	920.63	36.22	25.78	884.41	
6A	73	888.77	24.05	48.95	864.72	Recharge +1.32 ft.
6B	34	889.30	23.26	10.74	866.04	

* units in feet

Table 18-Continued

Well	Depth	Ground Elevation	Static Water From Ground	Depth of Submerg.	Static Water Elevation	Flow Designation
7A	93	867.49	24.44	68.56	867.49	Discharge
7B	43	861.23	30.59	12.41	861.23	-12.41 ft.
8A	53.5	905.71	45.94	8.10	859.77	Discharge
9A	19	865.88	5.25	13.75	860.63	Transi.
9B	42.5	866.29	5.67	36.83	860.62	+0.01 ft.
10A	74	883.50	10.17	63.83	873.33	Transi.
10B	21	883.81	10.49	10.51	873.32	-0.01 ft.
11A	73	908.12	22.86	50.14	885.26	Recharge
11B	19	908.26	18.11	0.89	890.15	+4.89 ft.
11C	38	907.02	16.89	21.11	890.13	

* units in feet

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